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Exploring the role of physics representations: an illustrative example from students sharing knowledge about refraction

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Abstract. Research has shown that interactive engagement enhances student learning outcomes. A growing body of research suggests that the representations we use in physics are important in such learning environments. In this article we draw on a number of sources in the literature to explore the role of representations in interactive engagement in physics. In particular we are interested in the potential for sharing disciplinary knowledge inherent in so-called *persistent representations*, (such as equations, diagrams and graphs) which we use in physics. We use selected extracts from a case study, where a group of senior undergraduate physics students are asked to explain the phenomenon of refraction, to illustrate implications for interactive engagement. In this study the ray diagram that was initially introduced by the students did not appear to sufficiently support their interactive engagement. However, the introduction of a wave front diagram quickly led their discussion to an agreed conclusion. From our analysis we conclude that in interactive engagement it is important to choose appropriate persistent representations to coordinate the use of other representations such as speech and gesture. Pedagogical implications and future research are proposed.

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1. Introduction

Probably the most successful teaching-learning approaches informed by physics education research have been based on the idea of interactive engagement. Here the interaction may be between peers ('convince your neighbour discussions', Mazur, 1997, p. 12), or between students and teachers. It has been shown that such interaction has the potential to significantly enhance learning outcomes (see Deslauriers *et al.*, 2011 for a recent, much acclaimed study; and Hake, 1998 for one of the original ground-breaking reports). Highly regarded research-designed physics learning environments that have successfully incorporated aspects of interactive engagement include; Active Learning (Van Heuvelen and Etkina, 2006), Peer Instruction (Mazur, 1997, 2009), and Tutorials (McDermott and Shaffer, 2002). Research on these learning environments has shown that their application significantly improves both conceptual understanding and problem solving skills (Redish, 2003; McDermott, 2001). Recent work by, for example, Rosengrant *et al.* (2009), Airey and Linder (2009), and Tang *et al.* (2011) suggests strongly that the representations we use in physics (such as diagrams, graphs, equations, spoken and written language, gesture, etc.) play a critical role in the effectiveness of the interactive engagement between students in these learning environments. However, little research has been done in this area. In this article we explore the potential of different representations to enable the

sharing of physics knowledge. As an illustration, we present an analysis of an interactive engagement sequence where senior undergraduate students attempt to provide an appropriate and adequate explanation for the refraction of light.

1.1. Affordances of representations

The importance of representations in the learning of physics is increasingly attracting the attention of researchers (for example, Airey and Linder, 2009; Hestenes, 2003; Kohl and Finkelstein, 2006; Kohl *et al.*, 2007; McDermott, 2001; Meltzer, 2005; Podolefsky, 2008; Rosengrant *et al.*, 2009; Scherr, 2008; Tang *et al.*, 2011; Van Heuvelen and Zou, 2001). The essential underpinning assumption of this growing body of research is that different representations have different potentials for communication, what Gibson (1979) calls affordances.

The affordances of different representations determine the role they can play in communication, and thus in the sharing of knowledge. Mathematical symbolism affords, for example, ‘logical reasoning through the precise encoding of mathematical participants and processes in a format which facilitates their rearrangement’ (O’Halloran, 2010, pp. 219-220). Images, on the other hand afford, for example, the sharing of spatial and directional relationships (Kress and van Leeuwen, 1996). The possibility then arises to choose a constellation of representations that offers the best set of affordances for the situation at hand (Airey and Linder, 2009).

In this article we are particularly interested in the *disciplinary affordances* of representations. We define the disciplinary affordances of a given representation as the inherent potential of that representation to provide access to disciplinary knowledge. Thus, it is these disciplinary affordances that enable certain representations to become legitimate within a discipline such as physics. Physics learning then, involves coming to appreciate the disciplinary affordances of representations.

Another important aspect when thinking about the affordances of representations is the notion of persistence (Kress, 2010). Kress relates persistence to the physical nature of certain representations that allows us to readily refer to them at any point in time. Examples of persistent representations are written language, pictures, diagrams, etc. The strength of persistent representations is that they can easily be referred back to, for example by pointing. Non-persistent representations, such as spoken language, gestures and facial expressions, are temporal in nature and therefore more difficult to refer back to effectively in interactive engagement (Wells, 1998; Kress, 2010).

1.2. Common persistent representations in the area of refraction

In exploring the disciplinary affordances of persistent representations used by students involved in interactive engagement, we will use the area of refraction of light as an example. The most common persistent representations typically used in explanations of refraction, apart from written text and equations, are ray diagrams and wave front diagrams. In a recently completed review of 93 German and English undergraduate physics textbooks, Hüttebräuker (2010) reported that some type of ray diagram was almost always presented, and that wave front diagrams appeared in less than half of the reviewed texts. Research has shown that it is not always clear to students how to represent refraction using the wave model of light. For example, Sengören (2010) found that many first-year university students, despite saying that the wave model of light would be appropriate for explaining the refraction of light, did not appear to appreciate the affordances that wave front diagrams have for such an explanation and this could be seen in the inappropriate wave representations that were drawn by them.

1.3. Research questions

The background provided in the Introduction sections led us to develop the following research

questions:

- Which persistent representations are used by a group of students when engaging interactively in explaining the refraction of light?
- Can differences in disciplinary affordances of the persistent representations used by the students be observed in such an explanation?
- What aspects of the persistent representations used in explaining the refraction of light can account for their differences in disciplinary affordances?

2. Method

2.1. Data collection

In order to address our research questions we present an illustrative case study with a group of third year physics undergraduates who we expected to be well acquainted with the phenomenon of refraction. The group was comprised of three academically successful students, Mike, Nick and Vera (pseudonyms). The students were given the task to provide an appropriate and adequate explanation for the refraction of light to a hypothetical peer student. The students did not know about the task beforehand and therefore had no time to prepare their answer. The interactive engagement between these students took place in the student physics laboratory. This setting was chosen purposefully, so that items such as water, a glass tank, laser pointers, etc. and a blackboard and chalk would be available if needed by the students to help them constitute their explanation. However, since we wanted to observe how the students constituted their explanation, we did not provide explicit access to textbooks or the Internet. This approach was chosen because it is the engagement, complete with dead-ends, and its ultimate progress towards an agreed solution that is of interest for our exploration. Very occasionally, one of the researchers asked a clarification question that the hypothetical peer could have asked. The presence of a researcher provided the possibility to ask the students to take their explanation further, if found to be desirable. The students' engagement with the task lasted for approximately 30 minutes, and was audio and video recorded. However, the whole transcript of the session is not reported here—only those sections critical for the analysis are presented.

The fundamental value of performing a case study is that they provide in-depth insight, that is 'detail, richness, completeness, and within-case variance', through "the force of example" (Flyvbjerg, 2011, p. 314; 305). At the same time, we appreciate that by using a case study to illustrate our exploration, the possibility exists that a different experimental setting, such as having a different group of students, and/or having an actual peer present, could have generated different illustrative aspects. However, the implications that we suggest in section 5 capture what emerged from our case study, and we think this insight will prove fruitful for the development of the teaching and learning of physics.

2.2. Method of analysis

Our analysis was accomplished by first transcribing 'multimodally' (Baldry and Thibault, 2006) the audio and video data from the whole 30-minute engagement. This means that the spoken and written language, diagrams, equipment, mathematics, and gestures, etc. that the students used, were reproduced or described in parallel in a chronological order. By abstracting concepts from the multimodal transcript we then created a form of data mapping that was based upon Lemke's (1990) notion of 'thematic patterns'.

Thematic patterns were first introduced by the physicist Jay Lemke (1990) in order to analyse teacher talk in school science. Rather than presenting data chronologically, as in the case of the multimodal transcript, a thematic pattern approach aims to provide a synoptic, time independent, analysis. Thematic patterns can be thought of as being similar to 'concept maps' (Novak and Cañas, 2008) constructed from interviews, in that they display relationships between concepts, however, the analysis

is generated in more fine-grained detail. Our goal in using thematic patterns was to present the physics meanings that were negotiated in the students' engagement with their given task. Especially, we have chosen to highlight in thematic patterns one part of the discussion, which we think is particularly decisive for the students' successful task completion. The multimodal transcripts and thematic patterns resulting from our analysis are shown in figures 2, 3 and 4.

3. Results

The three students, Vera, Mike and Nick, began their explanation of refraction by discussing with speech and gestures what happens to light as it passes an air-water boundary. They then went on to draw a 'canonical' ray diagram (figure 1) on the blackboard. The students also decided to immerse a washing-up brush in a glass tank that they had filled with water. After this, Vera attempted to further problematize why light bends by suggesting the use of wave fronts, however, her suggestion was not taken up by Mike and Nick. Mike instead stayed with his idea that the reason why refraction occurs is that 'water is kind of thicker than air'. Vera then inserted mathematical symbols for two angles into the ray diagram, and wrote the mathematical inequality below the ray diagram, as shown in figure 1.

Figure 1. A computer-generated reproduction of the ray diagram drawn by the students (including the mathematical symbolism for two angles and their mathematical inequality that was inserted later).

The two persistent representations, ray diagram and mathematical symbolism (figure 1), were accompanied by speech and gesture (non-persistent representations) in order to pinpoint what it was that Vera found unsatisfactory in their explanatory efforts (the inability to explain *why* the light bends). This is shown in figure 2, which also shows how the students' explanation at this stage included Mike's assertion that light bends because one medium 'is denser' than the other. At this point the students' explanation appeared to reach a dead end.

Transcript of spoken language	Transcript of other representations	Thematic pattern
<p>Vera: Why is it, why is this smaller and not bigger?</p> <p>Mike: Well, because this is denser, kind of.</p>	<p>Vera: Points at θ_1 in the inequality (figure 1).</p> <p>Mike: Points below the horizontal line (in figure 1).</p>	<p>The diagram illustrates a thematic pattern for refraction. At the top is a box labeled 'Light (Object)'. A solid line connects it to a box labeled 'Travels in (Process)'. From 'Travels in', two lines branch out to 'Air (Location)' on the left and 'Water (Location)' on the right. Below 'Air' is a box labeled 'Less dense (Property)', and below 'Water' is a box labeled 'Dense (Property)'. Horizontal lines connect 'Air' to 'Less dense' and 'Water' to 'Dense'. A dashed line encloses the 'Air' and 'Less dense' boxes, and another dashed line encloses the 'Water' and 'Dense' boxes. A vertical dashed line separates these two groups. A solid line connects 'Less dense' to 'Dense', with the label '(Contrast)' next to it. A solid line connects 'Travels in' to 'Bends (Process, consequence)' at the bottom. A dotted line encloses the entire structure from 'Light' down to 'Bends'. To the right of the diagram, the word '(Cause)' is written.</p>

Figure 2. Multimodal transcript (LHS) and thematic pattern (RHS) of the initial part of the discussion. The chain line encapsulates the cause of refraction, as it appeared in the students' explanation. The broken and dotted lines encapsulate the physics meanings that were contrasted in the discussion.

The analysis presented in figure 3 focuses on how the students resolved this stalemate. Vera posed the question 'Why... does [bending] happen because [one medium] is denser?' This led to the mentioning of Huygen's principle and a reconceptualization of light as a wave, which had not been seen as necessary by the group earlier in the discussion. Then Vera returned to her earlier suggestion to draw on the idea of wave fronts. This time the other group members acknowledged this as a potentially fruitful way forward.

Figure 4. The thematic pattern illustrates how introducing the wave fronts afforded the students' explanatory focus to shift to the speed of light. The chain line encapsulates the cause of refraction, as it appeared in the students' explanation. The broken and dotted lines encapsulate the physics meanings that were contrasted in the discussion.

A comparison of the thematic patterns in figures 2 and 4 reveals the differences between conveyed meanings at different times in the students' discussion. That is, that the contrast between 'dense' and 'less dense', which earlier appeared to be critical for the bending of light (see the thematic pattern in figure 2), is superseded by a contrasting between 'fast' and 'slow' (see the thematic pattern in figure 4), which is the difference between the speeds at which a wave front would travel in air and water, respectively. Finally, following the part of the discussion that is shown in figure 4, a wave front diagram was drawn by Mike (see figure 5). All three students then took the opportunity to individually formulate a detailed explanation by coordinating their oral descriptions and gestures (non-persistent representations) around the persistent wave front diagram shown in figure 5. Our analysis of these individual reformulations is that they do not affect the thematic pattern presented in figure 4, but rather served to confirm and cement the relationships between the physics concepts that had already been fruitfully established.

Figure 5. A computer-generated reproduction of the final hand-drawn wave front diagram that was produced by the students.

4. Discussion

The students who participated in our case study used a number of different representations to constitute their explanation of the refraction of light. As we mentioned in the introduction, part of our analytic framework included the notion of disciplinary affordances. We now show how the notion of disciplinary affordances of persistent representations can provide a rich and insightful way to discuss the analysis and to formulate the essence of our interpretation.

In order for the students to reach some sort of ‘conceptual convergence’ (Roschelle, 1992; Oliveira and Sadler, 2008), they needed to choose as a starting point an aspect of physics knowledge that they could mutually take to ‘stand fast’. By standing fast we mean something that a person or group of people can call upon and ‘use without hesitation or without further questioning’ (Wickman and Östman, 2002, p. 608), around which, in our case, the participating students build their continued discussion. Thus, in the presented analysis, what we found to be standing fast was initially represented by spoken language (a non-persistent representation), but quickly progressed to being represented diagrammatically as a ray diagram (a persistent representation). We suggest that this shifting to a persistent representation for what is agreed as standing fast is particularly powerful in interactive engagement. As our analysis clearly illustrates, persistent representations can be seen to play a vital role in interactive meaning making by facilitating the coordination of non-persistent representations such as gestures and spoken language (see also Kress, 2010).

Our analysis also illustrates how different persistent representations have different disciplinary affordances. Some persistent representations of the same phenomenon appear to be more appropriate than others for the sharing of particular physics knowledge. For example, in the presented analysis, Vera suggested that wave fronts could be a good way to represent light. But since neither of her collaborators, at that stage of the engagement with their task, could appreciate the value of representing light in this way, a ‘meaning-making negotiation’ took place that ultimately resulted in the students being able to see shortcomings of the ray diagram that they may not have noticed before. The mentioning of ‘Huygen’s principle’ at that stage led the students to quickly reformulate the way they were talking about light; in terms of ‘electromagnetic waves’, and ‘wave fronts’. Mike’s simulating gesture representing a moving wave front made the students aware of one of the critical aspects of a successful explanation of refraction: the change in speed of light upon passing the border between media with different refractive indices. Not until they had finally ‘agreed’ on wave fronts as an appropriate way to represent light for the purpose of explaining refraction, did the students start to draw a wave front diagram, which then in turn became the new persistent representation that stood

fast. The wave front diagram was then used to coordinate non-persistent representations in the students' continued efforts to constitute an appropriate explanation for the refraction of light.

In effect, our analysis illustrates how different persistent representations can be better suited to play different roles in interactive engagement, depending on their particular disciplinary affordances. Thus, for the optimization of interactive engagement it is important for the participants to be able to come to a point where they can choose an appropriate persistent representation to stand fast.

As we have seen, the students in our study did not initially choose the wave front diagram, even though it later turned out to be the most useful representation for the constitution of their explanation of the refraction of light. Hence, we also suggest that there may be a relationship between the persistent representation that is first chosen and the frequency with which that representation occurs in learning resources such as undergraduate textbooks. The ray diagram, which is the most frequently occurring persistent representation in textbooks, did not require negotiation before standing fast—this was a taken for granted starting point. The wave front diagram on the other hand, needed an engagement of quality before its disciplinary affordances were perceived, and then drawn on.

The fact that different aspects of light are represented in ray diagrams and wave front diagrams may account for the different affordances they offer for an explanation of the refraction of light. The ray diagram, for example, could be seen as taking an indifferent or 'agnostic' position regarding the wave/particle nature of light, and only affords a showing of the (change in) direction of propagation of light. The wave front diagram, on the other hand, is dependent on the choice of the wave model of light. This representation of light as being spatially extended enables a division into different parts, travelling at different speeds in media with different refractive indices. The students in our study appeared to experience this as providing a plausible and fruitful mechanism for modelling the bending of light at the interface between the two media. The students could also have become aware of this difference in speed by noticing the difference in distance between wave fronts in the different media. It is interesting to note that the students in our study also produced persistent mathematical representations; however, these were not built upon in their discussion. Therefore in our system of analysis we find no evidence that these particular persistent representations stand fast for the students.

5. Conclusions

We started this article by noting that when students engaged interactively, extensive research has shown that this opens the way to improving conceptual understanding and problem solving skills. Then we argued that the representations we use in physics play a critical role for the efficiency of this interactive engagement, and presented our illustrative analysis of the use of representations by a group of students working in the area of refraction. Building on these aspects of physics learning, we now highlight what we feel are the most interesting pedagogical implications for potentially enhancing the teaching of physics that are supported by the analysis:

- A critical feature for successful interactive engagement is having something that stands fast for the participants. Persistent representations are particularly useful in this respect.
- Different persistent representations have different disciplinary affordances.
- It is thus educationally critical for students to learn which persistent representations have which disciplinary affordances.

Based on our analysis of the students' discussion, we also suggest that:

- The persistent representation initially chosen by students to stand fast may depend more on its frequency of use rather than its disciplinary affordances for the task at hand.

6. Future research

We suggest that it would be interesting to investigate our hypothesis that, in interactive engagement, the persistent representation routinely chosen by students to solve physics problems primarily depends on the representation's frequency of use in textbooks and lectures, rather than its suitability for the task at hand (i.e. its disciplinary affordances). This suggestion can be seen to be supported by recent research into how students decide what is relevant for solving problems in physics (for example, see Bing and Redish, 2012).

7. Summary

In summary, we argue that students need to develop an understanding of the disciplinary affordances of different physics representations. Similarly, we suggest that in order to optimize physics learning in interactive contexts, physics teachers need to know more about the range of persistent representations available, and their associated disciplinary affordances.

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