The Joint Work of Connecting Multiple (Re)presentations in Science Classrooms

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Abstract

The aim of this study is to advance current understanding about the transactional processes that characterize students' sense-making practices when they are confronted with multiple representations of scientific phenomena. Data for the study derives from a design experiment that involves a technology-rich inquiry-based sequence of activities. We draw on interaction analysis to examine the work by means of which a group of upper secondary school students make sense of a number of different ways in which a physical phenomenon—a phase transition—is presented to them. Our analytical perspective, grounded in a cultural-historical framework, involves scrutinizing how the different materials emerge and evolve as signifiers for something other than themselves during teacher-student and student-student transactions. This approach allows us to trace the emergence of students' interpretations of the relations between phenomena and their diverse presentations without committing to any preconceived notion of what these presentations stand for. We describe how students' bodily and pragmatic actions become reified in conceptual terms and how these index to lived-in experiences rather than to formal underlying concepts. Findings are discussed with regard to the central role of body and praxis in research on learning science with multiple representations.

Keywords Multiple representations, Sign, Cultural-historical theory, Interaction Analysis, Body

Introduction

The competence of relating and coordinating multiple representations with each other and with the phenomena they stand for is a central aspect of science learning and practice; it is also an important concern in research in science education (Klein & Kirkpatrick, 2010). Many received theories situate the work necessary to establish such relations—the relations between the original phenomenon and the ways it is made present again—in psychological, private processes of information processing that mediate between *external* and *internal representations* (Mayer, 2003; Schnotz & Bannert, 2003). Whereas research informed by these frameworks has provided taxonomies and guidelines for the design of multi-media instructional materials (e.g. Mayer & Moreno 2002; van der Meij & de Jong 2011), a difficulty in the literature is that the analytical and theoretical attention is often withdrawn from the situated, material, and public operations by means of which students relate phenomena with the signs and symbols that come to stand in for them. For example, students may do an investigation to find the relation between temperature and volume of a gas and subsequently are confronted with a diagram depicting the phenomenon. Students encounter the same phenomenon made *present* (i.e., represented) by different means. How do they come to relate these to constitute a single and coherent scientific understanding? Emerging *situative* approaches argue that a focus on internal, individual processes of comprehension does not adequately address this question because it does not explain how learners come to develop the competencies necessary to read the different notational systems associated with each representational form in the first place (Kaput, 1998; Klein, 2006; Roth, 2004).

To address these limitations, research has turned attention towards the analysis of *referential practices,* "the ways in which reference can be seen to be thoroughly embedded in, and inexorably intertwined with, the interactional activities in which they emerge and are constituted" (Hindmarsh & Heath, 2000, p. 1856). From this perspective, the work involved in relating and coordinating the multiple forms in which a scientific phenomenon is presented does not only have a private and individual component, but also, and most fundamentally, emerges in and through social and public activity (Vygotskij, 2005). Research within this view has started to investigate how scientific literacies such as interpreting graphs, digital simulations and other forms of presentation, emerge from bodily and practical actions during joint activity rather than from cognitive, information processing capabilities (Roth, 2004; Roth & Lawless, 2002a).

The aim of this paper is to advance current understanding about the situated and social nature of students' sense-making practices when they are confronted with multiple representations of a single scientific phenomenon. To that aim, we first review mainstream literature on learning with multiple representations, and contrast it with studies that focus on the situated work that learners perform to make sense of instructional materials. We then describe a semiotic analytical lens for the study of learning in multiple representations environments that draws on cultural-historical theory (Vygotskij, 2005; Vygotsky, 1978) and builds upon previous research on scientific graph reading and layered representations (Han & Roth, 2006; Roth & Bowen, 2001). We use this approach to examine the sense-making practices in which a group of upper secondary school students engage during a sequence of inquiry-based activities in which a scientific phenomenon—a phase transition—is presented first as part of a hands-on activity in which a spray can of compressed air is manipulated, and later as part of a set of linked digital models of the phenomenon. In our analyses, body and praxis emerge as fundamental dimensions in the students' sense-making practices. In a concluding section, we discuss the relevance of these findings with regard to current research on learning with multiple representations.

Background

Research on Learning with Multiple Representations

Research generally reports that environments where the "same" or related scientific phenomena are presented (again) in different forms—such as physical experiments, graphs, and digital simulations—support students' development of scientific understanding (Adadan, 2013; Tsui & Treagust, 2003; van der Meij & de Jong, 2006). However, these studies also show that learning in these environments is not straightforward. Researchers report that students tend to focus on surface features of the experimental materials and visuals rather than on the conceptual aspects related to them (Krange & Ludvigsen, 2008), fail to draw relations between otherwise linked representations (Chittleborough & Treagust, 2008; Kozma, 2003), and do not necessarily make sense of the presented phenomena in the same terms that experts (designers, scientists, educators) do (Kozma, 2003; Roth et al., 1997).

A widely held assumption in the literature is that learning from multiple representations involves a mental process of information decoding and integration. Thus, to learn in this kind of environments, students first "must understand how a representation encodes and presents information" (Ainsworth 2008, p. 200). Even when learners understand this, "they still need to understand how this representation relates to the specific topic it is representing" (p. 201). In addition, to achieve an integral understanding, learners need to be able to *relate* and *translate* across the multiple representations (van der Meij & de Jong, 2006). Thus, "only when learners identify these references within and between the external representations they can construct a coherent mental representation and come to a deeper understanding of the subject matter" (p. 321). Consequently, much research within the field has been concerned with investigating the cognitive *effects* that different instructional interventions have in supporting the students' academic performance (e.g. Bartholomé & Bromme, 2009; Seufert, 2003; van der Meij & de Jong, 2006). However, findings often suggest that the complex nature of these learning environments does not lend itself to factorial descriptions (Waldrip et al., 2010). In this regard, a review of research in the field points out that "little is currently known about how learners achieve . . . integration . . . and attempts to help learners do so by providing instructional support or software tools are far from proving invariably successful" (Ainsworth, 2008, p. 204).

At least two critiques to the view sketched above have been raised in the recent literature. First, in viewing learning as a matter of an individual's decoding of information, the empirical focus tends to be on correlations between pre-specified design features and measured learning outcomes, thus treating actual social, bodily and material actions that take place during episodes of learning as epiphenomenal to learning itself (e.g., Furberg, Kluge & Ludvigsen, 2013). Second, just which features of the different instructional materials represent which "information" is often considered with regard to normative models of expert knowledge rather than on a thorough examination of how phenomena and the corresponding representational features are related in the learners' experience, who do not yet know the expert models that the instructional setting intends them to learn. In this regard, researchers from situated and sociocultural perspectives have argued for the need of taking more learner-oriented approaches in the study of science and mathematics education (Lave, 1988; Lobato, 2012; Roth, 2012a).

Social and Situated Perspectives

Studies concerned with the question of how learning with scientific representations is achieved in and through situated social practice have increased in the last years (Waldrip et al., 2010). Here, the focus is not on the "information" that learners do or do not recognize in and across representations. The interest is rather on how the learning materials become means in and for establishing social relations. Accordingly, representations and other instructional materials are described as *semiotic resources,* which emerge and evolve as material features of the setting and are recruited in the course of social transactions. In this regard, research has shown that an important aspect of learning and teaching with graphs, simulations, and other forms of representation is that these become *deictic resources* (they can be pointed to by means of the hand or "indexical" terms such as "this"), making it possible that teachers and students jointly attend to particular features of the local environment that then can be the object of collective discussion and activity (Furberg, et al., 2013; Nivala et al., 2012). Importantly, research shows, rather than in terms of the intellectual "contents" that experts and educators may associate with them, learning materials first acquire their sense as they are recruited with respect to practical demands of ongoing tasks. That is, their sense first emerges as a *practical* understanding (Roth & Bowen, 2001). Thus, even expert scientists need to "undo decontextualization" to understand their own graphs, interpreting these in terms of their familiarity with the local contexts and methods from which the graphs were first derived (Roth, 2013).

Purpose of the Study

As the preceding review of literature suggests, the significations that curriculum designers intend to emerge for students should not be taken for granted but rather must be seen as *potential* inscribed in the different instructional materials and settings. Whether students actually *realize* this potential is an empirical matter. Accordingly, to understand learning with multiple representations from the perspective of the learners, who do not yet know the curriculum, we need to look at external representations (inscriptions) and other instructional materials not as "re-presenting" content, but as forms of *presentation.* That is, something first comes to be present for the students, as form, before it comes to be present again, in and through the representation. Therefore, to understand learning with and across multiple representations, we need to understand how such movement from form to *re*presentation takes place in and through situated classroom transactions. Yet, research in the field of learning with multiple representations has not yet addressed this question in terms of the analytical implications it has. In addressing this question, we contribute to the growing body of literature concerned with the situated and social nature of learning by first articulating an analytical framework that focuses on how science phenomena and representations thereof emerge and evolve as *signs* in the course of practical social action. First, the relation between signs and signification is not straightforward but involves transactional *coordination work;* this work produces the social relation between actors and, simultaneously, the sign relation between multiple forms of presentation. Second, we provide empirical examples that illustrate the proposed framework by means of a case study from a technology-enhanced learning environment.

A Cultural-historical and Pragmatic Approach to Learning with Multiple Representations

In this section, we first describe the theoretical underpinnings of a cultural-historical, semiotic approach to the *sign*, of which the signifier (representation) is only one half, the other half constituting the signified, some original phenomenon that is made present by means of a representation. This will serve us to lay out an analytical approach for analyzing the emergence of sign (presentation) relations in educational settings with multiple instructional materials that are aimed at presenting "the same" scientific phenomenon.

The Sign—a Social and Material Relation

The relations that link one segment of the material continuum (e.g., the sound dictionaries transcribe as /ˈspreɪ ˈkæn /, the (corresponding) written word "spray can," or the pictograph "  ") to another segment of the material continuum (e.g., a real spray can) are referred to as signs (Eco, 1984). The segments of the sign, because they allow students who have played around or experimented with a spray can to make that object present, are denoted as representations. However, a focus on the sign allows us to highlight a second important dimension not made explicit when using the theoretical concept of representations. Thus, in the cultural-historical perspective on the sign, the primary function of signs is to act on other persons; they are primarily *a means of social contact*. For example, a toddler's reaching gesture, when recognized by her mother as a sign of the child's desire of reaching something—e.g., a toy—comes to accomplish a social function as the mother brings the toy closer to her daughter. Here, what initially was an immediate relation between the toddler and her environment becomes a meaningful relation between two people (Vygotskij, 2005).

From this function is derived yet another function: signs as a means available to persons for acting on themselves (Vygotskij, 2005). Thus, a sign that first emerges as a means of relating to others may be later internalized by the individual as a means for relating to herself. Signs are not stable but undergo cultural-historical, individual ontogenetic, and situational changes. According to this view, any sign is inherently a cultural phenomenon and constitutes a *social* means for acting upon others (Wittgenstein, 1953/1997). When signs become incorporated into practical action, the action itself is transformed just as it would be when a (new) tool[1] is introduced to an exchange. As forms of activity become transformed by the introduction of new signs, so the individuals' psychological functions are transformed too. Thus, to study how introducing particular teaching materials are involved in facilitating that scientific understandings emerge

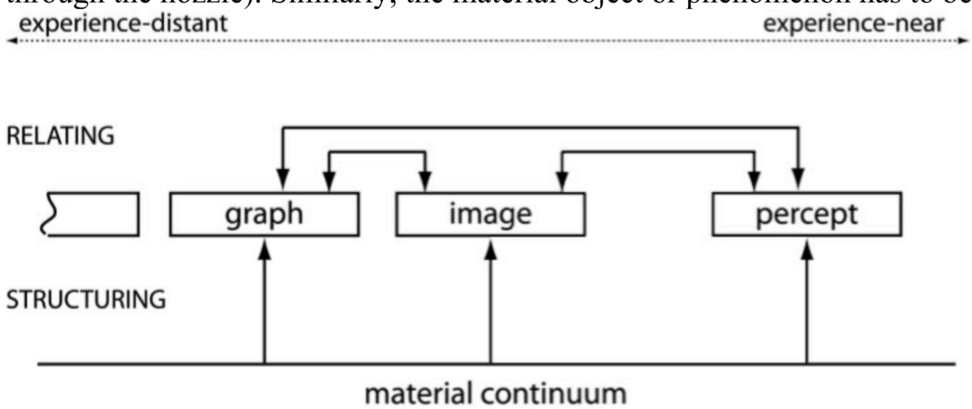
[1] Although Vygotsky (1978) makes a categorical distinction between signs and tools, more recent work

during inquiry activities, we need to examine the processes by which new signs are incorporated into and transform the students actions.

Structural and Relational Work

In our approach we draw, as others do (Kaput, 1988; Latour, 1993; Roth, Pozzer-Ardenghi, & Han, 2005), a clear distinction between the material continuum from which objects, artifacts, phenomena, inscriptions, or sound (voice) are made and the structural aspects that characterize their use. The relations between any two materials are based on structural and not on purely material or ideal properties. For example, the letters "E" and "M" consist of the same material but are structurally distinct and associated with different phonetic articulations; although a photograph of a flower and a graph of its growth rate may appear on the same book page or computer monitor, consisting of the same material basis, the significance of their relation is based on structural properties (Figure 1). There is therefore no "natural relation" between two presentations: there is an *ontological* gap between any two of these (Latour, 1993). This gap is bridged by means of social practices and the (arbitrary) conventions to which these adhere.

Previous research has shown that it is possible to describe the process of interpreting representations such as graphs and texts in terms of two activities, *structuring*—the activities that differentiate sign from ground—and *grounding*—the activities by which any structure is related to a familiar context of signification (Roth & Bowen, 2001). Building on this research, we assume here that any two instructional materials come to be linked as the result of two types of work: *structuring* and *relating*. First, the material continuum—e.g., the display of three arrows (Figure 3) or the spray can that appear in the study below (Figure 2)—has to be structured; it requires transactional structuring work (e.g., Roth, 2008). What structure related to an object, artifact, or phenomenon is relevant to any given situation is not self-evident, even for experienced scientists. For example, in the present study, students have available a spray can. What is it about the spray can that is relevant to understanding a heat pump, the topic of the curriculum? Because students are to learn about the heat pump, the function of which they do not yet know, *it* cannot serve as a referent for structuring the spray can or an aspect that turns up in inquiry (e.g., the slightly cool gas emerging from it, the lower temperature of the can itself, which appears to move downward in the can, the structure of the can, or its capacity to push gas through the nozzle). Similarly, the material object or phenomenon has to be structured.



The second type is *relating* work; it is by means of this work that a relation is established between the different presentations (Figure 1). In the work of biologists, for example, soil samples are entered into a two-dimensional array that corresponds to location along a transect and depth at which the sample was collected; this arrangement subsequently comes to be related to a graph that is said to feature the horizontal and vertical distributions of different kinds of soil (Latour, 1993). In this way, a feature in/of the natural world, soil found in different places, comes to be related to specific features of a graph on paper *in and through the scientific practices*. The relations between two very distinct material features—graphite lines on paper and soil samples—rather than being "natural," exist only in and because of this practical work.

With this background, the following empirical analyses describe how the practical work involved in structuring and relating unfolds in the context of an inquiry based learning unit on science where a series of hands-on activities have (curricular) connections with a later set of digital models.

Research Design

This study is part of a larger project (MIRACLE) intending to design science-learning environments that bridge activities across settings, including the school and the museum (Jornet & Jahreie 2013). MIRACLE employs the design experiment approach (Brown, 1992; Krange &

Ludvigsen, 2009), where pedagogical interventions are conducted to systematically observe and analyze the resulting learning practices to further inform the development of instructional designs and theoretical conceptualizations about learning. Here, we draw from an investigation conducted during an early phase of the MIRACLE design experiment. In that investigation, constituting a *case study,* a group of students was recorded while discussing and connecting multiple learning materials and representations. The case study allows us to investigate the coordination work that it takes to establish any connections that the students were making between multiple presentations. A case study approach is particularly appropriated for studying the development of sense-making practices as these unfold along unique situations within our own culture (Donmoyer, 1990). Case studies "produce the type of context-dependent knowledge that research on learning shows to be necessary to allow people to develop from rule-based beginners to virtuoso experts" (Flyvbjerg, 2006, p. 221). The case approach therefore affords us to gain proximity to the context-bound unfolding of the phenomenon of interest to describe precisely how it is related to the context of its occurrence.

Setting and Participants

An experimental setting featuring two different learning scenarios, a classroom and a museum space, was set up in a studio at the University of Oslo (Norway). Here we focus on the activities taking place in the school space. One group of three students from a Norwegian upper secondary school, together with their teacher of natural sciences, participated in the study. The students included a girl (pseudonym Kaamini) and two boys (pseudonyms Melka and Ishan). As part of a curriculum on energy, the students engage in a set of activities that, from the designers' perspective, are related to the topic of "heat pumps." Heat pumps are devices that transport (heat) energy from a colder source (external environment) to a warmer location (the interior of a house, for example) by means of mechanical work (pump). Understanding how heat pumps function involves understanding basic principles of thermodynamics. The unit also focuses on socio-economical issues related to energy consumption and the environment.

The experimental sequence occurred over a 6-hour one-day session. During the instructional unit, experimental activities in which the students act with relatively little guidance are combined with teacher-led interventions in which prior experiences are summed up and discussed with regard to curricular issues. The students are asked to investigate material artifacts, observe what happens, discuss with each other, and record a small video with their iPods in which they illustrate and explain what they have observed. These videos are then displayed and discussed with the teacher. The students later solve tasks involving digital models. The analyses presented here focus on how the different teaching materials and concepts are connected during and across these set of activities.

Data and Analytical Procedure

Events were video- and audio-recorded using two cameras and several microphones distributed in the learning space. One camera followed the students in close-up mode to obtain a complete record of talk and gesturing. The other camera was static and aimed at capturing contextual aspects that could not be captured by the first one, such as what was being displayed on the white board. Both verbal and non-verbal transactions were transcribed in Norwegian for the whole set of video-material using a software package for qualitative analysis (Nvivo 9). Video-recordings were analyzed building on interaction analysis (Jordan & Henderson, 1995). Interaction analysis is a multi-method approach for investigating "human activities, such as talk, nonverbal transaction, and the use of artifacts and technologies, identifying routine practices and problems and the resources for their solutions" (Jordan & Henderson, 1995, p. 42). Among other methods, interaction analysis draws on ethnography and conversation analysis, methods that involve detailed observation of human transactions and communication within contexts of social practice, such as educational settings. In our case, the analytical process involved several rounds of jointly analyzing the data material, and of refined identification of relevant episodes. In the process, we arranged collective data sessions were members of our larger research community also were invited to participate.

In preliminary analyses, we identified those instances in which topical connections between the different materials presented to the students emerged from their transactions. We were not only interested in graphical materials, as is common in the literature, but also in material phenomena that are often used in the classroom for *presenting* something other than itself, such as a physical law (e.g. Roth & Lawless, 2002a). These preliminary analyses led to an increasingly refined selection of clips for closer analysis of invariant (general) patterns. A more detailed transcription including gestural and prosodic aspects of communication was produced—following Jeffersonian transcription conventions (see Appendix 1)—and selected excerpts were translated into English. The excerpts here reported represent particular instances of transactional work involved in the constitution of continuity across multiple presentations during inquiry-based activities..

Analytical Policies

Following a cultural-historical approach, our unit of analysis extends beyond any participant's private thinking, and captures individuals and materials in their relations with others (Vygotskij, 2001). For this reason, we refer to the work as *transactional*, as it cannot be reduced to the work of individuals that is added up to make the joint work (Roth & Jornet, 2014). Rather, joint action and work, though it requires the participation of multiple individuals, is taken as a (irreducible) social phenomenon sui generis (Durkheim, 1919; Vygotskij, 2005). We attend to the *emergence* of signs with regard to the *what-for* and *in-order-to* of the actions taking place in, and as part of, *situations,* which constitute larger structures of signification that are experienced in a unitary sense (Dewey, 1938; Vygotsky, 1994). Thus, for example, in the current study, a stream of air resulting from pressing on the valve of a spray can is not experienced as it stands for itself, in isolation of anything else surrounding it, but takes place as part of an ongoing, purposeful action within a (science learning) situation. The phenomenon involves not only the stream of air, but also the background against which this stream is visible and takes its particular shape.

To understand how signs emerge from the point of view of the participants, without ascribing our own frames of reference to the semiotic process, we adopt disciplined ways to approach the recorded materials. We analyze participants' individual actions and utterances from a dialogical perspective, for which any contribution in transaction must be understood as responding to, and directed towards, other participants as well as to the actor herself (Bakhtin, 1986; Linell, 2009). Coherence and consistence are not assessed against external standards, but are regarded an internal (i.e., endogenous) achievement of the situated sequential organization of turn taking in conversation. Any turn is considered as part of the stretch of talk that precedes it, and its import to the constitution of ongoing action is examined with regard to the turn that follows it (Schegloff, 1968). Situational practices of social order provide participants with methods for holding each other accountable and make talk coherent despite the un-predictable nature of any stretch of talk because engaging in conversation already presupposes mutual understandings over matters such as, for example, that questions imply conditional terms upon the kind of next turns that are expected. In this way, the context in relation to which sense is constituted is not given by frames of reference defined a priori by the analysts, but are understood from what the participants make available to each other in conversation. This, however, does not preclude us from aiming to add to a more general understanding of particular *institutional practices,* here science learning in an (experimental) inquiry-based setting (Heritage, 1998; Mäkitalo & Säljö, 2002).

The Emergence of Sign-relations in an Inquiry-based Multiple Presentational Setting

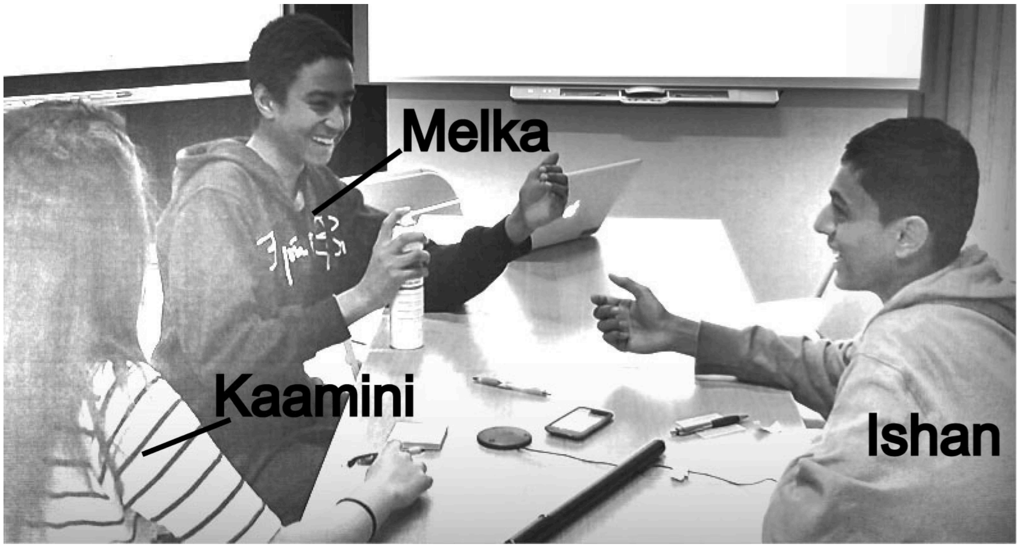
This study was designed to investigate how the different instructional materials presented as part of an inquiry-based sequence of learning activities emerge as salient aspects of participants' relations, and whether and how (if any) relations are established across them. In our analyses, we follow the students from (a) their first inquiries with a spray can of compressed air and a bicycle pump (Figure 2) to a later set of tasks involving (b) an interactive graph that displays a heat pump's coefficient of performance (Figure 3) and (c) a digital model of a heat pump (Figure 4). We analyze the work from which any relations between these different presentations emerge and study how the different instructional materials acquire their semiotic function in the course of the students' unfolding engagement with each other and with their teacher.

In the following, we analyze four excerpts[2] from the curricular sequence in chronological order. We complement the analyses with descriptions of the events that preceded or followed them to provide the reader with some of the same resources that the participants could draw from across the trajectory. Throughout the analyses, we first describe how, during students' bodily relations with the spray can, the first accounts of the observed phenomena emerge as intimately related to the students' experienced world ("Structuring an Unfamiliar Phenomenon"). We then describe how these initial accounts become reified in more disciplinary terms as students orient towards particular features of the setting that seem to make it *an* instructional setting ("What Happened? From Presentation to Representation"). We describe how the transactional work with the teacher was foundational to the emerging connections ("Teacher Contributions to Structuring and Relating Work"), and how the efforts to make coherent sense of a set of related digital models of the heat pump involves collectively doing reference to the students' prior history of concrete experiences with materials ("Connections to and Across Different Presentations").

Structuring an Unfamiliar Phenomenon

Experimenting with material artifacts provides students with a bodily sense and practical understanding of how the world works. Such experiences constitute the basis upon which the use of culturally specific language and visual representations are grounded (Roth, 2004). Here we investigate this in the context of a hands-on activity. The experimental tasks follow a teacher-led introductory lecture on basic socio-scientific aspects of energy use. These tasks, which involve manipulating a spray-can of compressed air and a bicycle pump, are intended to illustrate the physical principles deemed relevant for understanding how heat pumps work. In this analysis, we take the two artifacts as constituting occasions where students *may* discover relations between pressure, phase transition, and temperature.

[2] The excerpts are provided in the Appendix.



The experimental task is introduced by the teacher and, in addition, formulated on the electronic board. Students are instructed to (a) hold a spray can of compressed air with one hand and spray towards the other hand, (b) observe and discuss what happens, and (c) record a video explaining their observations. The episode begins when the teacher is about to leave the room. A few seconds prior to Excerpt 1, Melka holds the spray-can and is about to spray. The students appear excited, as if expecting something special, laughter and silence following each other. Finally, Melka sprays.

Excerpt 1 illustrates students' first contact with some of the phenomena their learning unit is about. After the first spray, Melka shakes his left hand that received the air from the spray can, produces an interjection, and then all the students burst out laughing (turn 2). Melka sprays again, this time longer (turn 2), and articulates his impression drawing attention to his left hand: "look at my skin" (turn 3). He then orients to the spray can surface, as he moves his right hand away and shakes it while uttering "it becomes freaking cold" (turn 3). Melka invites Ishan to feel the upper part and describes it as cold (turn 5), and both Ishan and Kaamini touch the surface of the spray can (turn 6). Ishan, then confirms the offered description that the spray can gets "ice-cold" and laughs. Kaamini further confirms the impression that it becomes cold "not down, but up" (turn 8).

Our main interest here lies in the question of how the spray can and the phenomena surrounding it emerge as accountable objects in the students' transactions; that is, how an unfamiliar, unknown, and uncertain "it" *presents itself* and, in so doing, turns into a more definite thing. Although the spray can may be a familiar object, how this object relates to *this* task is part of what the students have to discover. At first, Melka, by means of verbal and non-verbal expressions, invites others to attend to phenomena that become observable in and through his bodily engagement with the can. The others take up these invitations by exploring those phenomena, touching and producing interjections. This allows certain aspects to emerge as salient, including the coldness at the surface of the spray can and that it is cold in its upper but not in its lower part. In and through the social transaction, a set of observations *comes* to exist, *emerging* from a more or less undifferentiated material plenum (lower part, Figure 1). Everyday phenomena (the feeling of cold, the sensation of the air blowing on the hand), made salient in and through verbal and gestural deictic actions (pointing, referring to), emerge as a collectively achieved empirical ground that is closely related to immediate sense experiences.

Importantly, the students' deictic actions refer to the objects being pointed to and to the subjective impressions associated to them in the same move. In this sense, there is interdependence between the deictic gesture and the spray can, much in the same way as there is an interdependence of word and thing in children's early form of communication. The artifact, present in the situation, does not need to be made present again (i.e., *re*presented); it stands for itself and in relation to the students (Roth & Lawless, 2002b). At the same time, however, it is through the students' manipulations and talk that the artifact becomes objective, that is, an object to talk about and reflect upon.

What Happened? From Presentation to Re-presentation

As soon as students begin to talk about what happened, there is a shift from the immediacy of the initial experience associated with the objectifying nature of language. This shift is apparent in Excerpt 2, which immediately follows Excerpt 1 and where turns are numbered accordingly.

Ishan looks and points to the board while reading the instructions “feel, observe, and discuss” (turn 9), and asks, “what happened?” (turn 11). In the place of a possible answer, Melka invites Ishan to test for himself (turn 12) and the students experiment together and laugh (turns 12–18). Ishan, gazing towards the board, again utters, “what happened”? (turn 18). This is not immediately taken up as the other two continue to laugh (turns 19–20). Ishan then orients his body towards the board while uttering “yes, bu::t-“ (turn 21), and Kaamini and Melka begin to offer what can be heard as reply turns to Ishan’s question (turn 22). Melka offers up an observational statement about the differences where (“down there,” “up there”) something (“it”) happened (line 23). Kaamini then objects with a causal statement “pressured air inside the can … makes it to come out at once” (turn 24). Signaling uncertainty (“perhaps, I don’t know”), Ishan then offers another cause: “pressure makes it to become cold” (turn 25). The drawn out “yes” by Kamini appears to accept and confirm this statement (turn 26).

In this sequence, an interesting shift in students’ transactions takes place. First, the locution “What happened?” is followed by an invitation to “try and press.” Thus, rather than a reply to a question, there is an accepted invitation to make the material phenomenon *itself* present. This is precisely what has been reported in other inquiry settings, where students re-enact and present an investigation (or part thereof) again rather than *representing* it by some other communicative means (Roth & Lawless, 2002a). Communicative forms over and about the materials, such as gestures and talk, tend to follow before a full scientific discourse emerges that makes the phenomenon present when it is actually absent (Roth, 2003). But in this episode, following the invitation to orient to the task requirements (“feel, observe, and discuss”) a shift occurs. It is now that different verbal descriptions are offered for “what happened” and “why.”

In response to the invitation to attend to the task’s instructions, Melka articulates what has been a *shared* sense experience. However, Kaamini objects and articulates an assertion about pressured air inside the can. Although we have no means of knowing where the term “pressured air” has come from, the spray can, an office supply for cleaning desktops, is referred to as “pressured air” (*trykkluft*) and the term is used in everyday settings. Now, by means of a different grammatical structure, the physical artifact is referred to in a more decontextualized manner, incorporating a structure and terminology resembling scientific discourse. Pressure is the subject also in the next turn and, by means of a new predicate, it adds a novel dimension to the emerging explanation: whereas Kaamini articulates pressure as a modality of air, Ishan articulates it as an independent concept. This latter articulation comes thus closer to a scientific formulation: an entity (pressure) is isolated from contextual bodily experience. The students here shift from using deictic and iconic means to present the phenomenon for each other, to using phenomenon-unrelated means of presentation (i.e. predicates about pressure). A gap opens between language indistinguishable from practical understanding of navigating *in* the material world and language *about* the (functioning of the) material world.

Teacher Contributions to Structuring and Relating Work

Learning experiences like those described above, where students explore phenomena under relatively little guidance, often result in the students' appreciation of features that may be not relevant to, or even at odds with the purposes of the curricular activity (Roth & Duit, 2003). In this regard, teacher interventions become an important resource facilitating that relations of signification emerge as connected to the students' curriculum. In the following analyses, we focus on two aspects of the role of the teacher in the students' structuring and relating activities, namely, on how he facilitates the *loss of phenomena* that are not directly relevant to the curriculum, and how what he does comes to facilitate the making of connections between the emergent structure and prior curricular contents.

At the end of the task involving the spray can, the students record and upload a video in which they describe the phenomenon in similar terms to those described in the prior sequence. The teacher later accesses this video through SciHub and displayed it in a plenary session to discuss those observations with the students. Importantly, the phenomena that the students describe are wider and more complex than the physical principles that the curriculum aims at illustrating (presenting). In particular, the students report on the observation that the spray can first becomes cold in the uppermost part. The teacher's questions, however, seem to focus on particular aspects, and not on others.

Following the students' account, the teacher asks, "what happened with the temperature" (turn 01). The question is answered with an account in which temperature is said to be cold first on the top of the spray can and "then toward the bottom" (turn 02). It is further specified that it does not get "so much" cold at the bottom. The teacher consents (turn 03) and Kaamini further remarks that at the top "it was cold all the time." The teacher acknowledges this later assertion by repeating it (turn 05) and then adds another question, "any reason why it gets cold?"

In this sequence, the teacher initiates a recognizable instructional practice of talk organization, in which the teacher initiates a question, students reply, and there follows an evaluation (Mehan, 1979). Although often decried, this sequence is at the heart of a socio-cultural approach to the reproduction of cultural knowledge (Vygotskij, 2005). Here, a question about temperature is responded with a detailed description of "what happened" with the temperature. Interestingly, however, the teacher initiates a new question requesting an explanation of "why it gets cold," thus ignoring important details of the students' description. That is, although one of the main concerns in the students' explanations throughout the task was the fact that the spray can turns cold first in the upper parts, this observation is not problematized in the plenary discussion and is not taken up again during the remaining activities (i.e. it is lost). Although the experiment with the spray can has been an occasion for very different empirical structures to emerge and to be captured in task-related talk, only those observations fitting into the designed curriculum come to be retained. Just as the emergence of structure was achieved collectively, this *loss of phenomena* is also achieved through social transaction, disappearing because neither students nor teacher take them up again in the trajectory.

Despite the teacher's efforts in facilitating that the students account for phenomena in particular culturally (scientific) consistent ways, building connections with the curricular contents on energy is not a straightforward task. During this plenary session, we observe instances in which the teacher opens the conversational space for that possibility to emerge by invoking curricular contents from previous learning units. One such instance occurs a few minutes after the sequence described above. At this point, students and teacher appear to have agreed upon the observation that there is a liquid inside the spray can, and that this liquid turns into gas when coming out of the can. The teacher, however, notes that the students have not yet explained *why* the spray can becomes cold, and poses a question that makes reference to the term *phase transition* as part of a previous unit in the students' educational trajectory.

Melka responds to the teacher's question with a quick "yes" and articulates a conditional statement according to which going "to solid form" implies to become "cold" (turns 01, 02). His turn is received with a short silence (turn 03), to which Melka responds first by rectifying, and then by reasserting his previous statement (turn 04). Kaamini, however, objects as she points out a contrast indexed to the immediate material context, "this is not solid form" (turn 05).

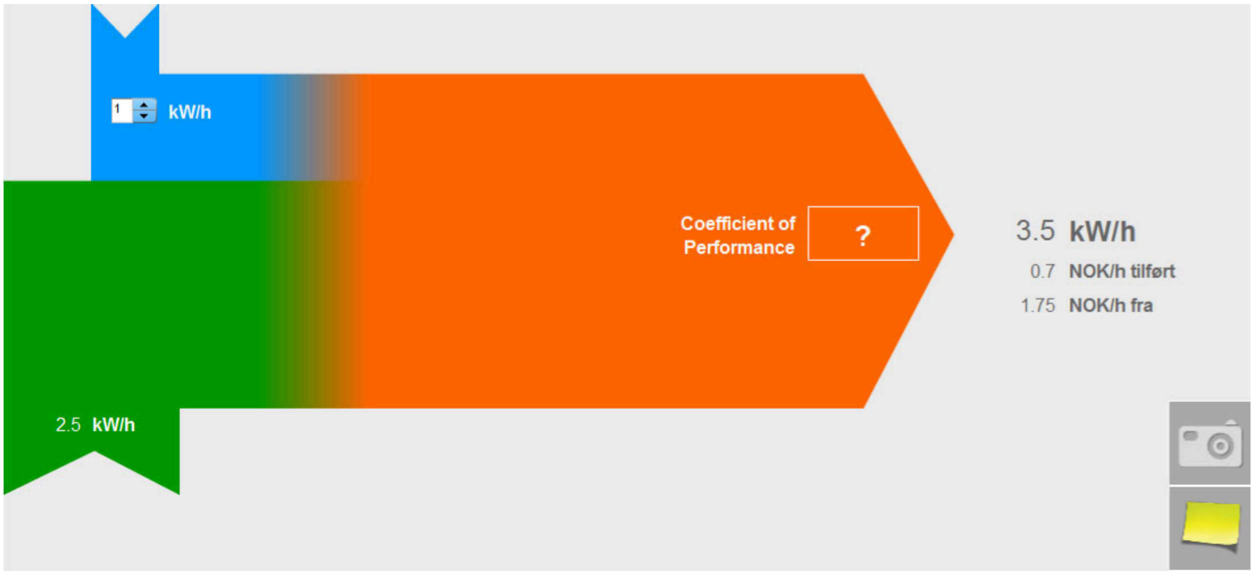
In the first turn pair, there is a request for the students to remember something from a previous grade. In the next turn, however, there is not only a reply in the affirmative, but also the formulation of a conditional statement that resembles a scientific law, as if this was part of the information the teacher was requesting. A short silence follows; and then there is a repair, a reassertion, and finally Kaamini's objection (turn 05). Here, the lack of an evaluation from the teacher is responded to as marking trouble, and Ishan initiates a repair. This then becomes an occasion for the students to negotiate a possible answer. In this, the students' talk about a particular phenomenon—the spray can—now involves the use of disciplinary terms such as *solid form*. That is, the students, to describe an immediate phenomenon, now use a sign vehicle of currency in the scientific discourse about phase transitions, a theme central to their curriculum. By using this vehicle in conversations with more knowledgeable others—here the teacher—students may indeed be saying "more than they know" (Wertsch & Kazak 2011). In this way, teacher and students constitute a *zone of proximal development* in which the potential for development is already present within the social transaction (Vygotsky, 1978). However, as the remaining analyses shows, the sense that the students come to develop with respect to any form of presentation, including disciplinary terms, develops as a function of the social relations in which forms are structured and further taken up and related.

By the end of this session, the teacher has facilitated a full account of the phenomena: an instance of a phase transition that occurs when the valve of the spray can is opened, making the air compressed into liquid transform into gas due to the reduced pressure. This phase transition requires energy that is taken from the spray can surface and, ultimately, from the surrounding environment. Here, the explanation offered draws from what students have reported in their deliverables (videos and accounts) and, thereby, appeals to earlier experiences in the curricular trajectory as resources for building a new understanding about phase transition phenomena.

Connections to and across Different Presentations

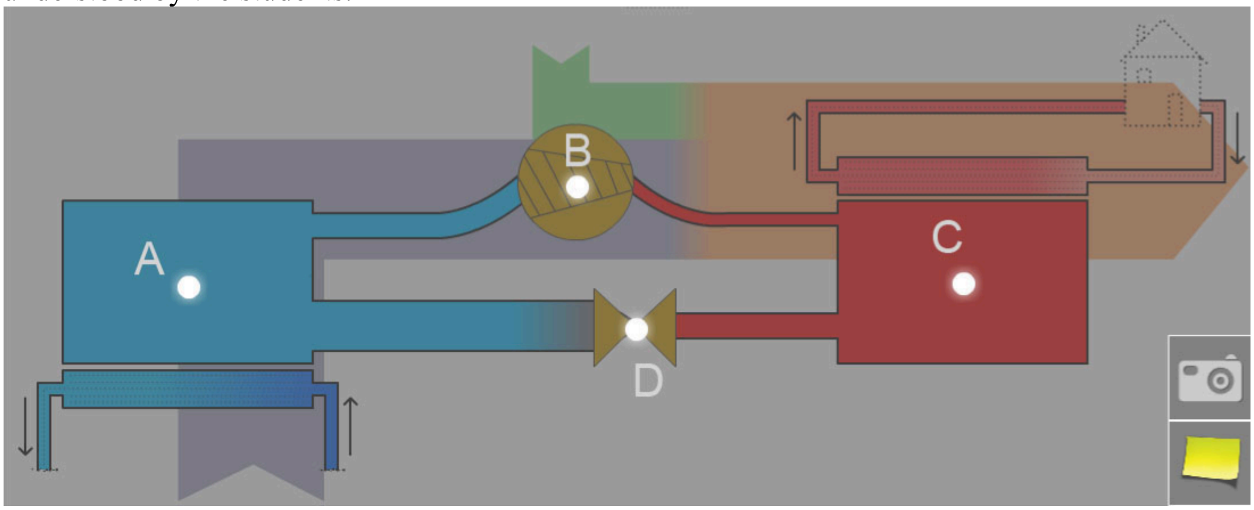
The instructional sequence is based on the assumptions that (a) the materials presented, including the “linked” digital models, bear structural similarities that can be recognized by the students, and that (b) earlier experiences with material artifacts later become resources for making sense of a set of visual models that represent aspects related to heat pumps. However, we take to be an empirical matter whether and how students *actually* take up on what designers believe to be an affordance. Here we investigate this matter in the context of a task involving three digital models of a heat pump. Our analyses show that the connections drawn with and across the materials do not appear to build upon formal descriptions of the materials, but rather are always indexed to a shared history of particular events. That is, the representations do not convey information, but become material resources for making the task *coherent* with such history of lived-in relations.

Before presenting the analyses, some specifications of the materials are required. Model 1 (Fig. 3) is a conceptual model of the efficiency ratio of heat pumps. From the curriculum designers’ perspective, the upper (blue) arrow represents the input of electrical energy into a heat pump. Students can modify the value displayed on this arrow. The lower (green) arrow represents the energy that the heat pump obtains from the environment. The value on the green arrow and the outcome value change as the input value is modified. Values are given kWh.



Digital model 2 (Figure 4) is intended to illustrate part of the inner mechanisms of a heat pump. It depicts a system of four connected elements. Heat pumps are a closed system of coils through which a refrigerant fluid is pumped. In one part of the system, the refrigerant is decompressed and takes in heat as it boils at low temperatures; in another the refrigerant is compressed and thereby condensates easily and releases the heat. This is so because phase transitions involve/require transfer of energy, which is transferred from the environment. It is according to this principle that a conceptual relation can be drawn between the hands-on activities and the digital models.

To facilitate students' connections across the visual models, digital model 1 is inscribed in the background. As students move the cursor over the figure, dialogue windows require the students to write down the functions of the different parts. To this end, the students can drag and drop digital post-it notes over the figure. A third digital model, in turn, is identical to digital model 2, but includes an animation of the boiling and evaporation processes taking place within elements A and B of the model (Figure 4). In this third model, students also can modify pressure, which leads to changes in those elements in ways consistent with the designers' notion of evaporation/condensation. The students can navigate across the three models. The designs' objective is that, drawing on their experiences along the trajectory and the materials' affordances, the connections between evaporation and heat pump's efficiency come to be understood by the students.



The episode presented here reproduces students' transactions with and around digital model 2 (Figure 4). The students previously have solved a task related to digital model 1, where they had to calculate the efficiency ratio. During that activity and the teacher-led sum-up session that followed it, the students have referred to the lower (green) arrow in digital model 1 as the "extra energy." The lower arrow comes to be called "extra energy" precisely because, as students and teacher have discussed during that activity, the energy input that the lower arrow represents does not come from the electric current but from the environment—it is "extra." In the current situation, we analyze how linkages between that arrow and digital model 2 are the topic of discussion when reference to this previous activity is made.

The excerpt begins in the middle of an exchange over one aspect of the interface. Ishan offers an explanation that relates two aspects of the material continuum—element A in model 2 and the upper arrow in model 1, to a third aspect—"normal energy"—by virtue of their color (turn 01). Kaamini acknowledges with an emphatic "yes" (turn 02), and the students stare at the screen in silence during some seconds (turn 03). Melka then offers an observational sentence, pointing emphatically over element A in model 2, and states "here is the energy we get", adding then "here is the small." Kaamini then objects "that's extra" (turn 05) and Melka objects back as he refers to a number (turn 06). Ishan repeats "it's extra" twice, interrupting thus Melka (turn 07), who however continues by identifying the element A in model 2 with another number, "two point five" (turn 08). Both Ishan and Kaamini reject this latter observation, and kaamini suggests her peer to "remember" that "that one was green and blue," and adds the imperative "check the colors" (turn 10). Melka, however, does not directly accept the latter command, as he questions whether they have to check the colors (turn 11).

Several aspects in this sequence provide evidence that a structuring activity is going on. The figure being discussed is obviously not self-explanatory. We can hear Ishan offering an explanation sentence that connects two elements of the models 1 and 2 to a third one—normal energy—on the basis of a similitude in the (blue) color (turn 01). But this connection does not seem evident to all the participants. Whereas Kaamini seems to agree, Melka provides with a different account, which relates the same element A in model 2 with another term, "the energy we get." In contrast to Kaamini, Melka makes salient the size of the element, not its color (turn 04). That is, there is not only disagreement on what the elements in the figure stand for (in particular, what the elements A and B in the model 2 are a sign of), but there is disagreement with regard to which material aspects of the figure are signals and which others are just noise. Although there is an explicit link and mapping between two representations from a design perspective—the shape in the background of model 2 is identical to that of model 1—this link does not exist in and for the students' transaction in the same terms. The material aspects of the figure do not present themselves as already structured, but the students must achieve such structure throughout transactional work.

In the sequence, there are also features that do not appear to require structuring work. In the sequence here analyzed, the students use words such as "normal energy," "extra," or "two point five" (turns 06, 08) without the emergence of repairs after next turns, such as requests for clarification of what is "meant" with such words (Schegloff, 1992). These terms have emerged and been used previously during the trajectory and are now shown to be part of the students' repertoire of resources for dealing with further structuring and relating work. They have become signs ready-to-hand for the *in-order-to* and *what-for* of the students' action (Roth & Hoffman, 2009). Thus, whereas agreement regarding what model 2 is to stand for is not achieved, observational sentences generated to structure the current situation are made not in terms of immediate experiences—as was observed in the first turns of the experimental activities with the spray can—but refer to aspects of familiar, prior shared experiences, that are here treated as the *substrate* (Goodwin, 2013) upon which the students' ongoing referential practices are grounded. In this work of making co-occurrent two situations—the deictic references to the immediate environment, and the talk that indexes to immediately prior shared experiences in the curricular trajectory—we observe how new sign relations between two segments of the material continuum are established (Figure 1).

Importantly, the words used have currency both in students' biographies—they have emerged in and are indexes to previous activities in the curricular sequence—and in the teacher's and designers' discourse about energy, with which the students have engaged in prior teacher-led discussion during the digital model 1 task. However, the double nature of those signs, biographical and formal or disciplinary, is not necessarily evident to the students. In the explanation sentences, there is no justification based on a particular body of knowledge that can be spelled out apart from the local contingencies of the situation. There is no articulated "meaning" of "extra energy" or of how this is re-presented in the figure, but prior bodily experiences are indexed. Thus, an element stands for extra energy or not with regard to colors or size on the premise of specific prior experiences, which students request to be recalled (e.g. turn 10).

The data also include instances where materials that where presented previously in the trajectory were indexed as part of the ongoing relational work. This aspect is illustrated in the following excerpt, which occurs few minutes after excerpt 5, where reference to the term "extra energy" is made again. In the sequence, the students are moving back and forth between models 2 and 3 to come to a coherent account of what happens inside a heat pump. They have just read pop-up windows that request them to articulate the function of each component in the model, such as "what does the compressor do?"

The sequence begins as Melka emphatically asks why it “goes in circles” (turn 01). Ishan quickly responds pointing over the screen, providing a performative interpretation that includes the production of a onomatopoeia instead of a verbal articulation (turn 02). Kamini seems to disregard the latter and argues, “it’s there where we get extra” (turn 03). Ishan objects and elaborates an account in which the assertion that element A “must be cold” is supported on a description of how the “air” was cooling down and warming up inside. The description involves references to both the screen and the physical spray can. Melka in turn objects (turn 05) and Ishan asserts again that “it became cold,” but raises his intonation towards the end of his utterance, as it occurs when someone poses a question (turn 06). Melka indeed responds as if it was a question and argues that the spray can takes in heat to “come out.”

In this excerpt, there are three different accounts and three respective objections. The objections concern first whether it actually is “there” where “we get extra,” whether and which elements in the model are “cold” and “warm”, and whether the spray can was “cold inside” or not. From the view of the designers, this is a wonderful opportunity for the intended connections to emerge for the students. This is so because an analogy between the spray can and the heat pump underlies the model’s design: as it occurs in the spray can, heat pumps get their “extra” energy from the environment through evaporation. Indeed, the account articulated by Melka seems to come very close to this canonical characterization. However, the links between the different elements laid out in conversation do not realize in the intended terms. Few moments after this sequence, the students will “complain” that they do not understand the figure. There does not seem to be a relation of the kind that Figure 1 displays.

During the discussion, references to materials such as the spray can seem central. First, Ishan gestures on the spray can to articulate an observation regarding temperature differences between the components of the model, and their relation with “compression” (note that a dialogue window that labels element B as “compressor” emerges when the cursor is moved over). Melka gestures again over the spray can to provide an account of how temperature and energy are aspects of the artifact. Interestingly, in both Ishan’s and Melka’s articulations, the past tense is used, thus indexing a past event. In this way, the spray can becomes an occasion for *collective remembering work* (e.g., Middleton & Brown, 2005) concerning their previous experimentations. Contrary to the assumption that learning involves abstracting knowledge from experiences, “knowledge” about any salient (material) aspects in the current situation appears to be tacitly indexed to aspects of prior experience that become reified in yet another material aspect—signs. Thus, the crucial aspect here does not lie in an iconic relation (perceptual similarity) between the two corresponding presentations (artifact and associated phenomenon and digital interface) but in a third presentational form, discourse, that can be used in the talk about both during joint, sequentially organized inquiry. Overall, our analyses in this latter section support evidence that shows how our bodily experiences in the world constitute the practical understanding, where any understanding of sign-mediated communication—vernacular or scientific—bottoms out (Roth, 2012b). In the present study, this is shown to be the case also in the relational work that students perform to make sense of a multiple presentational setting.

Discussion

The purpose of this study was to investigate how the structures of and connections (if any) between different materials and representational forms emerge in the course of students’ materially and socially situated activities. Although there are claims that one requisite for learners to take advantage of multiple representations environments is *first* to understand the presentation’s syntax and semantics (Ainsworth, 2008; van der Meij & de Jong, 2006), few studies actually investigate *how* such understanding emerges in the first place. In this study, we provide an account of such emergence from a cultural-historical and situated perspective.

We begun by elaborating an analytical framework for analyzing the practical work that learners must perform to make sense of a multiplicity of learning materials as connected. Drawing from this framework, we conducted our analyses without presupposing any particular content of the artifacts and visualizations that the students encountered and worked with. We took artifacts and visualizations as part of the material continuum, but whether and how they appeared as connected to the participants was taken to be an empirical problem. The analyses were grounded in the data to see what students make of and with these segments of the material continuum, what structural properties emerged from students' transactional work, and how different structures came to be related to each other. In our analyses, we document how something *comes to be* a *re*presentation (model, analogy, metaphor) of something else *in and as* the structuring and relational work that the students accomplish during social transactions.

In this section, we summarize our findings with regard to the observed structural and relational work. Two dimensions of learning that are often taken for granted or not attended to, the body and the praxis, appear to be fundamental to the emergence of signs, and, by the same token, to the development of new literacies. We conclude by articulating some implications with regard to research on learning in multiple presentational environments, and point out some limitations of the study and further research directions.

Multiple Presentations Require Coordination Work

In general, this study supports evidence that suggests that learning environments where multiple representations are available can facilitate students' development of conceptual understanding of scientific topics (e.g., Adadan, 2013). As most studies do, it also shows that drawing canonical connections in and across the different representations is a challenging task for the students (e.g., Kozma, 2003). However, this study departs from much of the literature in that it provides a description of the actual, bodily and practical work by means of which different presentations become structured and related from, in and through the learners' first-time-through perspective.

The study shows that there was a good deal of structuring work by means of which segments of the material continuum came to be isolated. This work, as apparent in Figure 1, is a prerequisite for the work in which multiple presentations come to be related; signs, the relations between segments of the material continuum, are emerging. In structuring the material continuum, students made extensive use of deictic and iconic gestures and expressions that made salient certain aspects of the setting, providing structure to a unified field of experience and, therefore, to the phenomena they could account for. Thus, phenomena were structured (emerged) as the material elements in the situation (e.g., spray can) were acted upon, and not before. The means by which such phenomena were structured and accounted for appeared inseparable from the bodies acting on them. This observation is not limited to the materials in the hands-on activity. Despite the intended pictorial and symbolic nature of their design, there was also bodily structuring work accomplished in the discussion over the digital models. Aspects of the digital visualizations were made salient as gazes, gestures, and talk were directed to them in the context of specific object-oriented actions.

Deictic gestures and expressions have been recognized to play a crucial role in the development of disciplinary competences in science learning (Roth & Lawless, 2002c). Studies investigating learners' conversations across different media (face-to-face, online) have shown that when face-to-face communication is restricted, gestures referencing the immediate context are partly replaced by verbal deictic expressions, suggesting thus the context-bound nature of communication in learning environments (Suthers, Girardeau & Hundhausen, 2003). In this study, deictic gestures do not only bear a referential function, but also become *fundamental* to the emergence of structure of the different presentations in the sequence. Bodily actions and gestures appeared integral to the coordination of activity and to the emergence of accounts the students accounts. More crucially, because structures were made present by means of body movements during social transaction, structure changed with action, even when the material presentations remained the same. This further points to the pragmatic rather than substantive character of the emerging significations that we elaborate further below.

The present analyses support the cultural-historical premise that the introduction of signs fundamentally transforms activity (Vygotsky, 1978). As signs transformed activity, the nature of the presentations was transformed too. Thus, aspects of situations that had been structured and stabilized in social transactions became uncertain and required of further inquiry as different ways of accounting for them emerged. In this progressive inquiry, signs that emerged in previous episodes of the curricular sequence became means for accomplishing new structuring work in further transactions, even when no articulated formal description of the significance of such signs seemed to be available. Interestingly, these signs appeared to be grounded on bodily experiences and a pragmatic sense of the current situation, rather than on formal descriptions or "information" that these signs were taken to stand for. This account of signs as inherently developmental and ever changing phenomena sharply contrast with conventional characterizations of representations as embodying information that can be then "searched," "recognized," and "processed" by learners (e.g., Bodemer et al., 2004).

Students made phenomena present in response to task demand, *language* appearing as yet another fundamental aspect of the coordination work. Orientation towards particular structures of relevance to the "doing" of science learning, such as checking the tasks' formulation, resulted in a shift of the conversational premises about what was relevant and what was not relevant during talk. On the face of more or less implicit disciplinary demands, observational sentences indexing to immediate sense experiences no longer were accepted as sufficient, and accounts adopted grammatical structures that more closely resembled scientific discourse. These demands, in turn, facilitated a *contextual* re-*configuration* in which participants "demonstrably" oriented to "a particular, locally relevant array of semiotic fields" (Goodwin, 2000, p. 1490). These findings are consistent with other studies that highlight the importance of considering the "institutional" practices embedded in the use of technology in educational contexts (Furberg et al., 2013; Krange & Ludvigsen, 2008).

An important aspect of the instructional setting was the design of teacher-led interventions to sum up and guide the students' activities. In our analyses, we showed how the teacher, drawing from discursive resources typical of classroom talk such as teacher-initiated questions, was also an important resource in the students' movement from their initial bodily understandings to more elaborate and language-dependent forms of representations. Accounts that were not directly relevant to the curriculum were lost, and episodes of prior experience were brought to focus by means of those questions. The teacher thus shaped the emerging structures, even when these were produced jointly with the students. Moreover, during our analyses we showed how such lexical elements such "phase transition" or "extra energy" that had emerged in joint discussion with the teacher where then further appropriated by the students when working on their own. These elements became thus part of the semiotic substrate upon which students were further laying out their accounts.

Despite the clear orientation towards disciplinary conceptual talk observed in determinate sequences, relational work remained clearly grounded in bodily, material, and pragmatic aspects of transaction—as this might be expected from the pragmatic (Dewey, 1938) or sociocultural perspectives (Vygotskij, 2001). In linking across aspects of the different presentations, the students offered explanation sentences to argue for particular observations. Such arguments indexed to situational aspects of prior shared experiences rather than to formal principles or curricular knowledge. Even when using terms of currency in the scientific discourse, these appeared inherently connected to the students' bodily performances and the students' particular history of transactions. In this regard, the co-presence of material artifacts was fundamental for serving as occasions for collective remembering work (Middleton & Brown, 2005). Yet, no material aspect was determining with regard to the structures and relations that emerged. Indeed, these were often different from the ones intended by the designers. Thus, it is not that the students *misinterpreted* something, as it is often held in the literature (e.g., Chittleborough & Treagust, 2008); rather, the emerging relations between diverse segments of the material continuum (i.e., Figures 3 and 4) differed from the intended ones.

Body and Praxis in Learning with Multiple Presentations

Throughout this paper, we emphasize the importance of attending to the intersection between social, bodily, and pragmatic aspects of learning with multiple representations. The empirical analyses presented above provide detailed descriptions of the transactional work that takes to isolate and relate segments of the material continuum in transaction. Two aspects that tend to be taken for granted and which therefore are rarely theorized or empirically scrutinized—the body, and the context of praxis within which the body finds itself—have been shown to be central for understanding how structures emerge in transaction. Here, we summarize two inter-locked competencies that become of interest when research shifts from focusing on re-presentations, to focusing on the first-time-through presentational aspects of learning environments: the role of the body and of praxis in the constitution of sense. As described in our analyses, it is through body movements that aspects of the environment first emerge as signs. That is, pointing, gazing, and other deictic gestures are the first materiality by means of which the materials of the situation acquire structure. The body is not just re-enacting those structures; rather, structures are not yet constituted as objective. There appears to be a knowing that is more fundamental than the conceptual understanding of substantive matters—such as what the "meaning" this or that segment in a digital visualization is. It is by virtue of being bodily sensed and produced that events in the world bring about the possibility of being further objectified by means of communication. The body then may be seen as a moment of *a larger unit of social transaction* (Roth & Jornet, 2013, 2014). Within this unit, unexpected sense phenomena—the sudden feeling of cold when acting on the spray can, the contour of a shape when gazing towards a digital model—become present in an immediate and irreducibly particular, once-ever-occurring manner. It is only when this immediacy becomes part of the ongoing social activity that it acquires signification. Thus, the students' bodily engagement serves as a productive entry point to develop vernacular language towards other forms of discourse or representation.

Throughout this study, we insist on the dual relational nature of the sign: a relation between segments of the continuum and a relation between people. The sign primarily emerges as a social function when it changes the behavior of others (Vygotsky, 1978). Only later does it become a means for mastering one's own behavior. Accordingly, the function of language, here understood to comprise both talk and body movements, is not substantive at first. Rather, language becomes a means for further coordinating activity. In this sense, we take *a genetic approach* that differs in focus from other studies that build upon embodiment theories, such as Lakoff and Johnson's (1980), where learners' embodied experiences are conceptualized as forming conceptual or linguistic schemata that come to give coherence and structure to the learners' experiences (e.g., Nieber, Marsch, & Treagust, 2013). Whereas our results are indeed commensurate with the finding that conceptual understandings in science classrooms "are embodied, meaning grounded, in real experience" (p. 871), the focus here is on how conceptual and linguistic competences for recognizing and relating objects *emerge* in and as social and bodily relations before any conceptual schemata has been formed.

Studies on learning with multiple presentations already suggest the importance of grammar as an important resource for the students to make sense of digital visualizations (Karlsson, 2010) and show how much of what students orient to when interpreting graphical materials during inquiry-based activities respond to particular institutional concerns associated to academic performance (Furberg et al., 2013). These studies show that the "students' scientific accounts are produced in the intersection between a formalized scientific language and the *logic* of everyday language" (p. 59, emphasis added). Our study adds to this literature by arguing that the characterization of the "logic" of everyday language requires of an account that does not presume formal structures as the ground for understanding. Instead, characterizations of how new intellectual competences and structures emerge out of relations between the body and situated praxis are required.

Throughout the study, we show how the processes by means of which a syntax that connects events and materials emerges during bodily, situated social transactions, and not as a purely conceptual compentence. Thus, understanding learning with multiple representations requires an understanding of the pragmatics of joint action, of how the body and the materials come to ensemble as a *unitary situation* in the learners' experience (Dewey, 1938; Roth & Jornet, 2014). This requires of detailed analyses of the bodily practices that make up concrete learning situations. In this sense, the present case study provides evidence from only one particular teacher in one particular setting. However, previous case studies have proven useful in developing new understandings of how students learn from representations in classroom settings with multiple representations (e.g., Tsui & Treagust, 2003). Further research exploring the role of the body-in-praxis in learning with multiple representations is needed. Most importantly, science educators may be interested in drawing from this kind of studies to develop and test new instructional designs that rest upon the bodily competences described here.

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Appendix 1: Transcription conventions

,?;.	Punctuation marks are used to indicate pitch toward end of an audible unit: slightly rising, strongly rising, slightly falling, and strongly falling
[ ]	Square brackets indicate beginning and end, respectively, of overlapping speech
(.)	Clearly audible pause of unmeasured length, evt. time in seconds (e.g., (2.0))
(())	Our own comments and observations
(??)	Words missing. As many "?" as words missing
-	Dash marks unfinished or interrupted utterance
(h)	Laughing inserted in talk
word	An underlined word signal stress in the spoken utterance
wo:rd	Colon indicates the prolonging of the prior letter or syllable

<word> Brackets pointing outward indicate word or phrase spoken more slowly than the surrounding discourse

>word< Brackets pointing inward indicate word or phrase spoken more quickly than the surrounding discourse

WHY Capital letters mark high intensity in the voice

Appendix 2

Excerpt 1

01 Melka: AGH:, *((shakes left hand))*

02 *((students laugh. Melka sprays again, this time longer))*

03 Melka: look at my skin. (.) agh. *((staring at spray can))* it gets cold. it gets freaking cold. *((shakes left hand))*.

04 Ishan: (let me see) if I feel it.= *((extends arm and touches base of the can))*

05 Melka: =it becomes freaking cold. just feel it. (.) feel up there; ((*touches upper part*)) it becomes cold on the top, or something.

06 ((*Kaamini also extends her hands to touch the surface of the can*))

07 Ishan: yes. ic(h)e cold. *((laughs))*

08 Kaamini: not on the bottom, but on the top. *((touching bottom and top of the can))*

Excerpt 2

09 Ishan: *((looks and points to the board))* feel, observe and discuss.

10 (1.8) ((*Kaamini laughs*))

11 Ishan: what happened?

12 Melka: just try and press yourself. *((offers the spray can to Ishan))*

13 Ishan: right.

14 (3.8) ((*Ishan sprays, Melka keeps one hand in front of spray. all laugh*))

15 Melka: look at the skin- *((laughing))* look at my hand, it
[feels like-

16 Ishan: [((??, *laughing*))
17 Kaamini: so funny. *((laughing))*
18 Ishan: you are quick, well ok *((looks at board))* [what happened?
19 Kaamini: [*((??))*
20 Melka: don't point it at me. ((*oriented towards Ishan. laughing*))
21 Ishan: yes, bu::t- ((*orienting towards the board*))
22 Kaamini: [there is much air-
23 Melka: [I don't know] what happened. I think it happened down there and suddently it happened something cold up there= *((touches top of can))*
24 Kaamini: =no, there is much pressured air inside, *((points to spray can))* which makes it to come out at once. *((pushes arms out))*
25 Ishan: pressure makes it to become cold, perhaps, I don't know.=
26 Kaamini: =yes:::.

Excerpt 3

01 Teacher: what happened with the temperature here then? *((pointing towards the spray can))*
02 Kaamini: it becomes cold up there *((holds the top of the spray can))* and then towards the bottom, *((slides her fingers over spray can surface from top to bottom))* but not so much as it was on the top.
03 Teacher: mmm,
04 Kaamini: there it was cold all the time-
05 Teacher: cold all the time, yes. can you think of any reason why it gets cold?

Excerpt 4

01 Teacher: do you remember something about phase transition? fro:::m eighth grade or so?
02 Melka: >yes<. when you go to solid form it becomes cold.
03 (0.7)
04 Melka: no. (.) yes. yes, when you go fro::m-
05 Kaamini: no. *((pointing towards spray can))* but this is not solid form,

Excerpt 5

01 Ishan: ((pointing over element A in model 2)) since this one is blue; ((shifts to model 1 and points over the upper arrow)) and this also is blue, so it has to be normal energy here. ((shifts back to model 2))

02 Kaamini: ye:::s::

03 (2.7) ((stare at the screen silent))

04 Melka: *((pointing over element B in model 2))* HERE Is the energy we get. Here is the small.

05 Kaamini: that's EXtra,

06 Melka: no, because here is one point eh=

07 Ishan: It's EXtra; It's EXtra;

08 Melka: =and here *((pointing over element A in model 2))* it's two point five.

09 Ishan: no

10 Kaamini: no, it's extra. Remember, that one was green and blue. Check the colors

11 Ishan: do we have to check the colors?

Excerpt 6

01 Melka: WHY does it GO IN CIRCLES?

02 Ishan: >I know what it is, I know what it is< look. this one *((pointing over element A))* is cold. (.) this one *((pointing over element C))* is hot. And then shu::: *((bring hands together from respectively A and C))*

03 Kaamini: what SHU:::? *((pointing toward the screen))* it's there where we get extra.

04 Ishan: no, *((pointing over the elements A and C in model 2 respectively))* it must be cold and warm, because when you compress it like this one here *((takes the spray can and gestures on it))*, it was compressed air. And then it was cold inside. And then when it was released out, it became warm air again.

05 Melka: it wasn't cold inside.

06 Ishan: yes, it became cold?

07 Melka: it became cold because *((mumbles))((takes the spray can))*. this one needs heat to come out. That's why it takes heat from here *((moves hands in the air))*.

List of Figures

[3] The units of energy were incorrect at the time of the study; this presentation no longer is part of the curriculum in its current form.