Variation theory as a lens for interpreting and guiding physics students’ use of digital learning environments

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Abstract

In this paper, we examine the implementation of a digital learning environment—namely, the physics software, Algodoo—which is less-constrained in its design than the digital learning environments typically used in physics education. Through an analysis of a case study, we explore a teaching arrangement wherein physics teachers responsively guide small groups of students as they use less-constrained DLEs in a mostly self-directed manner. Our analysis leads to practical recommendations for physics teachers in terms of (1) how to glean useful information about students’ existing physics knowledge through observation and (2) how to responsively intervene so as to productively guide students toward the learning of particular physics content. These recommendations stem from our use of the variation theory of learning as a lens for physics students’ use of digital learning environments.

Keywords: creativity, Algodoo, digital learning environments, variation theory, constraints, dimension of variation, relevance structure

(Some figures may appear in colour only in the online journal)

1. Introduction

Many digital learning environments (DLEs) utilized in and developed for physics education—such as PhET simulations (Wieman et al 2008), Physlets (Christian and Belloni 2001) and QuVis animations (Kohnle et al 2012)—tend to be centred on particular physics phenomena and/or concepts. These phenomenon-specific DLEs function for students as well-defined
arenas of attention: that is, in the words of their designers, these DLEs are ‘specifically designed to productively constrain students’ focus on the aspects experts believe are most important’ (Wieman et al 2008, p 395) for a given phenomenon or context. The DLEs that take this approach—which we refer to in this paper as constrained DLEs—conform to what researcher Manu Kapur calls the ‘deeply ingrained maxim’ in education research literature that students require significant, externally-imposed constraints to avoid failure during problem solving (Kapur 2008, p 382).

However, some education research scholars have begun to question the ‘overemphasis on efficiency’ (Schwartz et al 2005, p 34) implicit in some of the types of learning environments that present students with all of the ‘necessary’ aspects of a context up front. The pursuit of efficient conceptual mastery in constrained physics DLEs might inadvertently mean that students do not get the opportunity to engage in some of the messier aspects of doing physics (Bryan 2006, Chinn and Malhotra 2002), do not have the room to exercise innovation during problem-solving (Schwartz et al 2005), or do not falter in ways that may be beneficial to learning in the longer term (Kapur 2008, Kapur and Kinzer 2009). Beyond this, the imposed structure of constrained DLEs may inhibit desirable learning goals in physics education such as students developing an interconnected view of physics and/or students pursuing their own lines of reasoning in creatively-divergent ways.

In this paper, we examine the implementation of a different kind of DLE—namely, the physics software, Algodoo—which is less-constrained in its design than the DLEs typically used in physics education. Through the analysis of a case study, we explore a teaching arrangement wherein physics teachers responsively guide small groups of students as they use less-constrained DLEs in a mostly self-directed manner. Our analysis leads to practical recommendations for physics teachers in terms of (1) how to glean useful information about students’ existing physics knowledge through observation and (2) how to responsively intervene so as to productively guide students toward the learning of particular physics content. These recommendations stem from our use of the variation theory of learning (Marton 2015, Marton and Booth 1997, Marton and Pang 2013)—the relevant details of which are taken up later in this paper—as a lens for physics students’ use of DLEs (Ingerman et al 2009).

To begin, we motivate our interest in less-constrained DLEs such as Algodoo by further discussing the affordances/constraints view of physics DLEs as found in the existing physics education research (PER) literature. Thereafter, we introduce three key elements from the variation theory of learning that are pertinent for our analysis. Finally, via our case study of an activity in which a pair of physics students used the less-constrained DLE, Algodoo, for the first time, we illustrate the usefulness of variation theory for physics teachers as a lens for identifying students’ existing knowledge and informing interventions that support the learning of specific physics concepts within DLEs.

2. Constraints in digital learning environments

A predominant precept in the design and implementation of DLEs for the teaching and learning of physics is the notion of productive constraints\(^3\) (Adams et al 2008, Christian et al 2015, Finkelstein et al 2005, Podolefsky et al 2010, Roth 1995, Roth et al 1996, Wieman et al)

\(^3\) Such work borrows from Gibson’s (1977) framing of affordances and constraints in learning environments. Affordances can be thought of as the possible and productive actions to be carried out with a tool, as perceived by the user. Constraints, on the other hand, ‘restrict the actions that a user can take’ (Podolefsky et al 2010, p 3). Thus, in using the term ‘constrained DLEs’ within this paper, we refer to those learning environments that intentionally restrict the actions that students can take in the exploration of particular phenomena.
(Productively-) constrained DLEs are each focussed around a specific phenomenon (or small set of phenomena) such that students are granted intentionally-delimited control over a collection of variables that pertain to said phenomenon. For example, the Wave Interference simulation (PhET 2020) centres on interference phenomena in an interactive ‘wave pool’, affording users control over the frequency and amplitude of waves as well as the separation between wave sources and separation/width of slits in a movable screen (see Podolefsky et al 2010). The frequency slider in this simulation is purposefully constrained to the range of frequencies ‘that are pedagogically useful for exploring interference phenomena’ and a maximum of two sources and two slits are allowed, since any more ‘would be difficult for students to interpret’ (Podolefsky et al 2010, p 10). The rationale given in the PER literature asserts that constrained DLEs improve physics students’ conceptual mastery (seen in, for example, Finkelstein et al 2005, Keller et al 2006, Zacharia and Anderson 2003) due to the manner in which those environments provide students with, and direct students’ attention toward, the relevant features for each physics scenario. In a related manner, constrained DLEs have also been shown to support students’ productivity during self-guided exploration (Adams et al 2008, Podolefsky et al 2010). Results such as these lend credence to the argument that physics students need sufficient scaffolding during exploratory activities so as to prevent them from ‘creating situations which are unnecessarily complicated or distracting’ (Podolefsky et al 2010, p 10; see also the related discussion on the necessity of imposed structures during learning in Kirschner et al 2006, Sweller et al 2007). Aside from the theoretical arguments for the use of constrained DLEs in the PER literature, the extensive utilization of these DLEs in physics education likely stems from the pressures put on physics teachers to efficiently teach large numbers of students and/or manage limited sets of resources.

Though constrained DLEs may promote physics students’ conceptual understanding, there exist other potential learning goals for physics students that may not be promoted by the constrained nature of these DLEs. For one, since many students come to view physics as a fragmented field of weakly-connected facts (Bagno et al 2000, Elby 2001, Hammer 1994), physics educators may want to encourage students to work fluently across and between content areas to help construct a more topically-interconnected picture of physics knowledge. Constrained DLEs effectively isolate each physics phenomenon into distinct environments, so they may have the effect of contributing to students’ siloing of physics knowledge into separate thematic areas. Another objective in many modern science classrooms is, increasingly, for students to explore their own lines of inquiry in creative/innovative ways (Mishra and the Deep-Play Research Group 2012, Newton and Newton 2014, Schwartz et al 2005). Here again, by acknowledging that constrained DLEs purposely limit the possible outcomes that students can explore (so as to not be ‘distracting’), it appears reasonable that these environments could end up curtailng opportunities for students to exercise their creativity. For instance, physics teachers may want students to work in environments where they can construct their own testing experiments (Etkina et al 2019), make conceptual detours, discover the relevance of scientific variables for themselves, and even productively fail (Kapur 2008, Kapur and Kinzer 2009).

In light of these possible drawbacks to constrained DLEs, we are motivated in this paper to explore the potential utility of less-constrained DLEs—specifically, the physics software, Algodoo. Still, short of endorsing a discovery-only type of learning which seemingly avoids constraints altogether, we choose to investigate what we see to be the relatively underexplored teaching arrangement where students use less-constrained DLEs in combination with the guidance of a responsive teacher (Robertson et al 2016). Responsive teaching involves teachers

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4 In the context of Podolefsky et al (2010), ‘productive exploration’ referred to students remaining engaged in sensemaking and seeking answers for their own questions within DLEs.
foregrounding students’ ideas, explicitly recognizing their disciplinary value, and using them as starting points for classroom activity (Robertson et al. 2016). In the context of this paper, the guidance of a responsive teacher entails that students are initially given the choice to create freely within a less-constrained DLE and then the teacher selects relevant physics topics and phenomena from within the students’ creations as the topics of further discussion/unpacking.

The key difference between most physics education approaches based on constrained DLEs and the one we examine in this paper is that the constraints which serve to corral students’ exploration toward certain concepts and/or procedures are in part imposed by a teacher, rather than exclusively by virtue of the DLE design. Arrangements involving the ‘complementary roles’ (Tabak and Reiser 1997) of DLEs and teachers have been studied previously in the context of computer-supported collaborative learning (CSCL). Though few in number, these studies have found that teachers can play a crucial role in augmenting the work that students do within DLEs (Tabak and Reiser 1997), and that scaffolding which is productive for students’ learning might be ‘distributed’ (Puntambekar and Kolodner 2005) by means of a ‘synergy’ between software scaffolds and teacher scaffolds (Tabak 2004). In the present paper, we provide examples of how the combination of a less-constrained DLE with responsive teacher guidance can empower students to (1) transition smoothly between physics topics, (2) engage creatively with physics content, and, importantly, (3) still develop conceptual understanding of relevant physics phenomena.

In order for physics teachers to make productive use of less-constrained DLEs such as Algodoo, however, recommendations for optimally-responsive teacher guidance are warranted. To address this point, we choose to adopt the perspective of variation theory, which, when applied to students’ use of DLEs such as Algodoo, lends a useful frame for analysing the ways in which students come to discern the critical aspects of physics phenomena—and, thus, informs our recommendations for teacher interventions.

3. The variation theory of learning

The variation theory of learning (or simply, variation theory) emerged in the late 1990s from the Swedish research tradition of phenomenography (Marton and Booth 1997), the latter of which has sought to describe the qualitatively different ways that people experience or think about the world. As such, variation theory is a perspective on learning that focuses on the manner in which people come to perceive and discern things. While variation theory has been used to explain the entire breadth of learning processes from children’s first perceptions of noticeable differences in their environments (e.g. Holmqvist Olander and Nyberg 2014) to University students’ comprehension of complex fields of study (e.g. Marton 2015 and Marton and Pang 2013), the analysis we conduct in the present paper calls for the somewhat conservative use of three key variation theory concepts: (1) contrast, (2) dimension of variation, and (3) relevance structure.

3.1. Contrast (change against a background of sameness)5

The first concept from variation theory that we make use of in this paper is the principle of contrast—or change against a background of sameness. Put simply, this principle says that,

5 A note about contrast: there are numerous tenets of variation theory that coincide with the recommendations of research on contrasting cases (CC) (see, for example, Jax et al. 2019, Kuo and Wieman 2016), the latter being more common in PER to date. Still, despite the conceptual overlaps in the literature of variation theory and CC, the theoretical frameworks have yet to be meaningfully related to one another. As there has been a substantial research contributed under the banner of both perspectives, establishing a connection between the two—beyond the scope of this footnote—would undoubtedly benefit PER and education research more broadly.
in order to maximize the possibility of learning about an aspect, one should experience that aspect vary against a fixed background (Fredlund et al. 2015a, Marton and Booth 1997, Marton and Pang 2013). This contrast principle should ring familiar to scientists, especially since variable change against a background of sameness stands as a core tenant in empirical investigations that call for the control of variables. What Marton and other proponents of variation theory suggest, however, is that the systematic (though, often unconscious) variation of critical aspects underpins humans’ perception and learning from the earliest stages of childhood development onward, not merely the intentional practices of the scientist engaged in experimental work.

The emphasis on contrast is, perhaps, the key principle that differentiates variation theory from other learning philosophies. A common approach advocated for in teaching and textbooks is to provide students with ‘many examples in which the same concept is at work’ (Bransford et al. 2000, p 20). However, the principle of contrast dictates that students would be better served by being first shown a single context (background of sameness) within which the desired concept varies (changes). Consider an example from physics wherein students are expected to learn about the damping coefficient, $\zeta$, in second order systems (adapted from Fraser and Lindner 2009). In the pursuit of maximizing the possibility of learning, it is insufficient to show students the examples of critically-damped shocks on a dirt bike, a critically-damped pointer in the dial of a moving coil ammeter, and a critically-damped RLC circuit in a band-pass filter. The changing backgrounds in these examples would only be instructive for students vis-à-vis the damping coefficient insofar as the students had already perceived what a damping coefficient of one ($\zeta = 1$) means for the behaviour of a system (i.e. they had already learned what ‘critically-damped’ means). Instead, variation theory holds that with regards to the possibility that the students perceive the desired aspect of damping, the possibility for learning to take place would be optimized by first showing the students an undamped, under-damped, critically-damped, and overdamped version of a single oscillatory system (i.e. the change of the damping coefficient against the fixed background of, for example, the same dirt bike).

3.2. Dimension of variation (DoV)

Having established the importance of contrast (as a pattern of change against a background of sameness) for learning, the second concept from variation theory that we make of use of in this paper is the notion of a dimension of variation. A dimension of variation is simply an aspect across which a range of values can be experienced (Fredlund 2015, Häggström 2008, Marton and Booth 1997, Maunula 2017). In the example used above, the damping coefficient, $\zeta$, is a dimension of variation. Importantly for educators, a dimension of variation is an aspect which is ‘made possible to discern’ (Häggström 2008, p 57) through variation. Contrast is the suggested approach to varying things in order to maximize students’ discernment of a particular dimension of variation. In our use of ‘dimension of variation’ (henceforth, DoV), we refer in this paper to physical parameters such as velocity, density, and spring constant, which are involved in students’ exploration of Algodoo. The reason that we use the term,

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6 Instances where the background changes behind a focal aspect are quite common in teaching and learning. Proponents of variation theory recognize the value of this type of variation—which they call generalization (as opposed to contrast)—but, importantly, see it as pedagogically useful only so long as it is preceded by contrast (Marton 2015, p 51).

7 For the sake of clarity, we make use of the abbreviation ‘DoV’ so as to not conflate the ‘D’ of DoVs with the mainstream physics use of ‘dimensions’ in reference to spatial and temporal dimensions (though, to be clear, spatial–temporal dimensions could certainly be seen as DoVs in the context of learning).
DoV, in this paper rather than more generic (or, perhaps, physics discipline-typical) alternatives such as ‘aspect’ or ‘parameter’ is twofold: (1) the label, DoV, foregrounds that variation is at the core of how these aspects or parameters are first discerned (and later used) by students and (2) the term, DoV, aligns well with how parameters are made accessible to the user in DLEs such as Algodoo—i.e. through a user’s manipulation of buttons and sliders to achieve variation.

Proponents of variation theory have tended to track when and how certain DoVs are ‘opened up’ in the process of learning (i.e. discerned for the first time; see Marton 2015, Marton and Booth 1997, Watson and Mason 2006) and how certain representations provide access to particular DoVs (Fredlund et al 2015a, Fredlund et al 2015b). In this paper, we make use of the idea of ‘opening-up’ a DoV for when students first learn about a particular concept, but also depart from previous uses of variation theory in order to highlight how physics students can recruit already-learned DoVs. Specifically, we find it meaningful to track those instances when students choose to involve previously-discerned DoVs in their pursuit of a particular goal. We take the position that there is an important qualitative difference between those instances where a DoV is discerned for the first time (i.e. opened up) and those instances where a previously-discerned DoV is incorporated (which we call ‘involved’). This distinction is especially pertinent for an analysis of students’ use of less-constrained DLEs, where the students must select from a relatively large collection of DoVs which may or may not be relevant for the task at hand. In such environments, the students’ choice of which DoVs to vary is, in itself, informative (see below).

3.3. Relevance structure

The third concept from variation theory that we make use of in this paper is the construct of a relevance structure. From his research with physics students making predictions about torsion pendula, Székely (1950) found that some things come to be seen as being more relevant than others for a given task. Drawing on Székely’s work, Marton and Booth (1997) characterized this collection of things deemed relevant as a person’s relevance structure for a particular situation. A relevance structure is what is deemed to be needed (by the person) to appropriately deal with a situation at hand.

In paying attention to which DoVs students choose to involve in a given context (as described above), it is possible for teachers and researchers to gain insights into the relevance structures that students enact within certain contexts. This stems from the fact that, since less-constrained DLEs such as Algodoo host a wider array of parameters which may or may not be relevant to a particular phenomenon, the students’ choice of which parameters to vary provides the observer with a sense of what those students deem to be relevant. We refer to the relevance structures implied by students’ choice of DoVs as the students’ enacted relevance structures.

4. Algodoo and variation in digital learning environments (DLEs)

The less-constrained DLE that we feature in this paper, Algodoo (Algoryx 2019; for a more detailed description, see Gregorcic and Bodin 2017), is two-dimensional Newtonian
environment that allows students to draw shapes which fall down, bounce, swing, slide, and generally interact with one another according to Newtonian mechanics (images of the Algodoo interface as well as illustrations of how students interact with Algodoo on an interactive whiteboard are included in section 6). The software allows students to construct a wide range of models from the simple (e.g. projectiles or pendula) to the elaborate (e.g. suspension bridges or engine transmissions). While using Algodoo, students can create dynamic models of physical situations using geometrically simple shapes and disciplinary-relevant objects such as springs, axels, motors, thruster engines, ropes, and gears. Within the student-created constructions, the characteristics (physics-relevant DoVs) of each of these objects can be intentionally varied to explore how properties such as the coefficient of friction, spring constant, and even gravity/air resistance can influence the behaviour of a model.

For the purposes of this paper, our perspective informed by variation theory depicts physics DLEs—such as Algodoo, but also PhET simulations, Physlets, QuVis animations, etc—as collections of physics DoVs. We offer this as an alternative picture of DLEs to the affordances/constraints framing discussed by authors such as Podelefsky et al (2010). In our view, constrained DLEs provide only a select few DoVs at a time (a handful of sliders for key physics parameters, for example), while less-constrained DLEs host a relatively large collection of DoVs from which students can choose. Our proposal in this paper is that teachers can pay particular attention during students’ exploration of DLEs to see when and how certain DoVs are varied. By doing so, teachers can gain insights into what students think matters within a given context (i.e. the students’ enacted relevance structures) and can also direct students toward opening up DoVs for the first time.

5. Collection and presentation of data

In what follows, we present excerpts from a case study of two students as they interacted with Algodoo on an interactive whiteboard (IWB). The case we present was selected from a series of several data sessions collected with different pairs of students within the period of a month. This specific case was chosen due to the richness we saw in the students’ interactions with the DLE. All participants in our data collection sessions were pre-service physics teacher students who volunteered from a pool of students taking their first semester of physics coursework at a Swedish University9. We encouraged the students to sign up with another student with whom they were comfortable working, such that the pairs of students were self-organized. This particular class of students was selected on the basis that we had an amicable relationship with the course-responsible teacher and because we anticipated the students’ interest in becoming teachers themselves might make them more likely to volunteer for a study around physics instructional technology.

We arranged sessions with the pairs of students during which they were first asked to explore Algodoo at their own pace10. Each session began with a brief introduction to the technology (both Algodoo and the IWB) and we (the researchers) remained in the room, occasionally intervening with questions or tips throughout the sessions to assist the students in realizing their own ideas and suggest further avenues of possible exploration. Though our actions were not conceived as such at the time, the intermittent feedback that we instinctively gave to the students

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9 In the Swedish context where the data were collected, physics teacher training consists of five years of study at University. The pre-service physics teacher students who participated in our study were in the first of these years.

10 After the initial part of the session where the students got to know the technology, all the pairs of students were given a specific physics prompt involving a puck rolling down a ramp (see Euler and Gregorcic 2018). In the present paper, we choose to focus on only the first part of the session which at the outset did not have an explicit physics prompt.
during the data collection sessions now appears to exemplify the type of responsive guidance we recommend alongside students’ exploration of less-constrained DLEs in this paper. Each of the sessions was videotaped and later transcribed following a multimodal approach (i.e. accounting for the students’ talk, gesture, and interaction with the surroundings) (Baldry and Thibault 2006, Bezemer 2014).

In what follows, we present and analyse parts of one of the sessions (which lasted approximately 45 min in total), wherein the two participating students (referred to as S1 and S2) explored Algodoo with the responsive guidance of two researchers (R1 and R2). Our analysis of this case involved first categorizing the overall progression of the session into four episodic parts and then identifying instances within each part where the students meaningfully involved or opened up various DoVs. Our analysis includes sections of written transcript as well as line illustrations drawn from particular frames of captured video, taken together to constitute a multimodal re-representation of the audio and video data (Baldry and Thibault 2006, Bezemer and Mavers 2011, Hammer and Berland 2014). The sections of transcript comprise the students’ speech (written in plain or underlined text) and, when applicable, the students’ non-verbal actions (written in [bracketed, italicized] text). Underlined text denotes an instance of speech that coincided with nonverbal activity (with the bracketed text immediately following the underlined text used to describe the nature of the nonverbal activity; see Euler et al. 2019 for another example of this method). Additionally, at times in our analysis, things occurred between the chunks of transcript shown here in the manuscript, but are not depicted in full detail. When this is the case, standalone bracketed text is used to transition back into the point where the transcript resumes. If no bracketed text precedes a section of transcript, it can be assumed that the new lines pick up immediately from where the last lines of transcript left off.

6. Analysis

The overall progression of the case presented here can be broken into four consecutive parts (figure 1): in part 1, the students pursued—and successfully met—a self-set goal; in part 2, the researchers asked the students to reflect on what was done to meet that goal; in part 3, the researchers gave the students a new, related goal to build something based on the discussion in the part 2; and finally in part 4, the researchers guided the students toward learning about specific physics parameters with which the students did not immediately show confidence. With concern for the length of this paper, we present our analysis of parts 1 and 4 and summarize parts 2 and 3. While the entire progression of this case is useful and interesting from the standpoint of physics teaching and PER, parts 1 and 4 contain examples of the two central recommendations for teachers that emerged from our analysis of the entire session. Specifically, with part 1 we showcase how physics teachers can better understand students’ enacted relevance structures by observing which DoVs the students involve during their pursuit of a goal. With part 4 we highlight how physics teachers can responsively guide students toward opening up a new DoV by encouraging them to make simpler digital constructions where the variational pattern of contrast is more readily experienceable for that DoV.

6.1. Part 1—students pursue a self-set goal: puncturing the sponge

In part 1, we provide an example of how, in pursuit of their own goals within Algodoo, the two students choose to involve various DoVs and thus constitute an enacted relevance structure for
Figure 1. The four parts of the students’ exploration of Algodo. In this paper, our analysis focuses on the first and last of these (parts 1 and 4), as these two parts best highlight the two distinct ways that we see variation theory playing a productive role for physics teachers in interpreting and guiding students’ use of less-constrained DLEs.

Figure 2. S1 (left) selects the ‘Spongify’ option from the dropdown Edit menu (inset, taken from a screenshot of Algodo) as S2 (right) looks on. Images of Algodo are used with permission. Reproduced with permission from Algoryx (2019).

our analysis (and, similarly, for the interested physics teacher). By tracking the DoVs which students involve, we can construct a view of how students make sense of various disciplinary-relevant aspects of the physics phenomena at hand.

We begin our analysis of part 1 immediately after the students have ‘spongified’ an object using the ‘Spongify’ function in Algodo’s dropdown Edit menu. As both students try out the buttons of the software, S2 spongifies a roughly semi-circular object (figure 2). This results in the internally-segmented shape (figure 3)—referred to hereafter as ‘the sponge’.

It is useful to note that sponges in Algodo are modelled as a collection of rigid (non-flexible) discs held together by elastic connectors (springs). With some technical help from the researchers, the students draw a smaller object, lodge it inside the sponge, and then liquefy
Figure 3. A screenshot of the Algodoo interface with a recreation of the sponge object, selected to show the many internal objects making it up. Images of Algodoo are used with permission. Reproduced with permission from Algoryx (2019).

the smaller object to create a trapped pocket of red liquid. Once the pocket of liquid is created, S1 begins drawing a shape to the left of the sponge and R1 asks, ‘What are you trying to do?’

At this early stage of the students’ exploration of Algodoo, the students establish their own goal to puncture the sponge with a makeshift arrow. This goal emerges from the students’ engagement with the DLE and, importantly, is not something imposed by the researchers externally. In terms of variation theory, our analysis judges the relevance of the DoVs involved by the students based on whether or not the involvement of the DoVs move the students toward their own goal. For instance, S1 mentions the desire to involve the arrow’s velocity (line 1) and subsequently locates the Velocities submenu (line 6). With this act, it is

|   | S1: | Uhh... trying to make an arrow and give it a velocity to see if it can pierce the spongified big pink blob [gestures toward the sponge] |
|---|-----|----------------------------------------------------------------------------------------------------------------------------------|
| 2 | R1: | Ah okay!                                                                                                                            |
| 3 | R2: | So, you can maybe try like a uh– a sharp thing–                                                                                     |
| 4 | S1: | [draws an arrow shaped object as R2 is talking]                                                                                     |
| 5 | R2: | Yeah, yeah, yeah and then maybe drop it from– or throw it in–                                                                   |
| 6 | S1: | [continuing to work as R2 talks, double taps the arrow object to bring up the dropdown menu because I saw somewhere... [selects the 'Velocities' submenu] add velocity. [selects the 'Velocities' submenu] |

11 Though the goal of puncturing the sponge was first initiated by S1, it is apparent from the exchange that follows that the goal was quickly taken up by S2 as well.

10
apparent that the students are moving toward their goal, since the arrow-velocity DoV is, indeed, relevant for sending the arrow into the sponge. In what follows, the students go beyond identifying that the arrow’s velocity is relevant to enact how they see the arrow’s velocity is relevant:

[after some technical difficulties with the Algodoo software crashing, the students resume]

| Line | Actions                          |
|------|----------------------------------|
| 7    | S1: Let’s just speed this one up. [drags the ‘Speed’ slider to the right] How much? [leaves finger on the slider and looks to S2] |
| 8    | S2: Full speed. [laughs]         |
| 9    | S1: [moves the Speed slider all the way to the right] Full speed ahead. [adjusts slider to make sure it is at the maximum value] Like that. [closes the dropdown menu] |
| 10   | S2: And now we play. [taps the play button; the arrow flies off the screen to the left (away from the sponge)] |

The students ‘give [the arrow] a velocity’ (line 1) by dragging the Speed slider to the right within the Velocities submenu, but the resulting motion has the wrong direction. This is the first observable instance of actual variation that the students carry out for the purposes of meeting their goal. As such, the students’ involvement of speed provides an indication that, for them, the speed of the arrow—though, not necessarily the velocity, as they had stated earlier—is relevant for puncturing the sponge. Since the students’ manipulation of the Speed slider does not require them to explicitly attend to the direction of the arrow’s motion before hitting play, it is, at first, unclear from an outsider’s perspective whether the students appreciate both speed and direction as relevant for the arrow’s motion before hitting play. However, once the play button is pushed, Algodoo unavoidably couples a direction to the speed by virtue of physical necessity. Thus, the students are compelled to contend with the relevant DoV of direction as well as speed:

| Line | Actions                          |
|------|----------------------------------|
| 11   | S1: [presses pause] Whoops.      |
| 12   | R2: Wrong direction.             |
| 13   | S1: Yeah, uhh... [presses the undo button and then opens up the Velocities submenu again; he finds the slider labelled ‘Velocity (X)’ and slides it from the left end to the right end] Like that. And... [examines the other sliders in the Velocities submenu; then starts moving the ‘Velocity (y)’ slider slightly to the left, only to stop himself] Is negative-y up or down? [leaves finger on slider] |
| 14   | R1: Down.                        |

12 It is worth noting that the students opt to send the arrow into the sponge by imparting the arrow with an inherent velocity, rather than dropping it or throwing it as R2 suggests in passing (line 5). Imparting an arrow with a velocity is an ‘unrealistic’ approach for making arrows move in the real world, so when employed within the domain of Algodoo, S1’s choice here serves as an example of the students recruiting the mathematically-rich materials of the DLE in unexpected, yet fruitful ways (see Euler and Gregorcic 2019 for further discussion of this point).

13 This inevitable projection of the arrow’s speed onto a specific direction highlights a particular representational affordance of Algodoo and other visually-dynamic DLEs: though speed and direction can be disambiguated from one another in an abstract sense (as they are in this sentence and in many physics classroom discussions), actual motion (represented in Algodoo or otherwise) will necessarily involve both speed and direction. We can say that the meaning-making system of Algodoo forces the possible meanings of ‘speed’ in this case to be in a particular direction, just as a picture necessarily forces the possible meanings of ‘face’ to a particular set of facial features and hairstyles (see a relevant discussion of transduction in Volkwyn et al 2019).
Figure 4. The Velocities submenu in Algodoo, which the students use in lines 7 and 13 to vary the velocity of the arrow. Images of Algodoo are used with permission. Reproduced with permission from Algoryx (2019).

Here, from the perspective of variation theory, S1 demonstrates an appreciation for the relevance of the DoVs of $x$- and $y$-velocity by involving them in the pursuit of the goal at hand. Importantly, we observe S1 considering both components of the arrow’s velocity and (correctly) choosing to update only the $x$-component and not the $y$-component. It should be noted that the option to edit the arrow’s direction of motion directly (i.e. irrespective of the speed) exists in the Velocities submenu via the ‘Angle’ slider and wheel (figure 4). Still, S1 makes use of the Cartesian projection of velocity when redirecting the arrow’s motion. With each of these intricacies in mind, S1’s updating of the arrow’s velocity gives even stronger credence to the developing notion that these student(s) can meaningfully make use of the complex DoV of velocity in accordance with the conventions of the physics discipline—that is, a disciplinarily-correct version of velocity appears in the students’ enacted relevance structure for the given context.

Following the adjustments made to the arrow’s velocity shown above (lines 11–14), the students press the play button to run the simulation again. This time, the arrow is sent in the correct direction (into the sponge), but bounces off without successfully puncturing it. The students pause Algodoo and proceed as follows.

[after correcting the arrow’s direction of flight]
Here, the students involve two more DoVs—namely, the arrow’s density and the sponge’s density—thereby signalling their appreciation that these DoVs are relevant for lodging the arrow into the sponge. In fact, the students verbally announce that they want to ‘add mass’ to the arrow (line 15) and ‘decrease mass’ for the sponge (line 18), yet achieve both of these changes by means of the Density slider rather than the available ‘Mass’ slider for each. In doing so, the students continue to not only involve DoVs which we would deem as relevant from a disciplinary perspective, but also to vary those DoVs in a manner which is ‘correct’ for the specific context (i.e. such that they succeed in achieving their goal, shown in figure 5). In this way, it is apparent that the students’ enacted relevance structure comprises disciplinary physics concepts in two key ways: both (1) that particular parameters are relevant and also (2) how those parameters are relevant for the task at hand.

6.2. Part 2—students are asked to unpack the scene

Following the students’ success in lodging the arrow into the sponge, both researchers acknowledge the students’ achievement: one exclaims, ‘Nice! Well done,’ and the other says, ‘Did you actually just manage to… that’s awesome!’ This kind of enthusiasm for the students’ success signals to the students that their ideas are valuable, even novel, in this context of doing physics. The researchers take up the students’ success as a worthwhile topic, asking the students to explain how they achieved their goal from part 1. As the students explain the changes that they made to get the arrow to puncture the sponge, the researchers are provided with further insights into the students’ reasoning processes (Charters 2003) and a preliminary sense for the students’ fluency in the terminology of physics (in this case, especially the disciplinary terms of speed, x-direction, and density). R1 notices that there is a part of the students’ explanation of puncturing the sponge that could be further explored: while the students used the term density in a satisfactory manner with regards to the arrow and its likelihood to puncture something, the students’ responses make it less clear if they appreciate why the DoV of sponge density was relevant for their goal. Appreciating why changing the density of the complex sponge object...
changes its behaviour requires an understanding of the way in which sponges are modelled in Algodoo.

R1 pursues this gap in the students’ story by asking the students to ‘say a few words’ about why changing the density of the sponge mattered for their goal. As the conversation progresses, R1 encourages the students to ‘show’ what they mean in their explanation by manipulating the sponge itself in Algodoo. The students are quick to suggest that the sponge is made of solid sub-objects connected together with ‘some kind of strings or springs’. By moving the Density slider for the sponge object in Algodoo, S1 shows how, when the density of the sponge is altered, it changes the mass of the sub-objects without changing the strength of the spring connectors between them. Thus, the sponge, under the influence of gravity, sags apart (becomes ‘looser’) when its density is increased, and cinches up on itself when its density is decreased (figure 6).

S2 drags a corner of the sponge away from the rest to demonstrate clearly how the object is composed of smaller chunks attached together (figure 7). R1 prompts the students to incorporate formal vocabulary into their explanation, saying, ‘You mentioned some sort of spring. So, what are the things that determine how a spring behaves? Maybe you know a physics term that you use to describe springs?’ The students respond with ‘the spring constant!’

6.3. Part 3—students are asked to build something new: a sponge model

Directly following the discussion of springs and spring constants, R1 gives the students a new goal, secondary to the students’ original goal of puncturing the sponge: ‘So what if you were to create your own sponge [in Algodoo]?’ In response to this request, S1 draws three small shapes connected by springs (i.e. a sponge model made up of three bodies). Once the students’ build their three-body sponge model, they drag/throw the model around in Algodoo to compare its behaviour to the behaviour of the original spongified object (figure 8).
Figure 6. S1 varies the density of the sponge via the Density slider in the dropdown menu (inset, taken from a screenshot of Algodo). The sponge changes shape dynamically within the scene as the slider is moved, sagging downward as the density is increased and cinching up as the density is decreased. Images of Algodo are used with permission. Reproduced with permission from Algoryx (2019).

Figure 7. S2 drags a corner of the sponge, which stretches the object apart and allows the students to better perceive the internal components that Algodo generates when an object is ‘spongified’.

With their newly-built three-body sponge model, the students then begin to explore the role that the properties of the spring-connectors play in the overall behaviour of the sponge model. They double-tap one of the spring objects and the dropdown menu automatically opens to the
Figure 8. S1 swings their three-body sponge model (magnified for the sake of clarity via inset) around in Algodoo, allowing the three-body model to fall to the ground and bounce in an effort to compare the behaviour of their model to the behaviour of the spongified object from earlier.

‘Springs’ submenu (which happens by default in Algodoo when springs are double-tapped). In this submenu menu, the students first change the target length of the springs (the springs were relatively long compared to the size of the three bodies) and then the spring constant.

Part 3 provides an example of how teachers working alongside less-constrained DLEs can respond to students’ responses and set up new lines of inquiry around students’ ideas (Robertson et al 2016, Robertson et al 2015). This is an instance where the unique affordances of less-constrained DLEs like Algodoo are readily apparent when compared to what is capable within other (more common) constrained DLEs in the teaching and learning of physics. Students are able to build things themselves in answer to requests from the teacher, but do so for topics (in our case, examining springs and sponge-models) which are only tangentially related to the starting point of the activity (to puncture a sponge with an arrow in part 1). Allowing for students to transition between topical areas fluidly (and within the same DLE) could help support students forming the view that physics topics are interconnected (Bagno et al 2000, Elby 2001, Hammer 1994).

6.4. Part 4—students are directed toward new DoVs: spring damping

In this final segment, the students are encouraged by the researchers to open up a new DoV. To reiterate our use of the terminology, we use the phrase ‘open up a new DoV’ to refer to an instance when the students are first experiencing and identifying a physics parameter as opposed to expanding the range of values for a DoV or involving a previously-opened DoV with which they are ostensibly familiar. In what follows, the researchers do the former in that they guide the students toward opening up the DoV of spring damping.
Whereas, in the section dedicated to part 1, variation theory was helpful for gleaning useful information about the students’ enacted relevance structures during their self-directed puncturing of the sponge, in this section we show how variation theory can inform how a teacher might intervene during students’ use of less-constrained DLEs like Algodoo to support learning of specific new concepts. In a past issue of this journal, Fredlund et al. (2015a) recommend physics educators follow three steps in order to enhance the possibilities that students learn concepts based on variation theory: (1) identify the physics-relevant DoVs for a particular task, (2) select appropriate representations that provide access to those DoVs, and then (3) vary the DoVs within the selected representations. In less-constrained DLEs such as the one we explore in the present paper, students create their own dynamic models in the place of carefully-prepared disciplinary representations. Thus, we can reinterpret Fredlund et al. (2015a) recommendation as follows for the context of less-constrained DLEs: teachers can (1) recognize a DoV worth focusing on during students’ use of the DLE, (2) guide students to construct their own systems and models that provide access to that DoV (i.e. such that the model is uncomplicated enough that the significance of the desired DoV can be discerned within the context), and then (3) encourage the students to vary the DoV. Our analysis here in part 4 follows how the researchers engage in such a process with S1 and S2 for the DoV of spring damping.

We begin by looking at how R1 directs the students’ attention toward the DoV of spring damping by virtue of the fact that it is one of three DoVs listed in the Springs submenu. At this point in the session, the students have already altered the other two DoVs in the submenu while manipulating their three-body sponge model—that is, both the spring constant and target length of the springs—but they have yet to indicate (through their words or actions) that they have noticed the slider for damping. R1 encourages the students to look back into the Springs submenu for other constants and then, once damping is identified by name, asks the students to explain their understanding of the term:

| Line | R1 | S1 | S2 |
|------|----|----|----|
| 22   | Yeah what would [damping] be? | That I actually don’t know. Could be, like, how... [holds hands out as if to pantomime an accordion, but then drops them] nah, that’s how-- | Is it some... |
| 23   |       |     |     |
| 24   |       |     | [overlapping] Is it some-- |
| 25   |       |     |     |
| 26   | S2:  | Resistance to velocity or whatever it’s called? | Is there a way-- |
|      |     | Don’t know, [shrugs] |

In response to the R1’s question, ‘what would [damping] be?’ (line 22), S1 states that he does not know the term (line 23) and S2 offers a somewhat hesitant definition that damping involves ‘resistance to velocity or whatever it is called’ (line 26). Based on the students’ answers, it is reasonable to assume that damping is a DoV with which the students are less comfortable, especially when compared to the other DoVs involved in the session previously (e.g. speed/velocity, density, and spring constant). From the perspective of variation theory, then, damping appears as a good candidate DoV for the researchers to open up in the activity moving forward.

Following line 26, R1 encourages the students to test S2’s suggestion about damping as a ‘resistance to velocity’. He does so with the prompt, ‘Is there a way of testing that? ... I mean, you can create other stuff or you can try stuff on that one [you have already created]’. The students choose to change the damping of the springs in their three-body sponge model,
but in their attempt to reset the model to a baseline starting point, end up changing both the
spring damping and spring constant. S1 begins describing how the three-body sponge model
‘feels’ different after these changes. However, after R1 points out that they changed two things
at once, the students quickly realize that the change in behaviour cannot be attributed to the
damping alone, since the value of more than one parameter was altered before they ran the
simulation.

In what follows, the students proceed with testing the impact of damping on their sponge
model while holding the other parameters constant. As the three-body sponge model is a com-
plex entity, however, it is difficult to for the students to see the impact of varying the damping
DoV on the behaviour of the sponge model overall. The students end up using vague words
like ‘twitchy’ to describe the new sponge with low damping\textsuperscript{15}. Eventually, R1 suggests that
the students construct a model in Algodoo which is simpler than the three-body sponge model so
that they can more directly test what spring damping means: he says, ‘is there a way that you
could test what damping means in a system that is not as complicated as this… uhh, sponge
that you created?’

In response to R1’s suggestion, the students clear the Algodoo scene and create a new,
somewhat-simpler model with a spring and a square which can slide horizontally on the ground.
S1 suggests that they send a circle rolling into the square to see how the spring responds when
given various damping values, claiming that he thinks ‘damping means how much you can
[press a spring] together in itself’. After the students are given some time to work with this
new model (ultimately, they struggle with how to make the circle compress the spring in the
desired way), R1 asks the students how S1’s suggested definition for damping differs from that
of a spring constant. S2 responds that he thinks damping has to do with velocity, ‘similar to air
drag, but for a spring instead’ (returning to, and reiterating, his original answer given in line
26). R1 notices that the new model built by the students is still too complex for the students to
experience the role of the spring damping DoV. R1 suggests that the students think of a way
to test if S2’s velocity-related suggestion is correct.

[after trying to explore damping with the horizontal system of a spring, square, and circle]

\textsuperscript{15}Again, in principle, the students’ use of non-disciplinary language like ‘twitchy’ to qualitatively describe the
behaviour of the less-damped sponge model is not inherently undesired (Euler \textit{et al} 2019).
Here, R1 encourages the students to externalize some explanation of what ‘big damping’ and ‘low damping’ might look like within a real-world example (car suspensions). S2’s answer in line 30 includes the idea of a spring stopping when highly-damped, but also relates damping with speed of oscillation. S2 also employs the word ‘oscillating’, which R1 uses to urge the students to test out S2’s suggestion about damping:

31   R1: Mhm... Now what if you make an oscillator? How do you make an oscillator? [as R1 is asking these questions, S1 turns back to the IWB and resumes tinkering with the spring setup on the IWB]

32   S2: [overlapping] The easy way? In here?

33   R1: Or – or anywhere, really?

34   S2: We could, uhh, hang a spring. Add a weight– attach a weight to a spring [points to a spot above the ground in Algodoo near the top of the IWB] and give it some velocity downwards. [caps his hand to point downward and then moves arm down in front of the IWB] It should – it should start... oscillating. [forms hand into a blade and gestures back upward along the IWB]

By this point, R1 has led the students to come up with the idea for a model in Algodoo which is simple enough that the students can likely open up the DoV of spring damping (i.e. that the variational contrast of the damping DoV is discernible). Importantly, the students are maintaining some level of ownership of the process still, since they continue to come up with the details of the next step of action. R1 simply encourages them to think of taking certain steps which are, in turn, useful for progressing toward opening up the DoV in concern. Following the segment of transcript above, the students hang a box from a spring in Algodoo and make it oscillate for various values of spring damping (figure 9). At one point, S2 moves the damping slider all the way to the right to the maximum value\(^{16}\). This creates the condition of an overdamped oscillator:

[after the students have tried several values of spring damping with their oscillator]

35   S1: [drags the box away from the spring, releasing it to see how the damped spring will react] Yeah.

36   S2: Yeah.

37   S1: It’s like ccccccw [pitches voice downward and gestures like he is compressing an accordion]

S1 impersonates the behaviour of the (overdamped) oscillator by voicing a downward-warping sound effect and enacting a compression-like gesture. It is apparent at this time that the students are experiencing the behaviour of an overdamped oscillator, maybe even viscerally so, such that the DoV of spring damping is being opened up (especially for S1). Though informal in nature, S1’s embodied action in line 37 aligns well with a critical aspect of overdamped oscillators, namely, that the mass (box) returns to the rest position without oscillating. In other PER work, we have shown that non-disciplinary utterances such as this, which correspond well with the core ideas of a disciplinary physics concept without necessarily using the discipline’s agreed-upon conventions outright, can be valuable in students’ development

\(^{16}\) The ‘Damping’ slider in Algodoo actually allows users to alter the viscous spring damping parameter. When a spring is generated in Algodoo, the numerical scale of the damping slider is automatically set so that the middle position of the slider (and, thus, the displayed ‘Damping’ value) corresponds to the spring being critically damped. In a peculiarity of the Algodoo code, if the mass of a system containing springs is changed without changing any of the spring parameters (i.e. without moving any of sliders for the spring constant, damping, or target length), then the damping slider is not rescaled. As such, the value ‘1’ on the slider will no longer correspond to the system being critically damped.
Figure 9. S2 varies the damping of the spring in the simplified oscillator via the Damping slider in the dropdown menu (inset, taken from a screenshot of Algodoo) as the mass (partially-obscured behind the dropdown menu) continues to oscillate in Algodoo. Images of Algodoo are used with permission. Reproduced with permission from Algoryx (2019).

of explanatory (and/or mechanistic) models of phenomena (Euler et al. 2019, Gregorcic et al. 2017). As was discussed in parts 2 and 3 of this paper’s analysis, one way to build on students’ use of such language is to encourage them to later incorporate the disciplinary terminology after the non-disciplinary utterance has communicated the main thrust of what was originally experienced. Following S1’s impersonation of the overdamped oscillator, R2 encourages the students to try out other terminology with the question ‘what other words could you use to describe the spring based on this parameter?’

|   |   |
|---|---|
|38 | S1: Strange… [*laughs*] in a sense. |
|39 | S2: Stiff? |
|40 | R1: But you could– you could– in a sense, you could– yeah. You could use stiff also in another way, right? |
|41 | S2: Mhm. With the spring constant, yes. |
|42 | R1: So, it’s good that we have two words, [*laughs*] because they mean different stuff apparently. |
|43 | S1: Yeah, because this is… |
|44 | R1: I mean, because is it hard to press together or pull apart? |
|45 | S1: No. It shouldn’t be at least. Or I don’t know what we have set the spring constant to. |
|46 | R1: Or it depends on… you said before something about what it depends on. |
|47 | S2: *This?* [*gestures toward the IWB*] |
|48 | R1: Yeah, why– what’s– the– the damping… You mentioned before. |
|49 | S2: Velocity. |

Here, R1 explains how the colloquial term, stiff, is ambiguous in whether it refers to a large spring constant or a large damping. In doing so, R1 helps motivate the need for the disciplinary
terminology for the students. Furthermore, by the end of this interaction, the researchers finally confirm that idea of damping is related to the velocity of a spring’s oscillation. It should be noted here that, while this was the end of the damping discussion in our data, a teacher would likely do well to spend more time reflecting on what the students think damping means. A core recommendation of variation theory is for learners to take newly opened up DoVs—which are first experienced through contrast in simplified models for the sake of discernment—and embed them in broader, more complex systems to better contextualize how the DoVs play a role alongside other DoVs (see Marton’s 2015 (p 50) discussion of ‘generalization’ and ‘fusion’).

In the case presented here, it would have been useful for the students to return back to their three-body sponge model, for example, after having opened up the DoV of spring damping. Nonetheless, at the time of data collection, the researchers in the room were justifiably content with the fact that this session—which started as the students’ self-directed exploration of how to puncture a spongified shape in Algodoo—had naturally led to the pair of students learning more about a new physics parameter. Thus, such a recontextualization of the newly opened-up DoV did not occur.

7. Synthesis and discussion

In the analysis above, we highlight two key ways in which variation theory can inform responsive teaching alongside students’ use of the less-constrained DLE, Algodoo. In part 1, we show how the pair of students involved DoVs with which they had previous experience, thereby displaying an enacted relevance structure for the respective teacher/researcher. Attending to students’ enacted relevance structures in less-constrained DLEs—which by virtue of the environments’ design present students with a collection of DoVs to be varied that may or may not be relevant for the context at hand—corresponds well with Sayre et al’s (2004) analytic focus on student reasoning in ‘nearly-novel’ situations, wherein physics students have ‘studied all the relevant physics principles but have not previously synthesized the ideas in a specific setting’ (p 101). Nearly-novel situations are particularly apt for providing teachers/researchers with insight into ‘issues of transfer of knowledge, coherence of understanding, and student epistemologies and metacognitive skills’, among other things, especially insofar as they ‘[force] students in an uncharted area outside established conceptions but still near many resources’ (Sayre et al 2004, p 101). Our analysis of part 1 provides the interested physics teacher/researcher with a practical example of how to meaningfully observe students engaged in nearly-novel situations within less-constrained DLEs. We recommend that teachers pay attention to when and how students involve various DoVs (i.e. the physics parameters made manipulable by Algodoo) during pursuit of self-set goals. For the variation theory-informed teacher/researcher who utilizes less-constrained DLEs in this way, students’ playful exploration can materialize as fertile sequences of pedagogically-useful variations upon which future scientific inquiry can be built.

In part 4, we show how a physics teacher can guide students toward learning about a new physics parameter (i.e. open up a new DoVs) within less-constrained DLEs by leading students toward building simple models that make the contrast of that parameter more directly experienceable. Especially when students demonstrate a lack of confidence in the meaning of certain DoVs (e.g. line 23), teachers can responsively propose new, directed goals to students through questions like ‘is there a way of testing that?’ (following line 26) or ‘how do you make [something like that]?’ (line 31). In doing so, teachers can successively steer students toward the construction of more productive models for the discernment of the physics
DoVs in question. While aiming to experience the meaning of a particular DoV, students may naturally tend to vary more than one DoV at a time or create overly-complicated models which obscure the role of the DoV within complex contexts (as summarized before line 27). However, while an approach utilizing constrained DLEs would likely dictate that the digital environment itself be ‘cleaned up’ so as to minimize the possibility of students taking such detours, the approach featured in this paper allows students to not only be guided toward the optimally-simplified model through responsive feedback, but it also allows the students to experience the messy, non-linear progression of scientific exploration. This, in turn, also demonstrates to the students the value of simplified models. When compared to existing variation theory literature, the teacher intervention in part 4 can be seen as a responsively-improved rendition of a variation-theory-grounded instructional technique where teachers (1) recognize a DoV worth focusing on during students’ use of a DLE, (2) guide students to construct their own systems and models that provide access to that DoV (i.e. such that the model is uncomplicated enough that the significance of the desired DoV can be discerned within the context), and then (3) encourage the students to vary the DoV (adapted from Fredlund et al 2015a).

While, for the sake of brevity, the analyses of parts 1 and 4 are the only parts presented in depth, it is worthwhile here to briefly comment on the session altogether. First, the progression from parts 1–4 (shown in figure 1) is not meant to convey a prescribed sequence that students should follow. It is a description of what took place in this particular case study. For one, as we mention above, the conventional recommendation of variation theory would be for something of a fifth part to have followed after part 4, wherein students could re-contextualize the DoV of damping within more complicated contexts. Furthermore, teachers could reasonably choose any of the four parts seen in our data as a starting point for an Algodoo-based activity; students could initially be given a constructed scene to unpack (e.g. Gregorcic 2015, Gregorcic et al 2017; as per the aim of part 2), they could, at first, be explicitly asked to build a specific construction (e.g. Euler and Gregorcic 2018; as per part 3), or they could initially be directed toward learning about specific parameters (e.g. Vliora et al 2018; as per part 4). This is one of the unique benefits to less-constrained DLEs like Algodoo. Less-constrained DLEs allow for a diversity of activity type—and, importantly, for smooth transitions between each of these activity types—within the same software.

Second, despite our use of the ‘less-constrained’ framing in this paper, it is important to reiterate that each of the four parts of the session presented above did, in fact, involve constraints on the students’ activity to different degrees. There were conversational constraints imposed by the researchers in response to the students’ exploration which we have already highlighted (especially in part 4), but the Algodoo software itself also carried with it a structure that constrained the students to within a ballpark of useful phenomena. That is, the collection of variables in Algodoo are on-the-whole relevant for physics phenomena, so students can be anticipated to experience (and potentially discern) some parameters during their exploration which are germane for the discipline of physics. In fact, even in instances which might otherwise appear to be students uselessly ‘messing about’, we have found that students’ activities are always a close neighbour to something worthwhile for the physics classroom (Euler et al accepted). Thus, less-constrained DLEs like Algodoo may provide a productive balance between messiness and structure which encourages students to enact science-like behaviours while staying creative and intrinsically motivated.
7.1. Implications for students

At the beginning of this paper, we discussed the potential for less-constrained DLEs like Algodoo for promoting certain goals that go beyond the conceptual mastery intended with constrained DLEs: among them, for students to form a more interconnected picture of physics knowledge and for students to work creatively toward solving their own lines of inquiry. In regard to the former, we have exemplified how a pair of students can seamlessly move from a self-set goal of puncturing a sponge (part 1), to construction of a non-rigid body model (part 3), to the exploration of damping with a harmonic oscillator (part 4). Much of the conventional wisdom in the design of physics DLEs would suggest that a physics educator who wants students to engage in any of these activities needs to involve three separate interactive simulations which each maximize student productiveness toward one of those activities. However, less-constrained DLEs afford students with the opportunity to explore phenomena simultaneously as part of complex systems—i.e. through the combination of unforeseen phenomena, like projectile motion and non-rigid bodies (part 1)—and/or sequentially as lines of ‘phenomena-hopping inquiry’—i.e. through the ‘zooming-in’ on a particular physics parameter, such as spring damping. The impact of this cross-topical capability should be investigated further to assess the degree to which it promotes students’ view of physics knowledge as interconnected. Nonetheless, as presented in the case study above, less-constrained DLEs show promise for encouraging students to see physics as an interrelated body of knowledge insofar as they allow for students’ intra-topical exploration and construction of physics-relevant digital artefacts.

To the second learning goal for DLEs, namely for the promotion of student creativity, the case presented above highlights how student creativity can be valued and built upon by responsive teachers. Software such as Algodoo is built with the intent of students actively constructing and manipulating digital objects relevant for physics learning (Euler and Gregorcic 2019), a design philosophy which relies on students working creatively with mathematically-rich materials. Especially in less-constrained DLEs, students have the creative leeway to bring objects together in unexpected, yet fruitful constructions (e.g. lines 1–23). As exemplified in progression of our session from part 2 onward, teachers can take students’ unique constructions as stepping-off points for discussions and as the basis for new prompts, all in a manner which explicitly signals to the students that their creativity is valuable and worthwhile (e.g. seen in the researchers’ affirmation of the students at the start of part 2). In this type of activity, wherein teachers can value students’ divergent thinking and productively build on student-made models for the purposes of learning physics, students are likely to be more intrinsically motivated and may develop more ownership of the physics content itself (for a discussion of these points, see Holmes et al 2020, Van Dusen and Otero 2015).

7.2. Implications for teachers

For the interested physics teacher, as well, the teaching arrangement that we advocate in this paper affords some benefits. First, teachers responsively guiding students alongside less-constrained DLEs like Algodoo are provided a unique vantage point from which to form a picture of where students ‘are’ in their understanding. This can be facilitated through an attention to the involved DoVs that constitute students’ enacted relevance structures—as demonstrated in part 1 of this paper’s analysis. Similar to the more familiar pedagogical practice of whiteboarding (Wenning 2005), students’ involvement of DoVs in less-constrained DLEs can act as a public display of their reasoning. In our experience as teachers, this is especially useful when a teacher is orchestrating feedback to several groups of students working independently within
the same physics classroom, since the teacher can glean insight into the progress of students within a relatively short window of attention\textsuperscript{17}.

Another benefit to working alongside students in the manner displayed above is that it allows the physics teacher to do the rewarding work of engaging with students’ inventiveness. The unpredictable constructions which students generate within less-constrained DLEs can function as interesting and exciting riddles for the responsive teacher to utilize in pursuit of tangentially-related physics content goals. We find that this type of improvisational work with student ingenuity is both gratifying and invigorating in our work as physics teachers, a point which should not be disregarded in the pursuit of bettering physics education overall.

8. Conclusion

In this paper we have used variation theory to analyse a teaching arrangement wherein physics teachers responsively guide students as they use less-constrained DLEs (such as the 2D Newtonian software \textit{Algodoo}). When compared with the predominant practice of using constrained DLEs in physics teaching, we argue that the teaching arrangement featured in this paper allows students to transition fluidly between physics topics and better promotes their creativity during physics learning. This may help physics students appreciate the interconnectedness of physics knowledge and provides physics teachers with better means for valuing and building upon students’ divergent reasoning.

A reasonable point could be raised that the arrangement of responsive teaching alongside a less-constrained DLE does not depart from a constraints-based pedagogical philosophy so much as it merely shifts the burden of constraints from within the DLE to the teacher. While this may be the case to an extent, we emphasize that ideally the constraints imposed by a responsive teacher would not only be more flexible in nature, but also fewer in number than the constraints employed within most constrained DLEs. This is reflected in the student-centeredness of responsive teaching, which calls for the foregrounding of students’ ideas and the utilization of them as starting points for educational activity—neither of which ideals are as supported in constrained DLEs. Instead, with less-constrained DLEs, students can be provided with opportunities to try out more of their own ideas—even the disciplinarily-incorrect ones. This is because such learning environments allow for a wider range of phenomena to be explored and for a larger diversity of DoVs to be incorporated. As with any recommendation for enhancing physics teaching, the implementation of responsive teaching alongside less-constrained DLEs comes with various challenges, especially vis-à-vis the proper training of responsive teachers (Goodhew and Robertson 2017) and the feasibility of implementation amongst common structural barriers (e.g. high student–teacher ratios, lack of resources). Since various PER efforts aimed at ameliorating such challenges already exist and/or are underway, we assert that it is sufficient in this paper to introduce and demonstrate the potential utility of this underexplored teaching arrangement involving a less-constrained physics DLE such that future work can be done to test its implementation in classroom contexts.

\textsuperscript{17} It should be pointed out that, while the data presented in this paper involved a single pair of students with a dedicated pair of researchers attending to their activity in isolation, we report anecdotally that the suggested role of teacher-as-responsive-guider alongside the less-constrained DLE, \textit{Algodoo}, has remained tractable for us in physics classes on the scale of 20–30 students per teacher (arranged in \textasciitilde 10 groups of 2–3 students).
The merits of constrained and less-constrained environments aside, in this paper we have provided an example of how the analytic frame of variation theory lends itself particularly well to the study of physics students’ use of DLEs. The digital environments used in the teaching and learning of physics comprise collections of physics DoVs to be discerned. In constrained DLEs, the DoVs are chosen sparingly in order to encourage specific lines of inquiry and particular conceptual mastery. In less-constrained DLEs, a wider range of DoVs are compiled in order to allow students’ divergent inquiry and creativity with physics-relevant materials. While we have focused on the latter type of DLE in this paper, the variation theory perspective we have developed arms the interested physics education researcher and physics teacher with a means of gaining insight into what students see as relevant in any physics DLE. Furthermore, we have provided educators with recommendations for how to guide students toward the discernment of new physics parameters within DLEs, especially where the structure of the digital environment provides students with sufficiently-creative space to do so. In this way, we further nuance discussions around the structure of the digital tools used in the teaching and learning of physics and contribute to the development of best practices in their use by physics educators.

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