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Using social semiotics and variation theory to analyse learning challenges in physics: a methodological case study

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Abstract

The aim of the paper is to create a way of extending the utility of using variation theory of learning (VTL) as an analytic tool for exploring student learning in interactive environments for highly complex disciplines such as physics that aims at obtaining additional insights and understanding of students' learning challenges in physics drawing on a phenomenography perspective. To do this we propose an analytical combination of two perspectives—social semiotics and the VTL—using theoretical constructs from both. Here, in keeping with the phenomenographic perspective that underlies VTL, learning is taken to mean coming to experience things in distinctly new ways. As a case study, students were video recorded during a group problem-solving session while working on circular motion tutorial problems. Through the combined analytic approach, we were able to identify the students' *relevance structure* as enacted as a function of what was in focal awareness and what dimensions of variation that were presented. A social semiotic multimodal transcription is used to illustrate the proposed methodology, which is made up of the semiotic systems that the students chose to use to build their discursive engagement on. As a methodology paper, and because such discussion already exists in the literature, how this kind of analytic combination can provide additional teaching insights and how these

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insights could be used to enhance teachers' understanding of their students' learning are not presented in this paper.

Keywords: social semiotics, variation theory of learning, dimensions of variation, relevance structure, circular motion, analytical exploration, focal awareness

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

1. Introduction

The aim of the paper is to create a way of extending the utility of using VTL (Marton 2015, Marton and Booth 1997, Marton and Tsui 2004) as an analytic tool for exploring student learning in interactive environments for highly complex disciplines such as physics that aims at obtaining additional insights and understanding of students' learning challenges in physics drawing on a phenomenography perspective. As a theory of communication practices by specific social groups, in this instance physics, social semiotics (for example, Halliday (1978), Kress (2010), Lemke (1998), van Leeuwen (2005)) has been shown to be a powerful tool that can be used to understand student engagement with physics tasks (Airey and Linder 2017). In this paper we wish to create close links between social semiotics and the VTL as an analytic tool. This stems firstly from VTL having a huge empirical base that points to ways of experiencing the object of teaching that successfully enhances learning outcomes, and secondly, an essential aspect of social semiotics being that meanings get made, shared, interpreted and remade through 'modes' of representational and communicational resources, language being just one of these (see discussion on 'multimodal discourse' by Kress and van Leeuwen (2001)). Furthermore, while both VTL and social semiotics have been widely drawn on analytically in many contexts, the two have not been analytically combined in the way that we now propose, particularly for an interactive physics learning context, even though the idea has previously been proposed (Linder 2012) and later theoretically supported in a physics learning context (Eriksson 2014, Fredlund 2015). The aim of the paper builds on the work of Ingerman *et al* (2009) who, for the first time, used VTL as an analytic tool for exploring student learning in an interactive environment. We illustrate our proposed approach using what in social semiotics is known as a 'social semiotic multimodal transcription' (Baldry and Thibault 2006, Flewitt *et al* 2014) to bring to the fore important VTL attributes. Our data consists of two purposely selected episodes of discussion that took place when a group of introductory-physics students were working together to solve circular motion problems. Since the focus is on methodology, an in-depth analysis of the physics aspects has been left to a follow-on paper. The methodological illustration is set in the identification of what students 'see' as being relevant for appropriately dealing with the given physics tutorial problems, and how this 'focal awareness' can limit or extend the 'space of learning' (Marton and Tsui 2004).

The interactive physics problem-solving context of circular motion was selected because it presented an opportunity to obtain data from student discussion in an area of introductory level physics that has long been recognised by physics educators to be challenging (for example, see Arons (1981), Gardner (1984), Pendrill *et al* (2019), Viennot (1979), Warren (1971), (1979)).

In part one of the paper we present a summary of the key features of social semiotics and VTL that are pertinent to the analysis presented. Part two of the paper presents the data in the form of 'social semiotic multimodal transcriptions' (Bezemer and Mavers 2011) for two different episodes—the first, where students are working on a circular motion problem in the vertical plane and the second, with a circular motion problem in the horizontal plane. Part three

is a two-part discussion that deals with arising analytic considerations and considerations for teaching. Finally, part four gives a short conclusion.

2. Part One: Theoretical frameworks

2.1. Social semiotics

The semiotics perspective developed for investigating important relations between physics teaching and learning, which we use for our analysis (for a recent summary, see Airey and Linder (2017)), is a perspective that draws on the broader social semiotic research community (for example, Jewitt and Kress (2003), Kress and Mavers (2005), van Leeuwen (2005)). This broader community focuses on the form and content of communication practices that particular social groups have developed and use (in our case, the discipline and classroom practices of physics). Put another way, the social semiotics perspective that we use is an emerging physics education research (PER) tool for ‘the study of the development and reproduction of specialized systems of meaning making in particular sections of society’ (Airey and Linder (2017), p 2) as it relates to the teaching and learning of physics. Here, all communication and its consequent facilitation of meaning making is situated in a particular collection of semiotic systems (such as, equations, graphs, diagrams, pictures, and apparatus) and the resources that these systems offer for a particular context of communication and meaning making (for an example from the physics student laboratory, see Volkwyn *et al* (2018)). Semiotic resources that can be found within physics are typically derived from the following semiotic systems: spoken and written language, mathematics, diagrams, gestures and apparatus. This perspective has been used in multiple studies recently as a way to understand student learning in various physics contexts (see Eriksson (2014), Euler *et al* (2019), Fredlund (2015), Volkwyn *et al* (2019), Weliweriya *et al* (2019)) and this paper extends these efforts by using it alongside VTL as an analytical tool (section 2.2).

To constitute the required meaning that underpins the appropriate understanding of a particular phenomenon in physics, certain vital aspects from a physics perspective—*Disciplinary Relevant Aspects* (DRAs)—need to be considered. Fredlund *et al* (2015a), p 2, following Fredlund *et al* (2015b) and Fredlund (2015), define disciplinary relevant aspects as ‘those aspects of physics concepts that have particular relevance for carrying out a specific task’. In our case, this is exemplified by the formulation of appropriate understanding and utility of particular cases of circular motion, where such DRAs include, radius of the circle, speed, the appropriate system, and the acceleration. These DRAs need to become an integral part of students’ ‘focal awareness’ (Marton and Booth (1997), see section 2.2) in all physics learning situations, i.e. the DRAs need be ‘discerned’ by the students for a given physics learning situation, or task, in order for them to constitute the intended meaning appropriately and for the students to successfully solve the given task. The consequence of such a view of learning is that the learning environment needs to present students with opportunities to discern the needed DRAs, particularly when they are not directly visible. A recent example of a study exploring such an environment is Fredlund *et al* (2014) who situate the students’ exploration in the ‘unpacking’ of complex ideas and actions. Whereas it has been shown that students often experience great difficulty in doing this by themselves (Eriksson 2014, 2019, Fredlund 2015, Fredlund *et al* 2014) there is a study that has illustrated how this can be facilitated in an interactive learning environment (Ingerman *et al* 2009). The work reported on in this paper builds directly on this possibility.

2.2. The Variation Theory of Learning

The second analytical tool used for the analysis given in this paper is the variation theory of learning (VTL). The setting for our introduction to VTL is that knowledge is constituted in terms of relations between the knower and the known. From here, learning becomes being about experiencing *qualitative change* in these relations:

[T]he kind of learning we are dealing with here is one through which the learner becomes capable of experiencing something in a different way from before. This means [...] becoming capable of discerning and separating aspects of a phenomenon the learner has not been able to discern and separate previously, and of being simultaneously and focally aware of aspects she not been able to be simultaneously and focally aware of previously. (Marton and Booth (1997), p 145)

Adopting such a perspective means that what becomes analytically interesting is the ‘how’ and ‘what’ of making the learning of some aspect of physics curriculum possible. This occurs when these aspects appear ‘in novel situations in a particular way (which goes beyond the other ways in which [the learner] has been capable of experiencing the phenomenon)’ (Marton and Booth (1997), p 142). In other words, one can use this perspective to analytically ‘see’ when new learning has, or has not, started to take place, i.e. when the relationship between the person and the phenomenon is seen to change. Put another way, when ‘the learner has become capable of discerning aspects of the phenomenon other than those she had been capable of discerning before, and she has become capable of being simultaneously and focally aware of other aspects or more aspects of the phenomenon than was previously the case’ (Marton and Booth (1997), p 142). This is where VTL comes into the picture, for it allows for the identification and analysis of such learning (for example, see Åkerlind *et al* (2014), Marton and Morris (2002), Marton and Tsui (2004)).

VTL is a very rich and powerful perspective that is used widely internationally across many different types of teaching and learning contexts (for a comprehensive overview, see Marton (2015)) but it has only rarely been used as an analytic tool in physics education contexts (some notable exceptions being Åkerlind *et al* (2014), Berge (2011), Euler *et al* (2020), Ingerman *et al* (2009), Linder and Fraser (2009)). While it is not possible to give a comprehensive overview here, interested readers are referred to Bowden (1994), Bowden and Marton (1998), Marton (2015), Marton and Booth (1997), Marton and Pang (2013), and Marton and Tsui (2004) which collectively provide both a broad and comprehensive description of the theory and its epistemic grounding, research drawing on VTL, and its broader use in educational research and curriculum design. Below are the central underpinning aspects of VTL needed for this paper:

- (a) it is an approach to viewing formalised learning which is grounded in *acquiring new meaning* as a function of noticing something that was not noticed before or seeing that particular aspect in a new way. (In our case, it is such a noticing something that was not noticed before or seeing that particular aspect in a new way that we refer to in terms of aspects that need to become part of the tutorial group members’ *focal awareness*);
- (b) such meaningful noticing is formulated as the *discernment that arises out of experiencing differences against a background of sameness* (in other words, experiencing a ‘dimension of variation’). Basically, discernment is made up of two components: experiencing variation in ways that facilitate noticing something and then making meaning from what is noticed in a new way. In other words, getting to see things in fundamentally new ways as a function of experiencing ‘dimensions of variation’ (see below) that have been opened around some critical aspect of a phenomenon or even the phenomenon itself;

- (c) from a disciplinary point of view, acquiring such new meaning calls for the discernment of the *critical aspects* that underpin the new meaning (in our case, the DRAs of circular motion for the task at hand);
- (d) the possibility of discernment that arises out of experiencing differences against a background of sameness calls for experiencing particular kinds of variation—dimensions of variation (see below); and,
- (e) aspects are considered *not* to be in *focal awareness* when they are:
 1. *transcended*—overlooked or not discerned at all; and,
 2. *taken-for-granted*—things that have been discerned previously and subsequently, unreflectively assumed to be applicable (or not), in the new situation.

The summary given above yields three important constructs for variation theory—*variation*, *discernment* and *simultaneity*:

‘Variation’ is an essential aspect of learning in this sense: that learning occurs (things are seen in distinctly new ways) when a dimension of variation opens around a phenomenon or aspect of a phenomenon that once was taken-for-granted. ‘Discernment’ is the act of seeing this no-longer-taken-for-granted phenomenon or aspect of a phenomenon in a new light. ‘Simultaneity’—seeing *both* the once-taken-for-granted and the no-longer-taken-for-granted—is demanded for the dimension of variation to open. Lack of understanding is thus linked with being unaware of the potential for variation—seeing only that which is taken-for-granted. (Booth and Hultén (2003), pp 69–70, emphasis in original)

In an area such as physics this ‘translates’ into viewing learning as being about what is needed to get to see things in specific, usually new ways and then being able to bring what is relevant from this learning into focal awareness for a particular area of understanding, application, task or practice. In VTL terms, such learning only becomes possible when a ‘dimension of variation’ is opened⁴ for a disciplinary relevant aspect that has been transcended or taken-for-granted or both of these. Here, simultaneity is vital: the once transcended or taken-for-granted must be simultaneously seen with the no-longer-transcended or the no-longer-taken-for-granted for a dimension of variation to be opened (for further discussion of simultaneity, see section 3.2.1). To discern a particular aspect not discerned before, or to discern this aspect in a different way, often means that one needs to experience *different facets* (or *values*) of that aspect simultaneously in order to be able to differentiate it from other aspects. For example, in introductory level classical physics, students need to be able to differentiate between a ‘system’ made up of one or more bodies that are being observed kinematically in an *inertial frame of reference* and in a *non-inertial frame of reference*. Such a differentiation calls for the discernment of disciplinary relevant aspects of the system under study. At the same time the discernment of some of these DRAs may have several features that also need to be discerned as part of the meaning making experience (i.e. to perceive, see, conceptualize, etc). In such cases, for the discernment of each of these features a *dimension of variation* will have (had) to be experienced. For instance, an inertial frame of reference has a distinct aspect—it moves with constant velocity—and a system made up of a single body moving with constant velocity has several features that need to be discerned.

Another example in classical physics is where in order to gain an appreciation of the importance of specifying a force in terms of the forces acting on a specified body (system), the student

⁴ When a ‘dimension of variation’ is being ‘opened up’, different values to a dimension of variation (a critical aspect) are being experienced or presented. One example of this is the colours ‘red’, ‘blue’, and ‘white’ as different values to the dimension of variation ‘colour of a car’.

has to experience *specifying forces acting on a body* as an aspect. And this aspect must come to the fore (be figural) in physics students' focal awareness. An illustrative question is that of a horse claiming that it is unable to pull a cart because it can quickly show how such specification is vital for a physics evaluation of this claim made by the horse. The horse's case to its cart-driver is that the harder the horse pulls the cart so, by Newton's third law, the harder the cart will pull back on the horse. The forces will be opposite in direction and equal in magnitude, and so they will cancel out. Thus, there will always be a zero net force to get the cart going and a zero net force cannot achieve this (this example is thanks to Paul Hewitt, private communication—see Linder *et al* (2006) for Hewitt's teaching-cartoon). The dimension of variation that needs to be opened is made up of all forces *acting on the horse* along the direction of motion. This dimension of variation must be simultaneously seen alongside a dimension of variation made up of forces that *act on the cart* along the direction of motion, and simultaneously seen against all other prior experiences of calculating the vector sum of forces acting on an object to determine changes in rectilinear velocity.

Drawing on ideas from phenomenology and Székely's (1950) study of physics students making torsion pendulum predictions, Marton and Booth (1997) introduced the idea of a person's *relevance structure* for a particular way of understanding a given phenomenon; for example, the framing of a task, or way of doing things. They defined relevance structure in terms of what is seen to be called for a given phenomenon to appropriately deal with a situation at hand. Hence, in the context of this paper there is a critical constellation of DRAs that need to come into *focal awareness* to make up a relevance structure that is appropriate for solving a particular problem involving circular motion. These critical DRAs need to be related to one another—the 'parts'—and to the 'whole' simultaneously. This is because it is how these DRAs are related to each other and in turn the whole, that determines how the situations get to be seen, experienced, or understood. In this way *focal awareness*, *simultaneity* and *relevance structure* are central to VTL and thus for understanding the analysis of the examples given in this paper. From this perspective, when the opportunity to experience relevant dimensions of variation is limited, or if the experience of a dimension of variation is countered by a person's own relevance structure of the situation, then opportunities for learning become limited for that person and vice versa. In the VTL literature such a learning opportunity is characterized by the term 'space of learning' (Marton and Tsui 2004).

Here, it needs to be emphasized that the relevance structure we consider is grounded in the DRAs which physics education deem as being relevant for solving the particular kind of task that the students were working with at the time of our study. Whereas such DRAs are taken as being self-evident for the effective teaching of circular motion, at the same time it must be acknowledged that they may present a learning space limitation for individual students or groups of students. This is because each person experiences a learning situation from the perspective of their own relevance structure, with DRAs which may or may not match the accepted ones for the situation. Thus, the educational aim for the physics tutorials studied is to engage the participants students in ways that lead to their collective relevance structure matching the DRAs of the physics situation(s) given in their assigned problems.

At this point, the reference to these 'dimensions of variation' requires some further explanation. Building on Booth and Hultén (2003) and Ingerman *et al* (2009) who for the first time, shifted the analytic focus of the *source* of variation-generation from teachers to students interacting in group work, it is the student-generated *dimensions of variation* that are of interest:

It is the individual and the individual alone that develops the capability to experience something in a new way. When speaking of the phenomenon in focus, the individual

directs his or her awareness towards the phenomenon, or towards some aspect of it, or towards the situation in which the phenomenon is perceived, or towards his or her own relation with the phenomenon in a reflective mode; the locus of learning is identical with the individual learner. In group discussions, however, the locus of learning is less clear. In the transcripts of discussions, utterances are directed to one another, or to the collective solution that is under way, rather than to oneself, and the locus of learning is distributed over the group situation—insights are jointly constituted [...] What we are suggesting [...] is that dimensions of variation can be opened in discussion, affording learning. This is not to say that learning takes place, neither in an individual nor in the group; but it can be said that a potential for learning is provided when a dimension of variation is opened—the conditions for learning are present to the group and to the problem-solving process. (Booth and Hultén (2003), p 70)

Furthermore, for the purposes of this paper, we define the students' space of learning as being the possibility for learning that is afforded by the social semiotic interaction in the tutorial group as they engage in the given problem-solving task. Thus, bringing in VTL as part of the proposed analytic framing that we explore empirically for this article does two things: firstly it brings to the fore an already well established set of constructs for both researchers and teachers to use when wanting to address learning challenges vis-à-vis a view of learning that is built on the fundamentals of how the critical aspects that make up an intended object of learning get apprehended, thought about, or perceived in the classroom context. Secondly, it facilitates the identification of instances of where learning is either limited or enhanced within the groups' space of learning. The simultaneous bringing in of the social semiotic analytic perspective facilitates the identification of the form and content of the semiotic systems and their resources utilized by the students. How this limits or enhances the space of learning allows us in turn to identify students' attempts to open up dimensions of variation, as manifest in their engagement in the group interactive discussions.

In our analysis, it is the *relevance structure* construct which has important relations to the space of learning that evolves in a tutorial group. However, since in the context of our study it is not possible to know what the students were thinking, but only what they communicated and how they semiotically did this, we will, following Euler *et al* (2020), use the term *enacted relevance structure*.

3. Part Two: Data—the learning episodes

As a case study, in this second part of the paper we present our data and analysis. The data is presented in the form of two different episodes; one where students are working on a circular motion problem in the vertical plane (section 3.2), and the other of students working with a circular motion problem in the horizontal plane (section 3.3)—this constitutes the 'framing' (in Goffman's (1974) terms) of our analytic formulation. The participating students are part of a first-year introductory physics class at a Swedish university (further details not given for ethical-permission reasons). At the time of the study the students had attended regular classes on circular motion, and these had included problem-solving recitations. The textbook that was used by the students (Young and Freedman 2016) dealt with circular motion in one of the earlier chapters. Before introducing circular motion in the text, it was explicitly stated that only inertial frames of reference would be used, i.e. a frame of reference where Newton's first law is valid. When covering dynamics of circular motion, the textbook further states that within an inertial frame of reference there exists a net force directed towards the centre of the circle but no such thing as a center-fleing 'centrifugal force'. Prior to the start of the data collection the students

who participated in the study gave their consent for the video and audio recording of the group discussions. All other ethical considerations were in line with the university's ethical policies and procedures.

3.1. Methodological considerations

In order to 'capture' all the semiotic resources utilised by the students, we made video recordings of each group's discussions as they attempted to solve the given tutorial problem. The semiotic systems that the students typically used to communicate with one another during these tutorial sessions included spoken language, gestures, diagrams and mathematics. A transcription that comprises a collection of these elements is referred to in the social semiotic literature as being 'multimodal' (for examples, see Baldry and Thibault (2006), Bezemer and Mavers (2011), Flewitt *et al* (2014)). In adopting this approach we drew on the constitutionalist perspective of phenomenography to treat our transcription as another form of representation, the significance of which was guided by an ongoing development of the parts that made up the observed enacted relevance structure, i.e. what could be identified as 'focal awareness' and what 'dimensions of variation' that were being opened for a particular episode of discussion⁵.

Our analysis adopted an inductive approach. As a starting point, each of the authors individually watched and re-watched the video recordings of the group discussions making notes under the headings focal awareness, opening a dimension of variation, and episodic topic. In discussion together we then marked out the episodes that we wished to focus our attention on for the purposes of this paper. Once these had been identified we looked for commonalities and differences in our categories of focal awareness and dimensions of variation. We found no differences in dimensions of variation and no differences in instances of focal awareness. However, we did find differences in how we characterized those differences. All of these were in terms of the interpretative descriptions in terms of physics attributes such as: is this person talking from an inertial or non-inertial standpoint? Are they making reference to what they see as being centripetal or centrifugal or fictitious force? Later it became apparent that using such constructs made it difficult to follow the methodology that we wish to illustrate and decided to do this in a follow-on paper. Thus, for the illustrations we have used the semiotic significations themselves rather than interpretations of these.

When 'coding' our data we followed the approach of Bezemer and Mavers (2011) and viewed the (audio) transcripts and accompanying video recordings as 'theory' with *framing*, *selecting* and *saliency* attributes (see Kress (2010), (2013), for an in-depth social semiotic discussion of framing and saliency). In our case, framing refers to the enacted presentation of relevance structure; selecting, refers to the choice of episodes for analysis, which was based on where apparent inconsistencies in the views/explanations being offered by different group members presented possibilities for the exploration of dimensions of variation. And saliency refers to what is highlighted in the transcript:

Saliency refers to what is highlighted in the transcript, or which of the re-made features are given prominence. Researchers draw the attention of their readership to elements of the focal interaction by highlighting them in the transcript, for instance through size and positioning. The selected strip of interaction is reconstructed, foregrounding certain features, which may even have appeared in the background of the original interaction. (Bezemer and Mavers (2011), p 195)

⁵ For example, see Gee (2011), who refers to a 'stanza' of transcription where the sequence carries a thread of similar topic or content.

As described earlier, the working practice was to first undertake this analysis individually and then meet to compare our findings. Differences between us were then dealt with using an iteration between data and findings until no further differences existed.

The modes of communication (meaning the semiotic systems used) for the social semiotic multimodal transcription were not chosen in advance, and for the proposed methodology, should not be. The parts making up the transcription come from the semiotic systems that the students themselves chose to use. These turned out to be spoken language with and without emphasis, gaze (in added comment form), diagram and sketch, and gesture. This means that the social semiotic multimodal transcripts were ‘emergent’ (Bezemer and Mavers 2011, Kress 2013) in terms of what semiotic systems came to be included in the transcription as the analysis progressed. As such, they present a group tutorial problem solving genre which is situated in students’ choices of semiotic systems and their attempts to coordinate the ‘affordances’ (see Linder (2013)) of these systems as they engage in problem-solving tasks⁶. In other words, the transcriptions that are considered in this paper are regarded, as Bezemer and Mavers (2011), p 193, put it, as

empirical material through which transcription as a social, meaning-making practice (and changes therein) can be reconstructed [...] A social semiotic perspective on transcription draws attention to meaning-making principles, and the potentials and constraints of modes of transcription with the purpose of gaining analytical insights and developing theoretical arguments.

In our iteratively constituted multimodal transcriptions, we established salience in three ways: first, bold letters are used to show when spoken emphasis was made and underlining to indicate the accompanying aspects to the emphasis, as identified from the ‘run of the discourse’ to this point. Second, arrows are used to point to features in student-generated sketches and diagrams to establish elements of analytic prominence. Thirdly, where gestures and/or other formulations are simultaneous parts of a thread of discussion, these are co-presented with the spoken language.

As per normal tutorial procedure, during our video sessions the participating students were working without any direct teacher or researcher intervention. However, it was normal for there to be ‘observational visits’ from the teaching staff to observe how the groups were progressing with their assigned tutorial problems. And while it was possible for students to request teacher assistance, this did not occur during either of the two chosen episodes.

In the sections below, the multimodal transcripts of the chosen episodes are presented. Together with each transcript we also present the analytically identified focal awareness and dimensions of variation as the *key components of the relevance structure*. Since these are observational items from communicative interaction they are collectively referred to as the observed (i.e. enacted) relevance structure. This construct is further described in the analysis section (part three). Although the identification of focal awareness and relevance structure are given at specific rows (labelled as lines) of the transcription, they should not be interpreted as solely representing an analysis of that particular line of communication detail—the analysis draws on the continuous thread of communicative up to that point (see Jewitt (2014) for a wide variety of multimodal-transcription presentations). The identification of these entities was made through both individual and joint iterative cycles of induction. During this part of the analytic process, two university physics teachers, who were not associated with the study, with extensive experience and high repute were asked to review the analytic conclusions which we had

⁶Note that we in this paper do not make any claims about these affordances.

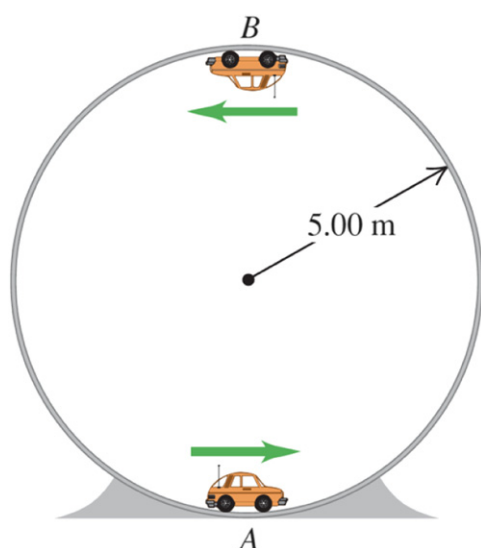


Figure 1. The given diagram for the problem in episode 1 (figure E5.45, p 187) (Young and Freedman 2016). Reprinted here by permission from Pearson Education Inc, New York, New York.

made. Where differences were identified, we all looked at the sequence of data together and discussed it until we reached a mutual agreement of interpretation. This final step represents the establishment of the kind of reliability and validity needed for the proposed methodology.

3.2. Episode 1: Vertical motion — ‘But how does it stay up?’

The first episode comes from observing a group of four students (pseudo-named as Alex, Billie, Charlie and Drew⁷) working on a vertical circular motion problem that presents a car moving with constant speed on the inside of a vertical hollow cylinder (see figure 1 and appendix A for a full copy of the problem). The given task is to find the ‘magnitude of the normal force exerted on the car by the walls of the cylinder’ in two different positions; at the bottom (marked A) and at the very top (marked B) of the cylinder (see figure 1). The speed of the car (constant), the radius of the cylinder, and the mass of the car were all given in the problem’s description.

At the start of the group’s discussion of how to do the given task, Alex appears to be the most confident about how to proceed, however their approach at this stage is largely numerically orientated. Billie then starts to question this approach—they are not convinced by Alex’ descriptions of what forces are acting on the car at the prescribed points A and B. In an effort to create a compelling conceptualization of these forces, Billie draws a large diagram (figure 2) of the car in the cylinder and then uses arrows to show the forces that they see acting on the car at the points A and B. This diagram then becomes the conceptual working document that the rest of the group uses for the rest of an emergent discussion. The thread of this emergent discussion starts with strong disagreements about what forces are acting on the car at the points in question. At this stage the group are discussing three forces, which they refer to as normal force,

⁷For ethical reasons we have chosen to use gender neutral names for all students in this paper, and will, when appropriate, refer to individual students with singular ‘they’ instead of ‘he’ and ‘she’.

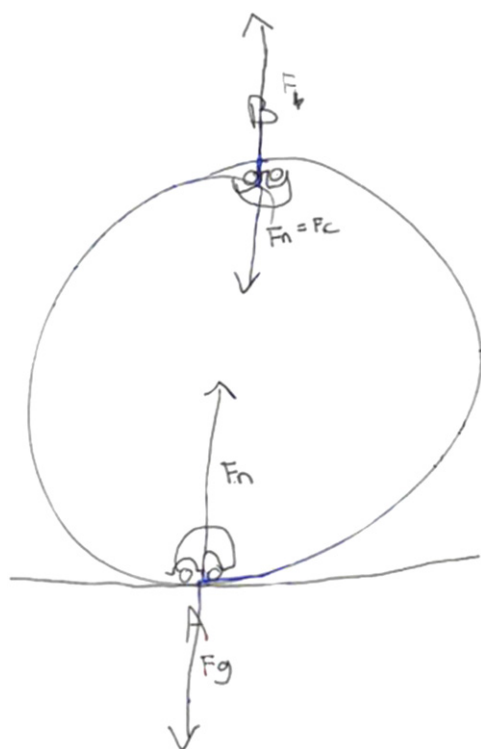


Figure 2. The diagram that Billie drew, which the group then centred their emerging discussion on.

gravitational force, and centripetal force. However, they quickly enter into a lack-of-agreement phase with respect to the direction of the centripetal force and from where it originates. Drew proposes that there should be a force acting on the car directed upwards at the top of the loop (a ‘keeping it up’-force), else the car would fall straight down. The discussion excerpt in table 1 starts at the point when Charlie proposes that the proposed upward force does not exist (i.e. does not act on the car).

In this section of the discussion Charlie opens up the possibility that the suggested upward force acting on the car at point B does not exist (line 307). At this stage in the conversation, neither Billie, Drew nor Alex, agree with Charlie; they remain convinced that the car needs a force to prevent it from falling straight down—‘something has to keep it up’ (see lines 311 and 313). However, Alex is starting to show signs of giving serious thought to Charlie’s explanation following their opening up of new dimensions of variation (see line 312), i.e. Alex is starting to incorporate new DRAs into their relevance structure. The dimensions of variation that Charlie opens up are underpinned by a shifting from a static thinking stance to a dynamic thinking stance vis-à-vis an inertial reference frame point of view. Charlie does this by drawing on the gesture semiotic system to use semiotic resources made up of two sliding arms, each with two finger aligners (see the Gesture column under lines 312, 316 and 318). We characterize this as a ‘gesture-based unpacking’ of the physics relationships that Charlie sees between the instantaneous velocity of the car, the corresponding acceleration, and the specifying of the net force responsible for that acceleration. To do this, Charlie generates variation within the DRAs, thus opening up the corresponding dimensions of variation.

Table 1. Verbatim multimodal excerpt from the first discussion between Charlie and Drew.

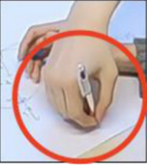
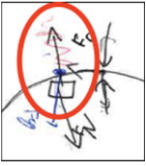
Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that get introduced
307	Charlie	I don't think <u>this force</u> [<i>the 'keeping it up'-force that Drew has drawn on the common sketch of the problem situation, figure 307 a)</i>] exists. [<i>Scratches out the upward outward force sketched in acting on the car at point B from one of the used diagrams, figure 307 b)</i>]			The force that the cylinder exerts on the car to get it to follow a circular path	Forces that are acting and not acting on the car
308	Alex	No, it does.			The force that the cylinder exerts on the car to get it to follow a circular path	None
309	Billie	It does.			Experienced outward-acting forces in circular motion	None
310	Charlie	It doesn't, but let me- [<i>interrupted by Drew</i>]			The force that the cylinder exerts on the car to get it to follow a circular path	None

Table 1. Continued


Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that get introduced
311a	Drew	But how would it stay up otherwise? [looking at Charlie challengingly]			Sum of forces equals zero for a static situation	The direction of the normal force acting on the car
311b	Alex and Billie	[looks at Drew and chuckles insecurely when they ask the question]				
312	Charlie	Oh, because the velocity is this way [puts right hand fingers horizontally in the air, figure 312 a) nr 1], but the acceleration this way [adds left hand fingers vertically upwards to the other hand towards centre of the circular motion, figure 312 a) nr 2. The image being seemingly transposed 360 degrees was a functionality of Charlie's gestured explanation],			Direction of the velocity vector, acceleration vector and force vectors for an object in circular motion	Changing of the different vectors

Figure 312 a)

Table 1. Continued



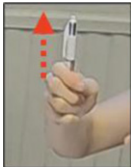

Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that get introduced
		<u>and as the force exerts</u> [puts left hand fingers vertically downwards to the right hand, figure 312 b)],				
		<u>the velocity changes like this.</u> [Moves right and left hand simultaneously to represent the car going downwards in the circle, figure 312 c)]				
		So, there is no force going like this. <u>[Moves pen upwards, figure 312 d)]</u>				
		But the force acts like this- [puts right and left-hand fingers together similar to figure 312b) and c), figure 312 e)]				

Table 1. Continued

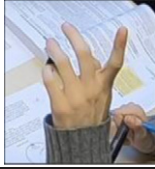
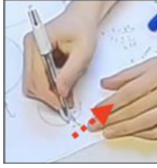
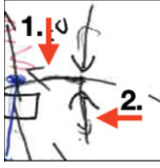
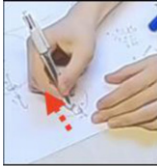

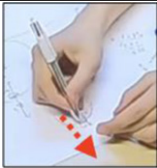


Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that get introduced
313	Drew	But something has to keep it up? [<i>uses index finger to point up</i>]			Treating the car as being in a static situation at top of the circular cylinder	The direction of the normal force acting on the car
314	Charlie	No, no-			N/A	N/A
315	Alex	Ahh! [<i>indicating that they are starting to construct a new understanding</i>]			N/A	N/A
316	Charlie	The velocity is going <u>like this</u> [<i>draws velocity vector horizontally, figure 316 a) and b) nr 1</i>], but then the <u>force goes like this</u> , [<i>draws force vertically downwards from the top, figure 316 c) and b) nr 2</i>]	 Figure 316 a)	 Figure 316 b)	Changing velocity and force that the cylinder exerts on the car and these are responsible for the circular motion	Changing direction of velocity
			 Figure 316 c)			

Table 1. Continued

Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that get introduced
		<p>which makes it change. [gestures with pen the circular path, figure 316 d)]</p>	 <p>Figure 316 d)</p>			
317	Drew	<p>But- [interrupted by Charlie from going back to their question of what would stop the car from falling down]</p>			<p>What would happen to a static car in this position?</p>	<p>The direction of the normal force acting on the car</p>
318	Charlie	<p>But there is no force [acting on the car] going like this [outwards]. [uses pen to gesture force vertically upwards on top of diagram, figure 318 a) and b)]</p>	 <p>Figure 318 a)</p>	 <p>Figure 318 a)</p>	<p>Normal force acting on the cylinder is not a force acting on the car</p>	<p>Forces acting on the car</p>
319	Alex	<p>It's the other way. [Uses index finger to gesture the direction of the force acting on the car]</p>			<p>Car pushes on cylinder outwards and in return the cylinder pushes on the car inwards</p>	<p>N3 pairs of forces</p>

Right after the discussion part given in table 1, one of the teachers who were present during this activity approached the group and, after being asked, confirmed Charlie's case regarding the non-existent force—the upward force acting on the car at the problem-given point B. Both the teacher and Charlie clarified what they meant by the “force does not exist” by stating that there is no upward force acting *on the car at point B*. However, this is *transcended* (i.e. *taken for granted*) by the group, which is taken on by Drew who again asks how the car could stay up otherwise (table 2, line 336). In the table 2 piece of the discussion, Drew and Charlie continue debating the upward force. Charlie (lines 337 and 339) tries to once again demonstrate to Drew how the velocity, acceleration and force are related with respect to having the car follow a circular path. Charlie does this by opening up a dimension of variation based upon the direction of the relevant velocity vector, using gestures and sketches as illustrated in table 2. Even though, finally, in line 340, Drew indicates that this aspect is now in their focal awareness, they do not go on to try and have this aspect become part of the group's focal awareness (a shared focal awareness). Thus, we have taken their response in line 340 to be seen to be wanting to agree with the teacher, and the aspect remained transcended for them.

This outcome leads to the question of why VTL does not seem to be opening up the space of learning for the group? What our analysis suggests is that there are two essential things missing in the group interaction; (1) a readiness to take on what became discernable with the new experiences of dimensions of variation that were introduced by Charlie to form a reconstituted relevance structure for the given problem; and (2) what is referred to as ‘diachronic simultaneity’ and ‘synchronic simultaneity’ in VTL. A short discussion of these two constructs thus follows.

3.2.1. Simultaneity re-visited. Earlier, in the section that introduced the essential features of variation, simultaneity was characterized as an essential part of the learning process as follows: the once *transcended* or *taken-for-granted* must be simultaneously seen with the *no-longer-transcended* or the *no-longer-taken-for granted* for a dimension of variation to be opened around some important disciplinary aspect. In this section a more fine-grained discussion is provided.

Having something brought into one's focal awareness is an important step towards enhancing one's relevance structure. But this may not be sufficient to learn something new. Complex phenomena need several ‘pieces’ of focal awareness to be brought together simultaneously for the constitution of new meaning. In VTL this dynamic has two threads (Marton and Tsui 2004). The first is referred to as *diachronic simultaneity*. This kind of experienced simultaneity is characterized by a bringing together of aspects of a phenomenon that have been discerned before, together with what is currently being discerned. In this way, *variation in the experience of the phenomenon* gets to become an experienced dimension of variation. This is how things get compared. For example, the differentiation of live versions of the famous opera masterpiece ‘Flower Duet’ from ‘Lakmé’ derive from many diachronically simultaneous aspects, for example, the venue, where one might be sitting in that venue, the singer, the orchestra, the conductor, and so on. Learning to distinguish between the different types of species of hyena—the spotted hyena, the striped hyena, the brown hyena and the aardwolf—one would need to start by knowing the specific aspects of at least one of the species and then experience diachronic simultaneity to be able to give distinguishing consideration to another of the species.

Then there is the experience of *synchronic simultaneity*. This kind of experienced simultaneity is characterized by a simultaneous bringing together of discerned aspects of a phenomenon that are considered to be important. For example, suppose that a spotted hyena and a striped hyena are presented together in photographic form. To make a definitive differentiation, the dimensions of variation of size, length of body hair, and markings on the body will need to

Table 2. Verbatim multimodal excerpt from the second discussion between Charlie and Drew.


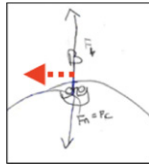

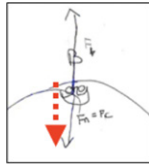
Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that gets introduced
336	Drew	But how does it stay up? [Looks at the teacher]			What would happen to a static car in this position?	The direction of the normal force acting on the car
337	Charlie	[Answering for the teacher] Because, the velocity is going <u>this way</u> [moves pen along velocity tangentially on top of the diagram, figure 337 a) and b)], and the <u>force is going this way</u> [gestures the direction of the force downward towards the centre of rotation, figure 337 c) and d)]	 Figure 337 a)	 Figure 337 b)	Velocity vector and how it changes and how the force that the cylinder exerts on the car is responsible for the continuous changing in velocity	Variation of the direction of velocity and simultaneously of the force that the cylinder exerts on the car.
			 Figure 337 c)	 Figure 337 d)		

Table 2. Continued


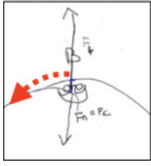
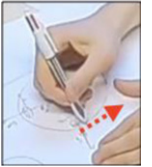
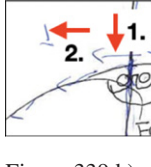


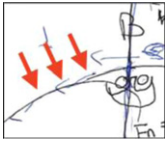
Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that gets introduced
		<p>which makes the velocity vector change. [Puts hands together with the fingers continuously changing direction as they align them along the changing displacement that makes up the circular path, figure 337 e) and f)]</p>	 <p>Figure 337 e)</p>	 <p>Figure 337 f)</p>		
338	Drew	<p>Yeah? [incredulous questioning to Charlie and teacher]</p>			N/A	N/A
339	Charlie	<p>[Attempting to have the dimension of variation that they opened become more discernable to Drew and the rest of the group]. But it [the car] stays up because it's going like <u>this</u> [draws velocity vector arrow tangential to the loop, figure 339 a) and b) nr 1],</p>	 <p>Figure 339 a)</p>	 <p>Figure 339 b)</p>	<p>Velocity vector and how it changes and how the force that the cylinder exerts on the car is responsible for the continuous changing in velocity</p>	<p>Variation of the direction of velocity vector as a function of the movement of the car in a circle</p>

Table 2. Continued

Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcript	Dimensions of variation that get introduced
		but the force goes like <u>this</u> [draws force arrow directed downward, figure 339 c) and b) nr 2)],				
		which makes it change like this- changes like this, and <u>so on</u> [draws how the velocity vector changes, figure 339 d) and e)]. It changes- the vector changes, but not-				
340	Drew	Oh, okay. I see.				

be opened simultaneously. The importance of experiencing such simultaneity is described by Marton and Pang (2009) as follows:

To experience or see a phenomenon in a particular way, one must discern certain aspects which correspond to the dimensions of variation of that phenomenon at one point in time, synchronically. For instance, to develop a way of understanding the Archimedes' principle, one must be able to discern the weight of a body immersed in water as compared to its weight when not immersed, and of the weight of the water displaced simultaneously. Thus, a particular way of experiencing or seeing something thus represents a set of related aspects or dimensions of variation which are discerned and focused upon synchronically. The limited number of qualitatively different ways of experiencing something can thus be characterized in terms of the discernment of aspects, the simultaneity of discerned aspects and the potential for variation in the discerned aspects of the phenomenon in question, which reflects the differences in the structure and organization of awareness (p 538).

In physics we have the possibility of describing light in terms of a wave. We also have the possibility of doing this in terms of particles (photons). Experiencing these two aspects with both diachronic and synchronic simultaneity is arguably what allowed Einstein and Infeld to observe the following:

It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do. (Einstein and Infeld (1938), p 278)

This is not to imply that the outcomes of such simultaneous experiencing leads to a fixed outcome. When Feynman discerned these different dimensions of light with both diachronic and synchronic simultaneity this is the kind of experience that could have facilitated the underpinning parts of his invention of quantum electrodynamics:

Newton thought that light was made up of particles—he called them ‘corpuscles’—and he was right (but the reasoning that he used to come to that decision was erroneous). [...] Light is something like raindrops—each little lump of light is called a photon—and if the light is all one color, all the ‘raindrops’ are the same size. [...] I want to emphasize that light comes in this form—particles. It is very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves. I’m telling you the way that it *does* behave—like particles. (Feynman (1985), pp 14–15, emphasis in original)

Mok *et al* (2002) and Tsui (2002) have illustrated how the order in which variation is introduced affects what is simultaneously in focal awareness. This could also be a factor in the sequence of events in the given data episode, but it would be extremely challenging analytically to ‘pull off’ a ‘staging’ of the ordering of the dimensions of variation that get introduced in such tutorial group discussion for empirical analysis.

3.2.2. Summary of episode 1. In episode 1 the students can be seen to be struggling to find a common relevance structure that includes a common perception of what forces acting on the car are relevant for correctly solving the tutorial problem (in this episode, at point B at the top of the circular loop). Drew is arguing for an upward force to keep the car from falling inwards, which is initially supported by Alex and Billie. At the same time Charlie opens up dimensions of variation to help Drew get to see how the velocity, acceleration and force from the wall acting on the car at this point are related, and in so doing wanting them to see why there is no

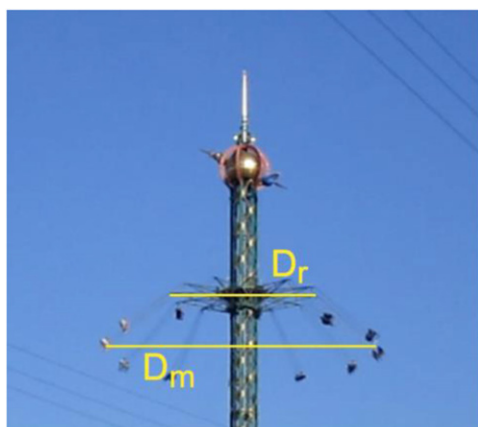


Figure 3. The figure to the problem given to the students in episode 2. The photo shows the swing ride *Himmelskibet* at Tivoli, Copenhagen. This figure is reproduced from Pendrill (2016, p 4) under CC-BY 3.0 license.

such upward force that is relevant for correctly solving the problem—in their words, it does not ‘exist’. To be able to share this part of their relevance structure, Charlie uses gestures (in addition to the diagram and spoken language) to open up these dimensions of variation. This is an example of how gestures and sketches can be used to generate *dynamic* dimensions of variation that call for experiences of synchronic simultaneity to foster understanding (which the analysis suggests does not occur for the rest of the students during this episode).

In this episode Charlie generates three different, but interconnected, dimensions of variation, namely the direction of the velocity, acceleration and force from the wall acting on the car. From the discussion that makes up the episode our analysis suggests that Drew is not able to see how the changing velocity of the car is related to specifying the forces acting on the car, i.e. this aspect is transcended to them and they have no experience of synchronic simultaneity. This suggests that their class engagement with what was presented about circular motion did not generate any experiences of diachronic simultaneity. Analytically this is why the changing velocity of the car is seen not to form part of the rest of the student’s enacted relevance structure during the discussion that makes up episode 1. Having this insight into the learning challenge presents teachers with their own challenges—discernment of the DRAs for a particular physics situation is necessary, but that is not enough. Creating appropriate experiences of simultaneity is also needed, and our position here is that the optimal way of doing this is by evoking variation scenarios using different semiotic-system resources—resources that are more easily used to constitute discerned DRAs—what are initially being experienced by students as quasi-independent pieces become emergent, context specific, coherently connected ‘wholes’.

3.3. Episode 2: Horizontal motion — ‘What stops you from getting pushed in?’

The second episode involves horizontal circular motion and comes from another group of four students (pseudo-named Eli, Frankie, Gale and Harper) who are working on a problem involving a horizontal ‘swing ride’ (see figure 3). This problem (see appendix B for a full copy of the problem) includes a part that asks ‘what forces act on a rider with mass m ’.

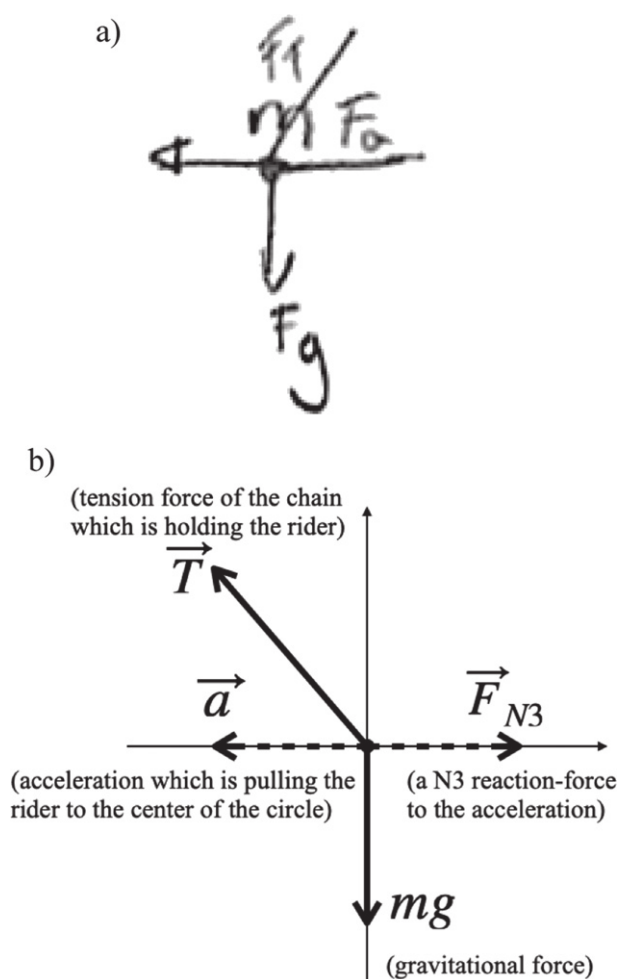


Figure 4. Gale’s free body diagram representing their relevance structure (a) made at the time of discussion that began in line 179, and an illustrated version of the enacted relevance structure of Frankie (b). Note that 4(b) is drawn from our interpretation of Frankie’s perspective and illustrates how Frankie views the swing and rider being in the right-most point of the horizontal circle.

In episode 2, the students are discussing whether there needs to be an outward force acting on the person on the swing (the rider) to get and keep the swing elevated in a circular orbit. Gale consistently argues for such an outward force while Frankie strongly disagrees with the proposal. Gale and Frankie thus lead the discussion. From the beginning, Gale and Eli agree that there is a tension force, a gravitational force, and an acceleration that is ‘pulling it (the swing) inwards’. However, Gale returns to what is in their relevance structure, which is that there needs to be an outward force acting on the rider—a force that acts in the opposite direction to what they refer to as an inward acting ‘acceleration force’ (marked F_a in figure 4(a)). Gale illustrates their argument using a sketch—a free body diagram of the rider showing the forces acting on the rider—which they then present to the other students (figure 4(a)). At this point in the discussion, Frankie who does not have such a force in their relevance structure (see figure 4(b))

declares it to be ‘not even a force’ (table 4, line 206). At this point, our analysis is that Frankie is experiencing diachronic simultaneity of what they have experienced in everyday life and what they have learned in their physics classes—this can be seen in their justification for the outward force not even being a force: ‘it is just created because of the third Newton’s law: *for every force there is a [unclear] force in opposite direction*’, which is ‘transduced’—meaning is shifted between two semiotic systems (see section 4.1)—into gestures using an inward and outward spreading of their hands.

Earlier, the analysis presented for episode 1 illustrated how spoken language was enabled by different physical movements and gestures to open up dimensions of variation for background elements that are not in the relevance structure for the task at hand. In contrast, the analysis presented in table 3 for episode 2 illustrates how spoken language is enabled by different physical movements and gestures to open up dimensions of variation for the taken-for-granted in ways that are directed towards seeing things in a new way; a no-longer-taken-for-granted way. The dimension of variation being discussed are the push and pull forces acting on a rider experiencing circular motion while on an amusement park swing ride such as shown in figure 3. The taken-for-granted is an outward acting force. Here, in particular, Gale and Frankie’s opening of new dimensions of variation manages to shift the taken-for-granted to a no-longer-taken-for-granted. And there is evidence that right at the end Gale is getting increasingly primed to enter into an emergent phase of getting to see the constructs of centripetal and centrifugal forces in a new light. Frankie, on the other hand, in this episode, can be seen to be strongly situated in this emergent phase of learning. In relation to relevance structure for this episode, we characterize Frankie as having a relevance structure that includes the velocity of the swing (referred to as a ‘dynamic relevance structure’) and Gale as not having velocity in their relevance structure (thus, referred to as a ‘static relevance structure’). This gets played out as follows: Gale presents their ideas of what forces are acting on the rider, which include a set of inward and outward acting forces (see their free-body diagram in figure 4(a)). Frankie is strongly opposed to taking such forces into account and argues that it is the velocity of the swing that keeps the rider from being drawn to the centre of the circle. Their opening up of a new dimension of variation for their argument does not convince Gale that there does not need to be a force to prevent the rider from being ‘sucked in’ (line 185) towards the centre of circular motion. Frankie then uses sketches to bring focal awareness to the instantaneously changing velocity vector and how this translates into an acceleration that is directed towards the centre of the circular motion. However, although Frankie identified the change in velocity as an important aspect, neither they (see line 184 and figure 4(b)) nor any other student extracted a horizontal force from the tension force in the rope.

Towards the end of episode 2 (see table 4, line 205) Harper re-introduces the idea that an outward force is needed to counter the inward pulling tension force of the swing chord. Frankie immediately challenges this by declaring it ‘not even a force’ just a consequence of Newton’s third law. But Harper’s proposal is authoritatively supported by Gale who establishes their authority from what they ‘learned in school’ before declaring that an outward force is needed to prevent the swing from getting ‘sucked in’.

3.3.1. Summary of episode 2. During the discussion piece transcribed in table 4 Frankie goes on to again try to get Gale to appreciate the changing direction of the speed of the swing-rider as they move in a circular path. However, Gale is committed to a static relevance structure and thus, discerning only what is taken-for-granted—that there has to be an outward facing centrifugal force (e.g. see line 207). Although Frankie has repeatedly presented a no-longer-taken-for-granted scenario, their associated dimensions of variation have not opened for the

Table 3. Verbatim multimodal excerpt from the first discussion between Frankie and Gale.



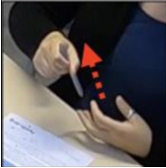
Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcripts	Dimensions of variation that gets introduced
179	Gale	At the moment <u>the tension force is</u> holding it, [<i>places pen vertically upwards, figure 179 a</i>)]			Tentative frame of reference. Tension force, centripetal acceleration, gravitational force, velocity	No variation, just identification of forces
		<u>the acceleration is pulling it inwards</u> , [<i>places pen horizontally and moves body as being 'pulled inwards', figure 179 b</i>)]				
		and your gravitational force is pulling you down, so <u>you don't fly up</u> . [<i>Moves pen vertically upwards, figure 179 c</i>)]. But what stops you from getting, like, pushed in ?				
180	Frankie	<u>Pushed in?</u> [<i>looks at Gale</i>]			What force could be pushing inward here?	The possible pushing and pulling forces acting on the rider

Table 3. Continued

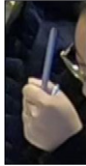


Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcripts	Dimensions of variation that gets introduced
181	Gale	Yeah [...] You have the <u>tension force which is holding [it]</u> - [places pen vertically upwards]			Tension force of the rope	Direction of the tension force
182	Frankie	No, <u>your velocity is</u> [places right hand vertically 'forward' to indicate an instantaneous tangential direction, figure 182 a)] <u>keeping you from going</u> [puts hands together to represent two opposing forces, figure 182 b)] inside.	 Figure 182 a)	 Figure 182 b)	Instantaneous velocity vector	Continuously changing direction of the velocity vector
183	Gale	Yeah. [looks at Frankie]			Seemingly the same as Frankie	Seemingly the same as Frankie

Table 3. Continued



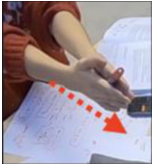
Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcripts	Dimensions of variation that gets introduced
184	Frankie	And <u>the rope</u> , <u>what it's doing is like, keeping you in a circle.</u> [<i>Makes a right angle with their right hand and arm and moves in a semi-circular path, figure 184 a)</i>]			Tension force in the rope and non-existing 'inward pushing' force	Changing direction of tension force provided by the rope. No pushing inside force just a force to change the direction of the instantaneous velocity
		But there is no force <u>going- pushing you inside.</u> [<i>Gestures with right hand how the rider should not be seen as being 'pushed inside', figure 184 b)</i>]		Figure 184 b)		
185	Gale	But how are you then <u>not sucked in?</u> [<i>peers at Frankie questionably^a</i>]			Acceleration being directed towards centre of circle assumes a force acting in that direction—a "sucking in" force. And this force needs to be counter balanced if the rider is to continue with circular motion	Pushing and pulling forces acting on the rider

Table 3. Continued

Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcripts	Dimensions of variation that gets introduced
186	Frankie	Because your velocity is always tangential. <i>[Puts both hands together and moves them horizontally forward]</i>			Tangential velocity vector	Direction of velocity vector
187	Gale	Yeah, yeah-			Seemingly the same as Frankie	Seemingly the same as Frankie

^aThis interpretation comes from consideration of the accompanying gaze and the thread of conversation to this point. The gaze is not shown for ethical reasons.

Table 4. Verbatim multimodal excerpt from the second discussion between Frankie and Gale.

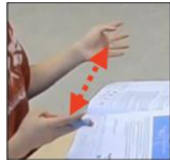
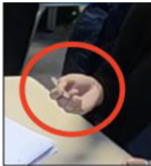
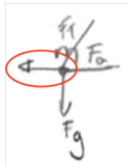



Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcripts	Dimensions of variation that gets introduced
205	Harper	<u>It is</u> always another force. [Looks at Frankie]			What is responsible for making the rider here follow a circular path?	Forces that are not apparent
206	Frankie	It's not even a force . It's just created because of the third Newton's law . For every force there is a [unclear] force in opposite direction. [Move hands back and forth]				N3 forces are 'not real forces'—just reactions to the real force
207	Gale	So, okay so for me- because I learned it in school , you draw the other side [force] too. [Points pen in direction of 'other side' indicating a centrifugal force, figure 207 a) and b)]. And that just makes sense because otherwise that looks as you are- yeah, you get sucked in. But because I am not allowed to draw a velocity force at the moment-			All forces acting on the rider, and in particular the apparent N3 force outwards, which is later in the explanation referred to as being the 'centrifugal force'	Variation in the direction of the centrifugal force

Table 4. Continued

Line reference	Group member	Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)		
		Spoken language	Gestures	Diagrams and sketches	Focal awareness seen in the transcripts	Dimensions of variation that gets introduced	
208	Eli	Okay-			Seemingly the same as Frankie	Seemingly the same as Frankie	
209	Frankie	<p>Because you- if you don't draw the <u>tangential velocity</u>. [<i>Draws a pictorial arrow to open up another tangential velocity dimension of variation, figure 209 a) and b)</i>]</p> <p>You have to <u>draw like this</u>. [<i>sketching an inward facing arrow, figure 209c)</i>]</p> <p><u>centrifugal force</u>. [<i>Makes quotations marks in the air, figure 209 d)</i>]</p>	 <p>Figure 209 a)</p>	 <p>Figure 209 b)</p>	 <p>Figure 209 c)</p>	Velocity vector's direction in relation to the direction of the centrifugal force	Variation of centrifugal force outwards (an N3 force and thus 'not even a force')

rest of the group—the dynamic of seeing both the taken-for-granted and no-longer-taken-for-granted simultaneously, does not materialize. Booth and Hultén (2003) explain this as follows:

‘Simultaneity’—seeing both the once-taken-for-granted and the no-longer-taken-for-granted—is demanded for the dimension of variation to open. Lack of understanding is thus linked with being unaware of the potential for variation—seeing only that which is taken-for-granted. (pp 69–70).

So, while the discussion revolves around the need for an outward force acting on the person on the swing, this outward force is proposed to be necessary to prevent the swing from being drawn to the centre of the circle by the force responsible for the (centripetal) acceleration that is directed towards the centre of the circular motion. On the other hand, Frankie is convinced that this outward force is not a real force, but a reaction force arising out of Newton’s third law. And even though they draw attention to some relevant physics by opening up a new dimension of variation of the direction of the velocity, because of the static nature of the relevance structures of their peers they get no access to the dimension of variation that Frankie attempts to open for them.

4. Part Three: Discussion

4.1. *Arising analytic considerations*

Our aim in this paper is to propose a bringing together of constructs from social semiotics and VTL to formulate a methodology that we see as being potentially useful for the physics education research (PER) community, in order to better understand learning challenges in physics from a VTL perspective. The proposal is illustrated empirically in ways that can promote a new thread of research aimed at informing and improving students’ educational experiences in ways that will make the use of VTL more attractive to physics educators (see Marton (2015), Marton and Pang (2013), and Marton and Tsui (2004) for a huge array of generalized support of this proposition, and Fredlund *et al* (2014) for support situated in the physics student-laboratory).

What differs in what we presented is that this was not another study limited to (say) gesture and sketches in meaning making; rather, the social semiotic multimodal transcriptions incorporate the range of semiotic systems that the students chose to use in their discussions. This is a significant methodological point of departure because it specifically does not treat the resultant communication presentations as being equivalent. Instead, when some aspect is presented in one semiotic system (say mathematics) and reformulated in that system, that is referred to in the literature as ‘transformation’. When it is presented in one system (say spoken language) and reformulated for presentation in another system (say gestures) that is referred to in the literature as ‘transduction’—see Bezemer and Kress (2008), Kress (2010), Volkwyn *et al* (2019), and Volkwyn *et al* (2020) for physics explorations of transduction making learning possible. What is seen in the multimodal transcriptions of our two episodes are transductions of spoken language (and mathematics) into gesture and sketch, and then having these semiotic parts supplement one another in the communication process. Having begun our analysis by identifying communicative episodes in the data sets that brought to the fore well-known learning challenges, our semiotic analysis of the multimodal transcriptions enhance the identification of key variation constructs. We then showed how these constructs had the possibility to generate analysis and insight not seen in this way before. In particular, we illustrated not only necessary conditions for learning, but what was needed to have those conditions work educationally.

The VTL perspective has for many years now offered both teachers and researchers a theoretical and practical framework for approaching learning and the addition of a social semiotic

perspective has already been posited as an enhancing of this framework (e.g. Linder (2012)). The analysis presented here is intended to show that empirically. In particular, each specific element of physics learning requires a relevance structure made up of context-specific disciplinary relevant aspects (DRAs). And since one of the basic grounding aspects of variation theory is that knowledge is characterized in terms of being a relation between the knower and known, any changes to a person's relevance structure reflect a change—a *qualitative change*—in the relevance structure. It is the emergence of such changes in the relevance structures which became observable through communicative action across semiotic-resource systems.

4.1.1. Identification of communicative sequences. The method of analysis that we illustrate began with the identification of educationally interesting threads of students' group communication. These were then placed into episodic pieces (see tables 1–4). The pieces were analysed first individually and then collectively by the authors in order to fulfill trustworthiness of the study (internal validity and reliability control). We used a combination of social semiotics and variation theory to create an analytic approach that looked at *the way* the students were communicating rather than only *what* they were communicating⁸.

In the illustrative episode pieces, the way the students communicated amongst one another in their tutorial groups was built on identifying what the relevant forces were that acted on the object of interest (car in the first case and swing-rider in the second), and what the direction of these forces was using both explicit and implied coordinate systems. The most critical identified DRAs for the students in episode 1 included velocity, acceleration, and the force from the wall acting on the car. For the students in episode 2, the most critical DRAs were identified to be the velocity and the tension force. The identification of these sequences was made possible by paying attention to the DRAs that the students were discussing. However, since the DRAs of this problem are identified from the discipline's perspective, the aspects that students chose to consider may or may not overlap with these DRAs. The observed parts of the (collectively) enacted relevance structure that matched DRAs consisted of the following components: the system, radius, mass, normal force, tension force, gravitational force, centripetal force, centripetal acceleration and instantaneous velocity⁹.

4.1.2. Students' enacted relevance structure. The next step in our analysis was to use our analytical framework to figure out what the multimodal transcripts could analytically reveal about interactive group learning for the given tutorial problems. In other words, we had to determine what the students communicated and what they intend to communicate in the chosen discussion episodes and tease these apart. As discussed earlier (section 2.2), a person's *relevance structure* is what a person finds to be relevant, what matters in a particular situation—in this illustrative case, solving a particular physics problem. Our empirical approach used an analytic tool (the enacted relevance structure) to link the students' positioning with their peers'. Two clear examples of where an enacted relevance structure presented itself in the data, was in episode 1, where Drew constantly argued that there needs to be something to stop the car falling down when it is at the top part of the circular loop and in episode 2, where Gale suggested that there should be a force directed outwards on the swing to prevent it from being 'sucked in' and when they goes on to say they are 'not allowed to draw a velocity force at the moment'.

⁸ As mentioned earlier, our focus in this paper is on the analysis rather than on the physics concepts and knowledge by the students. An in-depth analysis of the physics aspects will form a follow-on paper.

⁹ We use the term 'components' because what emerged was a series of descriptions that were not always fully compatible in the sense that different students presented what could only be characterized as DRA subsets.

Once the enacted relevance structures of individual students had been identified, we then sought to understand more about what learning possibilities were emerging from the group's interactive communication. For example, in episode 1, Charlie wanted Drew to see to the connection between the change in velocity and the force that the wall was exerting on the car—'because, the velocity is this way (pointing tangentially to circular path), and the force is going this way (pointing towards the centre of the circular path) which makes the velocity vector change'. And Frankie, in the swing problem, wanted Gale to see the connection between the change in velocity and the tension force of the chain—'no, your velocity is keeping you from going inside [...] And the rope, what it is doing is like, keeping you in a circle'.

Here it follows that while Charlie and Frankie were able to discern that velocity was relevant for successfully solving the respective circular motion problems, their colleagues were not. We characterize this as two different enacted relevance structures—either a 'dynamic' or a 'static' relevance structure, respectively.

4.1.3. Variation and dimensions of variation. The third step in our analysis was to understand more about *how* the students (Charlie and Frankie) went about trying to change their peers' relevance structures; what mechanisms and tools were they using to try to make this possible? In order to do this we looked more closely into the ways in which Charlie and Frankie's relevance structures diverged from their peers' and how they sought convergence by offering spontaneous variation around a certain important aspect of the problem.

To this end we analysed the communication from a VTL perspective while looking at the chosen sequences wherein students were trying to convince each other to change their relevance structure. Using this perspective, we were able to identify a structured, but spontaneous, variation in important aspects of the problem. Following the theoretical ideas presented earlier (section 2.2), VTL states that one needs to experience difference against a background of sameness to be able to discern a new aspect. This is how we interpret the students' communication while giving reasons or evidence in support of an idea with the aim of persuading others to share one's view. One example (tables 3 and 4) is where Charlie wanted Drew to focus on the velocity and thus created variation within this aspect—which represents different *values* of this dimension, in this case how the direction of the velocity vector changes to give rise to a centripetal acceleration.

One dimension of variation in particular, which we were able to identify that the students used in their discussions, was the *direction of the velocity vector*. Both Charlie (tables 1 and 2) and Frankie (tables 3 and 4) brought up this dimension of variation while trying to respond to Drew and Gale's proposals regarding the force situation for the car and the swing, respectively. Further, they are essentially attempting to open a dimension of variation when presenting different values of this aspect. However, from the analysis we see that this variation in itself may not be enough for the students to change their thinking if they cannot discern the appropriate DRAs.

How did the students offer this variation to their peers? Charlie used gestures (see table 1, line 312, and table 2, line 337) in addition to spoken language and diagrams. We suggest that the use of gestures could offer different possibilities for discerning the critical aspects of the problem, compared to what the diagrams and spoken language alone could do. Similarly, for the swing problem, Frankie also made use of additional gestures (see table 3, line 182–186) when trying to convey their message to Gale. In both cases, the different directions of the velocity vector (i.e. the changing velocity) represents different values of the dimension of variation for the velocity.

4.1.4. A brief note on relevance structure as a theoretical construct. Students' relevance structures for physics phenomena, parts of phenomena, problems to be solved and so forth, can be

related to the PER resources perspective (for an overview, see Redish (2003), (2014)). However, exploring this further requires a discussion that reaches beyond the realms of this paper, other than to acknowledge that the epistemic grounding for the PER resources perspective and that of relevance structure are quite different. Relevance structure is derived from the anatomy of awareness perspective drawn from phenomenology and phenomenography, whereas the PER resource perspective has its epistemic roots in discourse analysis, one of the principal roots being Tannen (1993).

4.2. Considerations for teaching

Although we have not presented an analysis of the physics required to correctly solve these problems, some considerations for teaching can be derived from what has been presented in this paper. There have been previously described approaches to improving physics learning outcomes through the use of variation theory (for example, Fraser and Linder (2009), Fredlund *et al* (2015a), Linder and Fraser (2009), Linder *et al* (2006)). These studies have shown how design-structured experiences of variation can be a key ingredient to enhance the possibilities for student learning. In our analysis, the explicit inclusion and consideration of the resources of semiotic systems (be it through semiotic transformation and/or transduction) brings with it the possibility of new understanding of learning challenges in physics. Being able to identify instances of limiting and enhancing a group's space of learning in terms of the DRAs that form part of the intended object of learning coupled with students' observed enacted relevance structure, offers new design tools for teachers wanting to enhance learning outcomes. Since the educational focus for us is physics, the discernment referred to here is best characterized as *disciplinary discernment*—'noticing something, reflecting on it, and constructing meaning from a disciplinary perspective' (Eriksson *et al* (2014), p 170).

We suggest that there are two aspects to understanding the role that a person's relevance structure has for their ability to experience disciplinary discernment. First, there is the role of experienced *simultaneity* as described earlier; without such simultaneity the discernment of transcended or taken-for-granted DRAs is theoretically not possible. This is the situation even when a person has a new dimension of variation opened for them (as confirmed in the earlier given citation of Booth and Hultén (2003), p 69). The second factor that we are proposing is one of 'epistemological commitment' (Hewson 1985). We see such epistemological commitment exemplified when a person is committed to a particular relevance structure from intuitive and experiential interpretations of a phenomenon (or part of it). Put another way, *epistemological commitment is about the commitment to a particular way of thinking about something. It is about deciding whether to notice something new in a meaningful way when one is given the possibility to do so—when that new meaning making does not well match a belief, understanding, or meaning that has already been constituted.* For example, in the transcribed discussion given in table 3 (lines 179–187), Gale's epistemological commitment to an outward facing ('centrifugal') force acting on an object following a circular motion path, is much in evidence. And this appears to be a contributing factor to their inability to access the dimensions of variation that Frankie was attempting to open for them to counter that understanding. How does this work with the variation theory-needed simultaneity? We propose that such epistemological commitments prevented the variation theory-needed simultaneity from emerging—thus preventing learning from taking place. Hence, our illustrative analysis has revealed a critically important aspect for variation theory to address—what is needed from an anatomy of awareness standpoint to promote a change in epistemological commitment that is preventing the needed experience of simultaneity?

5. Part Four: In conclusion

In this paper we have drawn on a phenomenography perspective to show how the VTL can be extended as an analytic tool for exploring student learning in interactive environments and in so doing provide additional insights and understandings of students' learning challenges in a discipline such as physics. In our consideration of students' interactions during tutorial group work, we illustrated how the proposed methodology facilitated the identification and interpretation of their enacted relevance structures during specific sequences of interactive discussion. We also demonstrated how a synthesis of VTL and social semiotics can be employed to analytically explore the opening (or not) of different dimensions of variation for group participants. We see research using this methodology as being able to present new design principles for teachers to use to enhance learning outcomes. At the same time, we see the analytical constructs and the literature drawn on in the paper as having great potential for enhancing teachers' understanding of their students' learning.

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Appendix A.

The full problem used in episode 1 (see also figure 1): exercise 5.45, with figure E5.45, p 187 (Young and Freedman 2016). The problem is reprinted here by permission from Pearson Education Inc, New York, New York.

A small remote-controlled car with mass 1.60 kg moves at a constant speed of $v = 12.0$ m/s in a track formed by a vertical circle inside a hollow metal cylinder that has a radius of 5.00 m (**Fig. E5.45**). What is the magnitude of the normal force exerted on the car by the walls of the cylinder at (a) point A (bottom of the track) and (b) point B (top of the track)?.

Appendix B.

The full problem used in episode 2 (see also figure 3).

This photo shows the Himmelskibet ('Star flyer') ride visible from Copenhagen Hovedbanegård. The diameter at rest is 14 m and the chain length is 8 m. From the photo, the ratio between the diameters at motion and at rest can be estimated to 1.9.

- What is the angle between the chains and the vertical?
- If the ride makes a full turn in 6.3 s, what is the speed of the rider in the swing?
- What is the acceleration of the rider?
- What forces act on a rider with mass m ? Draw a free-body diagram.
- How could you use the photo to estimate the acceleration? Compare the value to your result in 3.

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