Physics students learning about abstract mathematical tools when engaging with “invisible” phenomena

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The construction of physics knowledge of necessity entails the combination of a wide range of resources, (e.g. specialized language, graphs, algebra, diagrams, equipment, gesture, etc.). In this study we documented physics students’ use of different resources when working with an “invisible” phenomenon; — magnetic field. Using a social semiotic framework, we show how appropriate coordination of resources not only enabled students to learn something about the Earth’s magnetic field, but also about the use of an abstract mathematical tool; —coordinate systems. Our work leads us to make three suggestions:

(1) The potential for learning physics can be maximized by designing tasks that encourage students to use a specific set of resources. (2) Thought should be put into what this particular set of resources should be and how they may be coordinated. (3) Close attention to the different resources that students use can allow physics teachers to gauge the learning occurring in their classrooms.

I. INTRODUCTION

One of the major challenges to student learning in physics involves coming to terms with the role played by abstract mathematical tools when modeling physical phenomena (see for example, Refs. [1,2]). One such widely used abstract mathematical tool is the fundamental notion of coordinate systems.

In this paper an analysis of student engagement with an open-ended task designed to teach one particular aspect of coordinate systems, namely their *movability* is presented in terms of a multimodal, social semiotic framing [3,4]. The analysis demonstrates how student engagement with a particular set of purposefully chosen representational resources, quickly leads to them experiencing themselves as holding a movable coordinate system.

Physics sense-making is of necessity “multimodal” [5,6] meaning that it calls for a collection of different *forms* of representation. While a single representational resource may provide access to one or more aspects of physics knowledge, there is a case to be made that it is only through engagement with *particular sets of resources* that holistic, disciplinary learning can occur [5,6]. This leads to the suggestion that when designing tasks in laboratory settings, physics teachers should pay particular attention to the set of representational resources that they expect students to be able to use and how these may best be coordinated.

II. BACKGROUND

A. Representational competence, critical constellations and coordinating hubs

The discipline of physics uses a wide range of representational resources (from now on referred to simply as resources) such as spoken and written language, algebra,

graphs, diagrams, apparatus etc. (see for example, Refs. [5,7,8]). Thus, in the PER literature it is common to discuss students’ engagement with these resources in terms of the development of *representational competence* (see for example, Refs. [9–11]). In the broader social semiotic community there is a tendency to refer to representations in terms of semiotic resources (see Ref. [6]). In this paper the two terms will be used interchangeably in alignment with the literature that has been drawn on to frame the work. In other words, a social semiotic framework is being used to provide the analytical method for examining physics students’ engagement with a particular set of resources in the physics laboratory. The work leverages two established notions in this research tradition: *critical constellations* and *coordinating hubs*.

It has been suggested that understanding any given physics concept entails familiarity with a so-called critical constellation of resources [5,11,12]. Here, the argument is that for any given physics concept there is a specific set of resources that, when coordinated in a particular way, makes a significant contribution to making learning possible. Further to this, it has also been demonstrated how students can constitute such a critical constellation during interactive engagement when a persistent, tangible resource (for example a diagram or a piece of apparatus) functions as a coordinating hub for other non-persistent resources, such as gesture and talk [13]. From this perspective, a prerequisite for students to be able to constitute such a critical constellation of resources is that they have achieved a degree of representational competence with each of the individual resources that together form the constellation.

B. The movability of coordinate systems

Arguably one of the more challenging abstract mathematical resources used in introductory physics is the

notion of coordinate systems. In problem solving settings, one of the main *disciplinary affordances* [13,14] of coordinate systems is that their origin and orientation can be defined by the user, i.e., their position and orientation is a matter of user-choice. It is precisely this movability that often allows for the simplification of many complicated forms of physics modeling and application. However, coordinate systems are almost universally presented in physics textbooks in a particular orientation (see Fig. 1). This standardized presentation of coordinate systems risks students assuming that they are fixed in this orientation.

FIG 1. Coordinate systems as typically presented in physics textbooks. In 2-dimensions, the x-axis increases to the right and the y-axis up the page. In 3-dimensions, the z-axis tends to be portrayed as pointing up the page.

C. Experiencing magnetic field: the IOLab

The aim of the study was to provide experiences of the movability of coordinate systems while investigating a phenomenon that students cannot themselves directly sense; the Earth's magnetic field. A multi-purpose educational measurement instrument, the IOLab, was used because it can be hand held while providing a real-time display of the components of the magnetic field on a computer monitor. There is also a set of axes printed on the top and bottom faces of the device used to show the orientation of the instrument (see Ref. [15] for a presentation of the pedagogical uses for the IOLab).

III. METHOD AND ANALYSIS

The study involved an open-ended task (see for example Ref. [16]) presented in a Swedish upper secondary school. The students were simply instructed to use the IOLab to find the direction of the Earth's magnetic field and mark its direction using a red paper arrow. No other information was provided.

Students worked in pairs, with their interaction recorded by fixed video camera and desktop microphone (Fig. 2). A complete multimodal transcription of the video data was carried out following the approach laid out in [3,4]. This method involves carefully preserving the ways in which all possible resources for meaning making are coordinated in terms of synchronous and asynchronous usage during transcription.

FIG 2. Range of meaning making resources initially used in the task: graph, IOLab manipulation (proprioception), speech.

IV. RESULTS

After some initial discussion, the students quickly started to manipulate the IOLab, leveraging their natural *proprioception* to “feel” the orientation of the device whilst simultaneously paying attention to the results of this manipulation on the screen. For some time, the students had difficulties interpreting the components displayed on the computer. Initially they could not make sense of the zero, positive or negative components displayed for the magnetic field direction. For example, early in the learning sequence, the students moved the IOLab up and down (even getting up off their chairs to raise the device as high as possible), in an attempt to influence the y-component values (see Fig. 3). Arguably, this should be expected given the students’ prior experiences of fixed two-dimensional coordinate systems, where the y-axis always points “up” (see Fig. 1).

FIG 3. “Up” does not make the y-component more positive; negative is not necessarily down.

The set of resources that make up the IOLab system allowed the students to test ideas and resolve challenging sense-making questions. Moreover, in the process of resolving these conflicts, the students' actions also indicated that they were learning new things about the nature of the Earth's magnetic field.

Eventually, the combination of IOLab manipulation, proprioception, and talk led the students to formulate a strategy to make first one and then two components of the field zero (see Fig. 2). In effect, the IOLab was rotated so that two of the coordinate axes were perpendicular to the field. Students then fixed their paper "cut-out" arrow to represent the direction of the magnetic field (see Fig. 4).

FIG 4. The magnetic field direction represented by a red paper arrow, pointing into the ground at a steep angle that correctly matched the students' geographical location.

For the particular illustrative pair of students, the introduction of the arrow appeared to function as a hub around which they could coordinate other resources. From this point on the students produced expressions of insight and understanding with respect to coordinate systems and their movability. We take this as indicative of a critical constellation of resources being constituted [5,12] with the red arrow acting as the coordinating hub (see Fig. 5).

The data analysis also revealed a new previously undocumented step: the new meanings constituted by the students were quickly shifted to a new resource, *gesture*, hitherto not used by the students in the task. In Figs. 6 and 7 the female student introduces gesture into her explanations. In the first instance she is able to verbally express and simultaneously gesture her understanding of why the component value on the screen must be negative—since the *z*-axis is aligned anti-parallel with red arrow. In the second instance the student reorients the IOLab and curls her fingers, effectively sweeping out a plane perpendicular to the *x*-axis. She simultaneously expresses her insight that any component values in the plane perpendicular to the arrow must be zero. Clearly it is unlikely that the student would have been able to make these particular meanings in the absence of the red arrow.

FIG 5. With the arrow now acting as a coordinating hub, the students quickly grasp aspects of coordinate systems which had confused them before. The faces of the two students are shown by permission.

FIG 6. Introduction of gesture. The student explains, "...it [the *z*-component] is negative because it [the *z*-axis] points up [finger points directionally opposite to the arrow]." The faces of the two students are shown by permission.

FIG 7. Second instance of gesture. Fingers curl around thumb aligned with red arrow and *x*-axis. Student explains, "... they [any *y*- & *z*-components] would all be zero ...". The faces of the two students are shown by permission.

V. DISCUSSION AND CONCLUSION

Empirically, in their working with this open-ended task, students appeared to move from an initial experience of simply holding an unfamiliar electronic device in their hands to an experience of holding a movable coordinate system. From their discussion it was also apparent that the task gave them some insight into the properties of the Earth's magnetic field. The fact that in Sweden the angle of inclination of the Earth's magnetic field dips steeply towards the ground led to a discussion about "*what the field looks like*" across the hemispheres of the world. Discussions later shifted to other sources of magnetic field and how these could influence the information recorded on measuring devices. For example, the activity was followed with a task where students were asked to locate the building's reinforced steel beams, which are not visible under the concrete. Here, the IOLab's unique pedagogical affordances [14] (real-time display and leveraging of proprioception) seemed particularly apt for encouraging the necessary coordination of resources to occur.

Our intention in this paper has been to introduce the reader to the social semiotic perspective with respect to students learning about the movability of coordinate systems. Here, our data supports earlier findings that disciplinary meaning in physics activities is distributed across a range of resources and that students therefore

require a critical constellation of resources to discern the meaning of disciplinary content that is new to them. The data also confirms the value of a fixed resource (in this case the red paper arrow) as a hub around which students can coordinate other resources [13]. Here we advise that careful thought must go into what this coordinating resource should be. One new recommendation is that teachers should be looking for coherent introduction of previously unused resources. It is argued that such newly introduced resources (in this case two specific gestures) should be taken as indicative of what students are learning. Noticing such instances also presents a teacher with opportunities to confirm/challenge student conceptions.

Finally, these findings and earlier work in this area point to the wider importance of understanding the roles that different resources play and how they may be coordinated for optimal physics learning. It is therefore suggested that further research in this area is desirable.

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Within the social semiotic framing described here, 'disciplinary affordance' refers to the agreed meaning making functions that a representation or semiotic resource fulfils for a particular disciplinary community.
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