Describing and Analyzing Learning in Action: An Empirical Study of the Importance of Misconceptions in Learning Science

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Received 28 November 2006; revised 27 June 2007, 2 July 2007; accepted 2 July 2007

DOI 10.1002/sce.20233
Published online 22 August 2007 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Although misconceptions in science have been established in interview studies, their role during the learning process is poorly examined. In this paper, we use results from a classroom study to analyze to what extent nonscientific ideas in electrochemistry that students report in interviews enter into their learning in a more authentic setting. We audio-recorded talk between eight pairs of Swedish upper secondary students during a practical on electrochemical cells. Learning was operationalized on a discursive level as a description of what students do and say when taking part in an activity. This enabled an analysis of how encounters with misconceptions influenced the development of students' reasoning, compared to other encounters during the learning experience. Misconceptions did not constrain the development of students' reasoning. Rather, their reasoning developed in response to the contingencies of the specific situation. When misconceptions were encountered, they appeared as alternatives and questions not actively defended. Sometimes, encounters with these misconceptions were generative of the students' reasoning. The results indicate that demonstrating misconceptions in interviews is not enough to assume that they interfere with learning in other contexts. Educational implications and future

This study is part of the project "How Can Teachers Aid Students Towards Scientific Reasoning" funded by the Swedish Research Council.
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lines of research based on these findings and on the methodology applied are discussed.
 Sci Ed **92:**141–164, 2008

INTRODUCTION

It is well established that students express a variety of nonscientific ideas in interviews as well as in paper-and-pencil tests, covering most areas of science (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Duit, 2007). Traditionally, the impetus for the bulk of this research into students' misconceptions[1] is a concern that they interfere with learning the intended science content and that they therefore need to be overcome (diSessa, 2006). In this paper, we use results from a classroom study to analyze to what extent the nonscientific ideas that students report during interviews enter into their learning of a science content in a more authentic setting. The purpose of the study is to contribute empirically to the issue of what are the constraints and possibilities for science learning in the classroom, as well as to contribute methodologically with an approach that allows students' learning in science to be directly studied in authentic school contexts.

Some authors assert primary importance for misconceptions in learning science. Vosniadou (2001) stated that "science learning is characterized by misconceptions" (p. 179), on the grounds that they have been extensively reported in the literature, that they are often resistant to change, and that they have been replicated in studies in different parts of the world. Building on a significant number of studies within his group, Novak (2002) asserted that meaningful learning implies supplanting misconceptions[2] with valid conceptions and that misconceptions operate to distort new learning. According to Hammer (2000), physics education research has mainly considered student misconceptions to constitute obstacles to learning. Groves and Pugh (2002) argued that learning of complex environmental issues is hindered by simplistic mental models that they described as "cognitive illusions," and Songer and Mintzes (1994) showed that college students harbor alternative conceptions that impede and constrain their understanding of cellular respiration. In a review of research on student misconceptions of chemical bonding, Özmen (2004) noted that these misconceptions become a hindrance in acquiring the correct body of knowledge. In a case study of one student, Taber (1995) demonstrated that the student's alternative framework about charges acted as a block to learning about chemical bonding. Some studies suggest that such "blocks" or "obstacles" to learning need to be weakened or even abandoned before a new conception can develop (De Posada, 1997; Hewson & Thorley, 1989), and that such conceptual change requires rational considerations on the part of the learner (Carey, 1999; Strike

[1] Different authors have used different labels for such nonscientific ideas, implicating different assumptions about their nature and properties (Smith et al., 1993; Tytler, 1998). Here, we will use the term "misconception" in a general sense, without any particular connotations, and interchangeably with "nonscientific idea," in agreement with several other authors (Nicoll, 2001; Smith et al., 1993; Özmen, 2004). According to Smith et al. (1993), "misconception" is the most widely used term in the literature, as well as the "... central theoretical term [...] to describe and explain students' performance in specific subject-matter domains" (p. 117). A search in ERIC found 328 hits for "misconception AND science NOT alternative conception" between 2000 and 2006, whereas a search for "science AND 'alternative conception,' 'alternative framework,' 'intuitive theory,' respectively, gave 42 hits altogether (13% of the hits on "misconception"). Furthermore, we think our use of "misconception" is motivated, since it is the term being used in the specific studies on student misconceptions in electrochemistry underlying our study. Also, substituting "electrochemistry" for "science" in the above search gave 12 hits for "misconception" and none for the alternative terms.

[2] Novak suggested that misconceptions and other labels should be replaced by the term limited or inappropriate propositional hierarchies (LIPHs), but continued to use the term misconception interchangeably with LIPH (e.g., pp. 557, 558, and 559).

& Posner, 1992). Other authors, while still recognizing the problematic nature of students' alternative conceptions, have presented results showing that the process of reconceptualization is slow and gradual, that students may hold multiple conceptions simultaneously in that process, and that learning is affected by other than rational factors (Duit & Treagust, 2003; Taber, 2006a; Vosniadou & Ioannides, 1998). Furthermore, some authors have proposed that misconceptions will constitute very different problems for learning depending on the ontological status that the learner ascribes to a certain concept (Chi, Slotta, & deLeeuw, 1994).

Some authors, however, have argued for a more radical shift of research on learning in science, by focusing on possibilities and resources rather than constraints for science learning (Caravita & Halldén, 1994; Hammer, 2000; Smith, diSessa, & Roschelle, 1993). Clement, Brown, and Zeitsman (1989) identified potentially helpful beliefs, or "anchoring conceptions," as student resources for learning physics, and Hunt and Minstrel (1994) identified relevant student ideas on which to build instruction in physics. These authors did not question that misconceptions constitute problems for learning, but tried to extend the study of students' conceptions to include productive ones as well. DiSessa (1993), on the other hand, described learning of physics as making use of intuitive conceptual resources rather than overcoming conceptual barriers. Smith et al. (1993) presented empirical evidence that students successfully utilize prior conceptions to learn more advanced knowledge, and questioned to what extent misconceptions interfere with learning expert concepts. Schoultz, Säljö, and Wyndhamn (2001) demonstrated that a cultural artifact such as a terrestrial globe worked as a resource for students' reasoning about the earth, having the effect that previously recorded misconceptions (Vosniadou & Brewer, 1992) could no longer be seen (but see Vosniadou, Skopeliti, & Ikospentaki, 2005). Schoultz et al. (2001) raised doubts about whether nonscientific ideas reported during interviews actually appear in similar form during instruction (see also Johnson & Gott, 1996; Welzel & Roth, 1998), and consequently, whether they constitute significant problems for learning science. Thus, Wickman (2004) found that the difficulties experienced by university students during a chemistry practical were better explained as inadequate habits of action tied to the specific situation than as their having alternative theories or misconceptions about the content of the practical.

Authors questioning the importance of misconceptions in learning science have stressed the context dependency of students' reasoning, arguing either that misconceptions do not exist isolated from the context in which they appear (Schoultz et al., 2001) or that they consist of pieces of knowledge that are combined in response to contextual features of the particular situation (diSessa, 1993; diSessa & Sherin, 1998; Hammer, 2000). Thus, Tytler (1998) found that students were extremely fluid in their reasoning and inconsistent in their application of conceptions in different contexts. Welzel and Roth (1998) demonstrated that students' reasoning changed significantly even during a single interview, for example, in relation to contextual factors such as the complexity of the questions asked. On the other hand, Spanish and English secondary students' ideas about combustion were found to be consistent across a range of questions (Watson, Prieto, & Dillon, 1997). Although Taber (2000) presented evidence that students hold multiple conceptions simultaneously, each of those conceptions was nevertheless stable, coherent, and applied across a wide range of contexts. Ioannides and Vosniadou (2002) concluded that it was possible to explain the responses of most of their students (aged 4–15) by assuming that they were consistent in using one out of a limited number of meanings of force. Yet, diSessa, Gillespie, and Esterly (2004), repeating the study of Ioannides and Vosniadou (2002), demonstrated that the consistency of students' reasoning, as well as the assignment of students into simple conceptual categories, broke down on a wider range of problems.

Apparently, even though most authors agree *that* the identified nonscientific ideas have consequences for the learning of science (Taber, 2006a), there is no corresponding agreement as to *what part* they play in that learning, and in different contexts (Smith et al., 1993; see also Taber, 2000). It has long been recognized that research on students' difficulties in learning science need to build on, but move beyond, the enormous amount of data on students' nonscientific ideas collected in interviews and written tests, by determining how they work in action and how they interact with instructional practices (Driver & Erickson, 1983; Smith et al., 1993; Taber, 2006a). Leach and Scott (2003) observed that our knowledge of what kinds of explanations students offer, what difficulties they experience, and what mistakes they make is still limited, and saw a role for studies that describe how students act in learning situations. And diSessa (2006) stressed that contextuality should be made a central concern in learning studies, as well as pointing to the lack of studies tracking the specific learning process. Thus, studies that directly assess the role of misconceptions for students' learning in authentic school settings could contribute substantially to this issue.

One area where students' misconceptions have been described in detail is electrochemistry. In two much cited interview studies conducted in Australia, Garnett and Treagust (1992a, 1992b) investigated high-school students' conceptual understanding of electric circuits, oxidation–reduction equations, and electrochemical and electrolytic cells. Together with similar studies in the United States (Sanger & Greenbowe, 1997a), at least 17 misconceptions about electrochemical cells were recorded. Huddle, White, and Rogers (2000), referring to studies conducted in South Africa, concluded that most of the recorded misconceptions were common between all three countries which, moreover, were located on three different continents. These authors ascribed central import to the recorded misconceptions for students' learning of electrochemistry. Garnett and Treagust (1992a) concluded that students holding "misconceptions about the way electricity is conducted in metallic conductors and electrolytes . . . are highly unlikely to understand the operation of electrochemical . . . cells" (p. 140). In a subsequent study, Garnett and Treagust (1992b, p. 1097) found that students holding the misconceptions that "an electric current only involves drifting electrons" and that "the anode and cathode are charged" were unable to explain the movement of charge in electrochemical cells correctly.

In this study, we use an approach that (a) operationalizes learning as a description of what people say and do when taking part in an activity (Wickman, 2006, p. 53; Wickman & Östman, 2002b) and (b) takes the situation as a whole as the unit of analysis (Greeno, 2006). Through this approach, we investigate (a) how misconceptions reported in interview studies enter into the process of learning electrochemistry in a more authentic setting and (b) what aspects of the learning situation are important for what the students learn.

THEORETICAL BACKGROUND

Authors within a sociocultural or situative perspective have pointed to the benefits of focusing on activity systems when studying processes of learning and development, as a complement to more traditional studies of individual learners (Greeno, 2006; Kelly & Green, 1998; Magnusson, Templin, & Boyle, 1997; Rogoff & Chavajay, 1995; Säljö, 1997). Specifically, such a perspective opens up alternative ways of dealing with contextual issues of learning by including social interaction, communication, and sociocultural artifacts as constitutive parts of cognition (Dewey, 1925/1958, p. 170; Vygotsky, 1978, p. 89). Dewey, an early advocate of the study of systems larger than isolated individuals (Greeno, 2006; Rogoff & Chavajay, 1995), developed the concept of *experience* as an account of this integrity of human action, comprising both that which is experienced and those experiencing in an "unanalyzed totality" (Dewey, 1925/1958, p. 8). By studying cognition and learning as distributed events (Garrison, 1995; Greeno, 2006; Magnusson et al., 1997), a situative perspective can inform us about how various aspects of authentic school settings afford productive learning (Anderson, Greeno, Reder, & Simon, 2000). Significantly for the present study, an analysis of activity systems can contribute to our understanding of science learning by investigating how results from studies of individuals' thinking and learning apply to "real-world learning environments" (Greeno, 2006, p. 83).

For the purpose of studying what aspects of an authentic learning situation are important for what students learn in that particular setting, we need to operationalize learning such that (a) it can be described in detail before an analysis of its significance is made and (b) this description makes visible the connections between aspects of the situation and the learning process. In other words, neither do we want to overlook certain instances of learning because they were not included in the definition from the outset, nor do we want to specify in advance what parts of a learning situation should be included in the analysis or not. This calls for an operationalization of learning that is *generously inclusive* in the description phase, leaving for the analysis to decide what was significant in a certain learning situation. To this end, we will use the concept of experience in the Deweyan pragmatist sense, as something having

> its own objective and definitive traits [which] can be described *without reference to a self*, precisely as a house is of brick, has eight rooms, etc., *irrespective of whom it belongs to*. (Dewey, 1925/1958, p. 232. emphasis added)

On this account, individuals are part of every experience, transforming it as well as being transformed by it. But they are not obviously the exclusive seat of the experience. Rather, the selves are among, not outside of, the occurrences constituting an experience (Dewey, 1925/1958, p. 232). Dewey did not deny that individuals display attitudes, dispositions, and ideas, but stressed that these could productively be seen as involved in the world of common experience, coming from or being directed toward situations and things (Dewey, 1925/1958, p. 238). Experience in the Deweyan sense, then, is whole in action, and distinctions between what in an experience is external or internal, culture or individual, may rather be seen as the result of analytic reflection than as assumptions preceding the analysis (Dewey, 1916/2005, p. 99; Wickman, 2006, p. 69). So the concept of experience allows us to be generously inclusive in our description of a situation, in that it initially (i.e., preanalytically) assigns all parts of the situation to the same level. Moreover, Lave (1993) stated that activity always involves learning, although it is often unrecognized as such. To Dewey, an activity contains learning experiences whenever there are relationships or continuities perceived by those taking part in the activity (Dewey, 1916/2005, p. 84). Accordingly, as a first step toward making a generously inclusive operationalization of learning, we will treat learning as the act of *giving meaning to events in experience, by making them continuous with prior experience* (cf. Wickman, 2006, p. 42). To the extent that an activity contains perceived relationships and continuities, the question is not whether learning has occurred, but what directions learning takes in relation to the actions used by the students to deal with the events in the classroom (Wickman, 2006 pp. 52, 59). This should not be interpreted as a redefinition of learning, but rather as a treatment of learning that allows all relationships or continuities recognized by the actors in a situation to be initially described prior to an analysis of their significance for how the experience develops as a whole. To summarize, a situative and Deweyan pragmatist perspective on human action offers ways of studying events as they appear in experience, leaving for the analysis to determine which parts—misconceptions, artifacts, natural phenomena, or any other features of the situation studied—will stand out as important for how the experience develops.

How, then, will we be able to operationally describe a learning experience in a way that fulfills the intentions described above? Well, similar to a teacher involved in trying to understand how various curricular measures affect the routes her students' learning takes during authentic classroom work, we depend on what they do and say (Wickman, 2004). To study learning in action, we therefore need to operationalize learning on a discursive level as a description of what students say and do when taking part in an activity (Wickman, 2006; Wickman & Östman, 2002b). The concepts of an operational mechanism for describing learning on a discursive level of people acting in an activity, what Wickman (2004) called an *analysis of practical epistemologies*, were introduced by Wickman and Östman (2002b) and have subsequently been used on several occasions (e.g., Almqvist, 2005; Jakobson & Wickman, 2007; Lidar, Lundqvist, & Östman, 2006; Lundegård & Wickman, 2007; Wickman, 2004; Wickman & Östman, 2002a). As an activity proceeds, *gaps* are noticed as the result of *encounters*, either between persons or between persons and artifacts or natural phenomena. To fill a gap, new *relations* need to be established to what is immediately intelligible, that is, to what *stands fast* in the encounter. It is important to note that standing fast refers neither to the correct use of a word nor to any assumption about its stability as a conceptual structure within the person using the word. Standing fast simply means that actions and language uses are not questioned by the participants, and therefore work as temporary points of departure for further action in encounters with the word. If no working relations can be established to what stands fast, the activity stops or the theme of discourse changes (Wickman, 2004). The gap is then said to *linger*. Thus, the basic rhythm of a learning experience can be described as a series of encounters interacting with the filling of gaps through establishing relations to what temporarily stands fast (Wickman, 2006 p. 61). As such, it meets our requirement for a generous operationalization of learning, because any action that establishes continuity of experience through an explicit relation is recorded as a learning experience. The description of how students proceed with the activity through establishing relations in encounters is thus first made from the point of view of the learners, that is, what they count as sufficient for proceeding in a certain direction (Wickman, 2004). Only later, in the analysis, are the relations that were established and the directions that learning took in response to them considered from the point of view of the purpose of the class, or from the point of view of how it relates to what is accepted knowledge in the scientific community. To clarify, an analysis of practical epistemologies does not involve a normative definition of how students should go about learning science. Quite the reverse, the analysis is strictly operational, by allowing any action establishing a relation to prior experience in response to an encounter to count as potentially important learning. Moreover, although generous and inclusive in its initial description of learning, the analysis does not count all learning experiences as equally good or important. It is true that in the description phase, it takes the learner's perspective on what counts as sufficient action for further inquiry. But it saves the assessment of the *quality* and *importance* of these actions to the subsequent analysis of the direction learning takes, as made by a researcher or a teacher. In this paper, we will use this analysis of practical epistemologies to describe *how* students proceed with their activity in response to various encounters, specifically encounters related to misconceptions, and *what* consequences this has for the directions their learning takes.

Of course, recording the directions students' reasoning takes, that is, studying learning as "discourse change" (Wickman & Östman, 2002b), is a different thing from recording misconceptions or studying learning as conceptual development in interviews (e.g., Taber, 2001). In the latter case, the meaning that students ascribe to words and propositions is carefully scrutinized through further questions and by carefully analyzing the connections between statements. In fact, the purpose of such interviews is to elucidate what students mean when talking about scientific phenomena, and how the meaning they ascribe to concepts changes over extended periods of time. But in many learning situations, the purpose of the conversation is most likely not primarily to state knowledge or to understand what is really meant by an utterance. Rather, concepts and ideas are used within a context of inquiry in order to acquire enhanced meaning of an experience (Kruckeberg, 2006). When being instruments of inquiry rather than expressions of knowledge, words and propositions acquire their meaning from their consequences in actual and shared use (Greeno, 2006; Kelly & Green, 1998; Rhees, 1970; Wickman, 2004). So, from the point of view of the participants of an activity, propositions most often do not function as statements of knowledge but as doing a job. Preanalytically and in action, then, propositions are not primarily correct or incorrect, but variously useful, effective, or relevant with respect to the development of the students' reasoning (Hickman, 1998, p. 180; Magnusson et al., 1997). This implies that from a situative perspective, there are no neutral or context-free ways of assessing what students know or learn. Interviews have sometimes been treated as giving such privileged access to students' conceptual understanding (Johnson & Gott, 1996), but there are good reasons for rather considering them as very specialized discourse events, no less situated and context-bound than, for example, dialogues between peers during a classroom activity (cf. Schoultz et al., 2001; Welzel & Roth, 1998). Even if it is certainly possible to interview students after a learning experience, that would not show us what students actually learned during the classroom activity, but how they manage in another kind of activity (Greeno, 2006). The same is true of interview studies following a learner's development for an extended period of time. Likewise, determining students' misconceptions in introductory interviews would not automatically give us access to the starting points for their reasoning in a subsequent activity. These starting points need to be observed in ongoing activity. Thus, the extent to which misconceptions become important problems for learning science, in this view, becomes a question of (a) to what extent encounters with them constrain the activities in which they appear (i.e., descriptive phase/learner's perspective) and (b) whether these encounters cause students' reasoning to develop in an unwanted direction with respect to the purpose of the activity or the intended scientific knowledge (i.e., analytic phase/researcher's perspective).

By including all activities that render increased meaning to experience, operationalized as the relations established in encounters, we can empirically examine the role of different actions taken by students in their process of learning science. In this study, we empirically examine to what extent students' learning process in science is influenced and constrained by their having or forming misconceptions about the encountered phenomena, and look for complementary ways of describing the difficulties and possibilities that characterize the learning of a science content. We do this by investigating how students' reasoning develops during a practical on electrochemical cells. The specific research questions addressed are as follows:

1. To what extent do encounters with common misconceptions described in the literature influence how students establish relations to fill gaps noticed during a practical on electrochemistry?
2. To what extent do encounters with other aspects of the activity influence how students establish relations to fill gaps noticed during the practical?

The conclusions drawn from the main studies on misconceptions in electrochemistry are that these misconceptions have to be identified (Garnett & Treagust, 1992a), addressed (Huddle et al., 2000), and confronted in order to prevent or reverse their formation (Sanger & Greenbowe, 1997a). More generally, the studies conclude that effective learning is unlikely to occur if misconceptions are ignored (Huddle et al., 2000), because they will adversely affect subsequent learning (Garnett & Treagust, 1992b). Given our operationalization of learning as relations established to fill gaps noticed in response to encounters, the main hypothesis generated from assuming that misconceptions constitute obstacles to learning—rather than being neutral or constituting productive resources—would be that *encounters with misconceptions constrain the ways students establish relations to fill gaps noticed in encounters with the electrochemical cell and the instructions*, by making their reasoning (a) come to a halt or (b) go in unwanted directions with respect to the purpose of the class. From the literature, we may further hypothesize that the constraints will be seen as the students *sticking to their misconceptions* and having *difficulties handling encounters with alternative explanations*. The alternative hypothesis is that *other encounters than those with statements of misconceptions will have an important influence on the direction of the students' reasoning,* and that *encounters with misconceptions will also show neutral or positive effects on the students' reasoning*.

METHOD

Design and Procedure

We audio-recorded talk between eight pairs of Swedish upper secondary students during a practical on electrochemistry. Students in this school are generally highly motivated and most of them move on to higher education, although not necessarily science. The practical took place in the second semester of their first year, so the students were in the last part of the basic chemistry course. As to the other science subjects, the students had been studying biology in parallel and had just begun their basic physics course this semester. The present course (Chemistry A) is compulsory within the Natural Science Programme and as a rule the course extends over two semesters with approximately 160 minutes per week. The course covers all general chemistry taught in the Natural Science Programme (Chemistry B dealing with organic chemistry and biochemistry). The previous semester, the students had finished a unit called "Oxidation and reduction: electron transfers," extending over approximately 3 weeks. The current practical was part of the unit "Energy—the driving force behind everything," which so far had addressed thermochemistry. The class preceding the practical dealt with a revision of oxidation–reduction reactions. The time allocated to electrochemistry in this unit was scheduled for about 3 weeks. The practical was an established part of the unit, although it was rewritten by the authors to accommodate the demands of keeping the students near the recording equipment. It was also slightly adjusted according to comments made by the teacher concerning the accessible equipment at the school. Three weeks before the practical, one of the authors informed the class and acquired written permissions from the students. The students were told that they would be kept anonymous even to the authors, and that they were allowed to interrupt the audio recording at any time during the practical. All students in the class (32 students) agreed to take part in the study, although in the end, eight groups (16 students) were actually audio recorded. The sample is reasonably equivalent to previous studies on students' misconceptions in electrochemistry, regarding both student age and exposure to electrochemistry instruction (cf. Garnett & Treagust, 1992b; Sanger & Greenbowe, 1997a). Possible differences between curricula should be negligible considering the generality of the previously recorded misconceptions over two (Sanger & Greenbowe, 1997a) or even three (Huddle et al., 2000) continents. Thus, the central difference between the present study and earlier ones on students' misconceptions in electrochemistry concerns the way in which the studies were situated. Earlier studies used interviews with individual students, the purpose being to identify misconceptions in electrochemistry through interviews being centered around

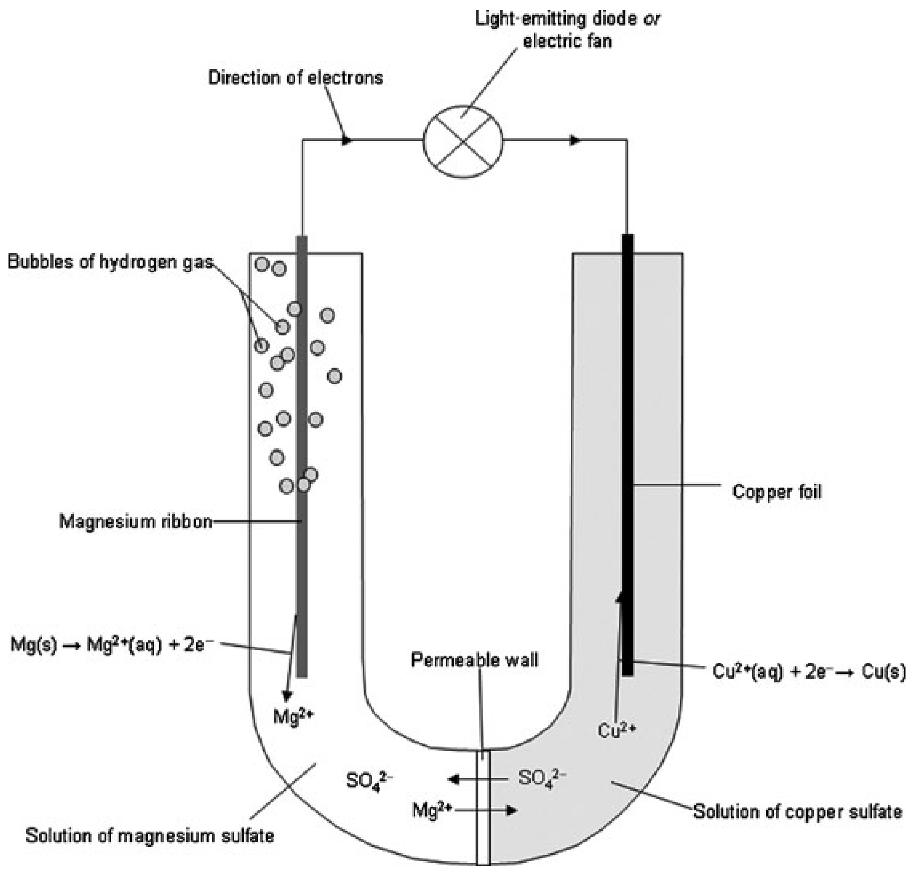

Figure 1. A schematic representation of the electrochemical cell setup in the practical, showing some of the observable events as well as the directions of the movement of electrons and ions. It was possible, although apparently difficult, to observe a precipitation of copper metal on the copper foil. On the magnesium side, a visible precipitation formed, possibly magnesium hydroxide. There was some leakage across the permeable wall separating the two compartments, causing blue copper sulfate to mix with the transparent magnesium sulfate solution. To make the light-emitting diode work, it had to be connected to the proper terminals, whereas the electric fan could be connected either way. Depending on which way the voltmeter was connected, it indicated either a positive or a negative voltage.

a set of questions and formalized drawings of electrochemical cells (Garnett & Treagust, 1992b; Sanger & Greenbowe, 1997a). In the present study, on the other hand, we recorded dialogues between students working with a real electrochemical cell, with the purpose of analyzing to what extent such previously identified misconceptions enter into the students' learning in a more authentic learning experience.

The practical was briefly introduced by one of the authors. The students were told to work in pairs without help from the teacher (the teacher and one of the authors being of help mainly with practical issues, e.g., missing items). The practical was scheduled for 70 minutes. Each pair of students was given all the material needed for the practical simply to make them stay near the audio-recording equipment. The material included solutions of copper sulfate and magnesium sulfate, magnesium ribbon and copper foil, a U-tube with a porous white glass wall at the bottom, and leads with appropriate accessories. Each group was also given a voltmeter and either a light-emitting diode or an electric fan to be connected to the electrochemical cell (Figure 1). The reasons for using either a light-emitting diode or an electric fan were initially practical, due to what equipment could be accessed at the school.

The instructions included five assignments, although only assignment 5 was brought out as "the assignment" in having its own heading:

1. Set up a working electrochemical cell (instructions for this were given)
2. Observe what happens in your electrochemical cell and to the electric fan/light-emitting diode
3. Measure the voltage of your electrochemical cell
4. Look closely at the metal strips
5. Discuss and try to explain
   a. how a current can occur in your electrochemical cell, that is, where the electrons come from and where they go
   b. which chemical reactions take place
   c. the role of the porous white glass wall at the bottom of the U-tube.

The students were also asked to draw simple sketches of their cells to illustrate how the cells worked. The students also wrote down their observations and answers to the questions in the instructions, although this was done in a rather informal manner.

Analytical Approach

Student talk was audio-recorded digitally with Olympus DM1 digital recorders and transcribed verbatim using Olympus DSS Player Pro transcription module. Recordings were between 28 and 61 minutes long, giving a total of about 300 minutes of student talk. When needed, we used the written material (sketches and written answers) to clarify student talk during the transcription. In some instances, it was not possible to interpret unambiguously what the students were saying due to the quality of the recording. Such missing talk was marked within brackets as "words missing." If we considered a passage too ambiguous due to missing talk, it was omitted altogether from the subsequent analysis. Thus, to the extent that missing talk occurs in the analyzed material, it has been judged not to be of crucial importance for the interpretation of what is said in the passage. All excerpts are translated from Swedish with as small changes as possible from the original wording. This means that some translations of idiomatic expressions in Swedish become nonidiomatic in translation. However, care has been taken to retain similar connotations in English. Now and then, however, a Swedish word has to be translated with a different word in English to retain the meaning (e.g., the Swedish word "ja," literally meaning "yes," in some contexts is better translated with "well"). Notations between brackets either indicate actions apparent from the audio recordings or contain clarifications, often of pronouns (e.g., "these" in line 110 being "the sulfate ions") or adverbs (e.g., "through here" in line 23 being "through the lead"). The expression "mm," being extremely common in Swedish, is also clarified in this manner with the help of the English words "yes," "well," or "right." The expression "mm" is primarily used in a neutral way to confirm that you are following the conversation. Underscored portions of the excerpts are those connected to a known misconception.

The transcripts were read through several times, and student talk was coded by marking (a) encounters of various kinds (with misconceptions, with the electrochemical cell, with the instructions, etc.), (b) gaps, and (c) relations to what stand fast, in accordance with the analysis of practical epistemologies outlined in the theoretical background. It was obvious that the students' main concern was trying to solve the problems given in the instructions, especially assignments 5a and 5c, combined with understanding what was happening, and why, in the actual electrochemical cell (i.e., assignment 2). These three commitments (i.e., assignments 2, 5a, and 5c) were intimately entwined, and together we refer to these commitments as "the purpose of the practical." The analysis of the practical epistemologies emerging during the students' discussions thus took this purpose as its point of departure. After having made this general coding, we identified gaps specifically relating to that purpose as well as the relations established to fill the gaps. Also, we looked for which encounters preceded these gaps and to what extent the encounters were made part of the established relations. These descriptions of the practical epistemologies (i.e., how the students established relations to fill the gaps identified, and in response to which encounters) were then compared to the list of misconceptions recorded in the literature (Garnett & Treagust, 1992a, 1992b; Sanger & Greenbowe, 1997a). In this way, it was possible to spot passages where the noticed gaps or established relations dealt with issues connected to these misconceptions. As noted in the theoretical background, the students holding on to or forming known misconceptions was only one out of many possible elements making up the learning experience. Thus, the description of the noticed gaps, the relations established, and the encounters influencing these processes enabled us to analyze how different aspects—encounters with misconceptions being one such aspect—of a situation took part in how the students proceeded with their discussion, as well as which directions their reasoning took as a consequence of these aspects.

We illustrate how the analysis was made through the excerpt below (group 3):

01	Gary:	What's this [the glass wall]
02	Hannah:	[words missing] that separates. . .
03	Gary:	Does it let anything through [words missing]?
04	Hannah:	Mm [Well]. It, might as well just consist of two test tubes. Or?
05	Gary:	Or, it lets through such. . . electrons. [words missing]. [That's] why it circulates,
06		has to circulate.
07	Hannah:	Well, could be.
08	Gary:	Well what do you say?
09	Hannah:	Mm. . . [Well. . .]
10	[long pause]	

Hannah and Gary, in an encounter with the electrochemical cell, that is, the glass wall at the bottom of the U-tube (Figure 1; line 1), notice the gap "what is—this [the glass wall]?" (line 1). Gaps may appear either as explicit questions, as in this excerpt, or as the implicit question with which a specific relation is dealing. The students attempt to fill the gap by forming the relation "it—separates" (line 2, although some words are missing), but in line 3 they notice a new gap, this time as to whether the wall is permeable to anything. Again, there is an attempt to fill the gap by the relation "it—might as well consist of —two test tubes" (line 4). They also establish the additional or alternative relations "it [the glass wall]—lets through —electrons" and "it [the current or electrons]—circulates." The remainder of this excerpt shows that the discussion comes to a halt and that the gap is lingering (lines 8 and 9).

First, we may observe that the relations in, for example, lines 4 and 5 are established to words such as "test tube" and "electron" that stand fast to the students. To see that these words stand fast, we do not need to make any claim as to which "meaning" Hannah and

Gary attach to the words, or what they "actually" are thinking when uttering the words. We only need to establish that they use these words without questioning or hesitating about what the words mean, and that this enables them to proceed with the activity.

In this *description phase* we thus take the learners' perspective, by establishing what they count as knowledge. If, for example, the relation established by Gary in lines 5 and 6 had been confirmed by Hannah by saying something like "Yes, that's right, it probably lets through electrons to keep the current going" and Gary had responded "Yes," this would have been recorded as their having successfully (from their point of view) filled the gap, and that the misconception was not constraining their reasoning. If, on the other hand, Hannah had objected to the notion that electrons move in the solutions while Gary had persisted, and this had led to their discussion coming to an end without settling the matter, this would have been recorded as the gap still lingering, and as an encounter with a known misconception obstructing their reasoning.

In the *analysis phase*, however, we need to view the relations established and the development of the conversation from the purpose of the task and from what counts as relevant knowledge in the area. Assuming the first hypothesized answer by Hannah, we might then have said that so far, their reasoning seems to be going in the wrong direction, if the purpose was to learn about the function of the glass wall. We could also have concluded that a previously recorded misconception, that is, misconception 2e (Table 1), "electrons flow in the electrolyte" (Garnett & Treagust, 1992a), here entered into their reasoning in a way that constrained it, although in this instance, not from their own perspective. Similarly, assuming the second development of their reasoning, we would have concluded that the encounter with this misconception hindered their reasoning both from their own perspective and from the perspective of the correct knowledge. Finally, an analysis of what actually happened shows that the relations are established in an unsure or tentative manner (e.g., lines 4–9). The reason why the conversation comes to a halt is obviously the well-known difficulty students have with the function of the glass wall, and that they cannot settle for any particular set of relations to fill that gap. But it is not the previously recorded misconception that constitutes a problem in this particular instance, since it is only touched upon as one out of two alternative explanations for how the glass wall functions, and not held on to particularly tight (lines 5–8). Thus, in an analysis of practical epistemologies, we first *describe* learning in terms of the relations that are continuously being established in

TABLE 1
The Number of Instances in Each Group Where Misconceptions in Electrochemistry Recorded in the Literature Were Touched Upon by the Students in the Current Study

	Group							
Misconception	1	2	3	4	5	6	7	8
2e: "electrons flow in the electrolyte" (Garnett & Treagust, 1992a)		2	1		2	1		1
10f : "only negatively charged ions constitute a flow of current through the solutions and the salt bridge (Sanger & Greenbowe, 1997)"					2			
11a: "the anode is negatively charged and releases electrons; the cathode is positively charged and attracts electrons" (Sanger & Greenbowe, 1997)				1		1		1

connection to different encounters made in a situation. Then, we *analyze* that learning in terms of how encounters and established relations are leading the reasoning in either the right or wrong direction compared to the purposes of the class.

Finally, it is important to stress that we are not concerned with what the students understood in any final sense, which would be incompatible with our intention of studying learning in ongoing activity.

FINDINGS

Three of the previously recorded misconceptions in electrochemistry were touched upon in 12 instances, distributed among six of the eight groups analyzed (Table 1).

The most commonly encountered misconception was that "electrons flow in the electrolyte," being part of the discussion in seven instances in five of the groups (2e; Table 1). Thus, both the number of observed misconceptions and the number of encounters with them is rather limited. It is this limited part of the student dialogues that is presented in this article. The point of the presented excerpts is that the noticed gaps were concerned with the same issues as the known misconceptions, thus allowing for the possibility that the relations established were being influenced by those misconceptions. The major part of all dialogues concerned gaps and relations not related to any of the known misconceptions. In these other parts of the material, the students were dealing with distracting events such as encountering negative voltage or bubbles of hydrogen gas, with what could be observed or what was happening in the electrochemical cell, or with conceptual issues not connected to previously recorded misconceptions in electrochemistry. In these other parts, there is, of course, the possibility that previously recorded misconceptions in other areas of chemistry or physics were touched upon. However, the objective of the study was to examine the importance of a certain set of well-known misconceptions in electrochemistry, not to examine the effect of misconceptions in general, and consequently, we have primarily searched the material for the former.

Misconceptions As Alternatives and Questions

With the exception of the last excerpt presented below (lines 127–131), all encounters with the three misconceptions (Table 1) showed a more or less pronounced uncertainty on the part of the students' reasoning. There were alternatives, questions, and tentative relations, but neither did the students stick to particular misconceptions nor did they refrain from considering and accepting alternative interpretations. This is demonstrated in the first two excerpts, where the known misconception that electrons flow in the electrolyte (2e; Table 1) is encountered as Alex and Becky (group 2) are trying to fill the gap of the role of the glass wall:

11	Alex:	Or wait. The magnesium ions forming. . . If we've got our salt bridge here. . . then they move
12		down there. At the same time, copper atoms are formed here, so then, sulfate ions become
13		free here, then sulfate is moving into and. . .
14	Becky:	The ion you mean, the entire ions?
15	Alex:	Well ma. . . , magnesium ions in this direction and sulfate ions in that direction.
16	Becky:	Not just electrons but, kind of, entire..?
17	Alex:	Uhm, God knows. Probably the ions.
18	Becky:	Mm [Yes].

Here, Alex establishes relations to the compensating movement of charge through the glass wall (lines 11–13). Becky notices an additional gap as to whether it is electrons or ions moving through the glass wall (line 14), and in this process touches upon misconception 2e (lines 14 and 16; Table 1). But the encounter with the misconception is in the form of an alternative, addressed as a question. Encountering the misconception as one of two alternatives is not obstructing their reasoning, which is leading in the right direction as the students fill the gap with the tentative relation "probably—the ions" (lines 17 and 18). If anything, the encounter with the misconception here is generative of the development of the students' reasoning, in that it provides ground for further reflection (lines 16–18). Shortly afterwards, when establishing relations to fill the general gap of how electrons circulate in the cell, they touch upon the same misconception (2e; Table 1) once again (lines 25 and 26):

19	Alex:	The electrons? They come from, these.
20	Becky:	Mm [Yes]. They start here [Mg-sheet]. Then they move like this, over and down into this one
21		[light emitting diode].
22	Alex:	Mm [Right].
23	Becky:	And then through here [lead]
24	Alex:	Mm [Right].
25	Becky:	And out there [copper solution]. Uhm. And then down into, this gadget [glass wall]. Since
26		they have to circulate, kind of.
27	Alex:	No, it doesn't have to.
28	Becky:	Why not? Is that why it doesn't happen anything [the diode not emitting any light].
29	Alex:	What? No but you see... copper doesn't want to give off the electrons it's accepted. Cause...
30	Becky:	So it just accepts all electrons coming in this [lead]?
31	Alex:	Yeah exactly. Cause magnesium isn't, how do you say, strong enough to, pull electrons from
32		copper.
33	Becky:	Ok. So, copper accepts... electrons [writes], and these [magnesium sheet] want to kind of give
34		off and those [copper ions] want to accept, is that it, why it happens like that?
35	Alex:	These, yeah, exactly.

On the one hand, the fact that Becky returns to the misconception shortly after the first excerpt indicates that she would prefer the interpretation that electrons constitute the entire current in the cell. On the other hand, as before, they deal with the issue in a straightforward manner by posing questions, that is, noticing gaps (lines 28 and 30), and filling these with relations (lines 29, 31, and 32) that lead in the right direction. Taken together, there is no indication of their reasoning being constrained by the misconception that electrons move through the solutions (2e; Table 1).

The ambiguity characteristic of instances relating to known misconceptions is also evident in the next excerpt, emphasized by words like "maybe" and "might" (lines 37, 38, and 41). The background to the reasoning below (lines 36–45) is a small side experiment made by Charlie and David (group 8) in order to fill the gap as to whether the glass wall is required for the cell to work. They simply separated the solutions into two disconnected beakers and checked if they could still detect a voltage:

36	Charlie:	Uhm, we have established that the connection has to be between a fine thin wall but yet not
37		mixing themselves, maybe the electrons go through but not the solution
38	David:	Well, the electrons might get a hunch of. . . Maybe they. . .
39	Charlie:	[words missing] that they have some special physical contact, only that there are electrons
40		that. . .
41	David:	Maybe it isn't physical contact but maybe just charge. That they sense the charge
42	Charlie:	Exactly. They experience some charge from the various plus and minus, they attract each
43		other in some way which makes it a better, cell.
44	David:	Well otherwise it can't be a cell
45	Charlie:	It might be like this, or it might not. . .

Here, they touch upon misconception 2e (line 37; Table 1), elaborating it somewhat in the course of the discussion (e.g., line 41). But despite having established that there has to be "a fine thin wall" (line 36) to get a voltage in the cell, this does not open up for the possibility of the wall being permeable to the solution or to ions. The bottom line is that the wall simply does not let through the solution (line 37). So what is constraining Charlie's and David's reasoning and potentially leading it in the wrong direction is the fact that they do not allow for a permeable wall, not a misconception that electrons move through the solutions, because there is no such stability concerning the misconception. On the contrary, the "misconception" (line 37) is nothing but one out of a number of alternative interpretations tried out.

One might, of course, wonder why they did not allow for a permeable wall in the first place. In fact, there were two instances, the one shown in the next excerpt arriving early on in the practical, where Charlie and David established relations to an impermeable glass wall (lines 47–49):

46	Charlie:	. . . the steel, no, ions are formed, which then move to copper. . . the copper, the copper foil
47	David:	[words missing] not move through here in any case
48	Charlie:	Can, are you sure?
49	David:	Yes, it's a, it's a wall right through.

On the other hand, groups 1 and 5, two of the groups allowing for a permeable wall (cf. lines 127–131 for group 5), established relations to a leaking (i.e., permeable) glass wall early on in the practical. Fred and Eddie (group 5) thus establish the relation "it—able to circulate" (line 51):

50	Fred:	But, as you can see it [the copper sulfate solution] comes down, some gets through down
51		there. So that means it has to be able to, circulate. I take the other one, magnesium sulfate.
52	Eddie:	There. Look. Now it's been forced back or, well, maybe it has mixed.
53	Fred:	Yeah, by the pressure [2 words missing] perhaps.

So, it is possible that these students filled the gap concerning what moves through the glass wall in response to contingent encounters with an impermeable or a leaking glass wall (lines 47–49 and line 51), although here, this interpretation is only conjectural.

Contingencies Influenced Reasoning More Than Misconceptions

Next, we present three successive but different encounters that were all part of the students' reasoning concerning the general gap about the direction in which the electrons move in the cell. Together, they constitute an example of the observation that encounters with known misconceptions had less influence on students' reasoning than encounters with the contingencies of the situation. In the first excerpt below, Charlie and David are encountering one of the previously recorded misconceptions:

54	David:	electrons from here to there, or the other way around.
55	Charlie:	Yes
56	David:	That is, from the blue [copper] to the white [magnesium] side or vice versa. And what
57		happens to them?
58	Charlie:	Electrons would go in the opposite direction, right . . . to that of the current?
59	David:	Uhm, yes, and the current goes from plus to minus. So the current goes. . . [murmurs]
60	Charlie:	Minus might be those who give off, maybe. Or perhaps it's different. . .
61	David:	The minus terminal is, you know . . . where there are electrons. This becomes the minus
62		terminal and this becomes the plus terminal if . . . or do I reason correctly? If it moves from
63		minus to, hum, plus to minus. . .

Charlie and David notice the main gap about how the electrons move in the cell (lines 54–56), and in the course of the discussion also the additional gap of which electrode is negative and which is positive (lines 60–62), touching upon misconception 11a (line 61; Table 1). But their reasoning comes to a halt because they are unable to form working relations to fill the gap about the signs of the terminals. In other words, they simply are not sure how to determine the sign of the terminals. Here too, there is a clear ambiguity in their reasoning (line 62), and the encounter with the misconception is in the form of one out of two alternatives presented (lines 60 and 61). On the other hand, shortly afterwards, they are able to fill both gaps by establishing relations in an encounter with the electrochemical cell (line 64 and 67):

64	Charlie:	It seems as if the metals have been oxidized a little, in some way, there is some metal
65		coating. . .
66	David:	Been oxidized, and, when something is oxidized, then. . . it gives off electrons
67	Charlie:	Yes. And this [Mg-sheet] has been oxidized no doubt, which means it gives off electrons. So,
68		that must be minus and that must be plus
69	David:	Yeah, that might be right. Now I forgot. . . hum. Ok, if we assume that. . .
70	Charlie:	We assume that the magnesium sheet has been oxidized and given off electrons to, the copper
71		foil in the other, and gone through the lamp.
72	David:	Yes

Here, encountering what they interpret as signs of oxidation on the magnesium sheet (line 67) makes them establish relations between being oxidized and giving off electrons (line 66) as well as between giving off electrons and being the negative terminal (lines 67 and 68 and cf. line 60). In turn, this leads to their filling the general gap concerning the direction of the movement of electrons (lines 70–72) in a way that is leading in the desired direction. Thus, the encounter with misconception 11a did not prevent these students from establishing working relations to explain the movement of charge in the electrochemical cell (cf. Garnett & Treagust, 1992b). Rather, they filled the gap in response to the contingencies of the situation, an encounter with signs of oxidation (lines 67–71) being related to oxidation, to the release of electrons, and to which terminal is positive and which is negative. To some extent, these relations are connected to the first of the two possibilities tried out earlier about how to determine the polarity of the terminals (line 60).

However, Charlie and David reversed the direction of the flow of electrons through the cell several times as a result of other encounters, for example, the release of hydrogen gas on the magnesium side. But, it was not just encounters with the electrochemical cell that influenced the course of the discussion. In the next excerpt, showing the last of the three encounters, they have once again become unsure as to the direction of the movement of electrons in the cell:

73	David:	Thus... they move... here... Hum... No but wait, oh, wait, if a metal is nobler... then it has...
74	Charlie:	Then the other one forms ion, the other metal ions.
75	David:	Wait wait. If a metal is nobler, yeah exactly. Then the less noble one forms...
76	Charlie:	Ions
77	David:	... ions. Because a nobler metal is less electronegative.
78	Charlie:	Well, it
79	David:	Thus it will move from the copper to there
80	Charlie:	Yes, no wait, copper accepts ions cause it doesn't want to give off. It wants an electron.
81	David:	But electronegative should be how easily you can take... and
82	Charlie:	Yeah, but then how would this one be able to accept, cause this one is almost, uhm, full outer
83		shell.
84	David:	Exactly, electronegative is how big a chance that someone wants to accept an electron. And
85		copper, is it, but met..., I mean metal shell, you're supposed to add, it's kind of totally
86		impossible
87	Charlie:	Whereas an atom having very high electronegativity...
88	David:	... tivity, they've got nearly completed shells. And then they want to accept.
89	Charlie:	Yes.
90	David:	And
91	Charlie:	Thus copper should accept then
92	David:	But wait wait, they've got
93	Charlie:	Copper's got six
94	David:	Wait they've got low electronegativity, if it, is, noble, haven't they?
95	Charlie:	But it still wants to accept, doesn't it?
96	David:	Hum. But I think it was low electronegativity.

97	Charlie:	Ok.
98	David:	Or?
99	Charlie:	Well let's go for something
100	David:	Yeah we, if it is low electronegativity then it gives off to. . . this, let's say it's magnesium here
101		[draws], uhm. . . then this one gives to this one.
102		[Another group says something completely irrelevant, which goes unnoticed by these students]
103	David:	And then that means that. . . then copper ions will form, because the metal copper gives off
104		electrons to here, and, it. . . well, and then it will accumulate
105	Charlie:	Oh, let's just drop that and take the next one [question] instead

Here, the two words noble and electronegative do not stand fast, which leads to the general gap lingering as the discussion comes to a halt (line 105). They agree on the relations "less noble one—forms ions" (lines 75 and 76) as well as "high electronegativity—nearly completed shells—want to accept" (lines 87 and 88), but cannot decide on the relation between the two words noble and electronegative (lines 77, 78, and 94–99). It is true that there is an encounter with a misconception concerning the concept of electronegativity (Coll & Taylor, 2001), but that is not constraining their conversation (lines 87–91). The constraint, it turns out, is the encounter with the relation "nobler metal—less electronegative" (line 77). To fill the general gap concerning the movement of electrons in the cell, they simply would have needed help to restate this relation as "nobler metal—more electronegative." Again a contingent encounter, this time with a confusing relation being established between the terms noble and electronegative (line 77), was influencing the course that their discussion took. Judging from these three excerpts, the known misconception concerning what is implied in the signs of the terminals (line 61; Table 1) seems to have played at most a peripheral role as a determinant of how the students filled the gap about the movement of electrons in the cell, even though the gap was closely connected to the conceptual content of the misconception. Rather, contingent encounters (lines 64, 65, and 77) seem to have been comparatively more important.

Forming a Misconception or Gaining Increased Meaning of Experience?

The last two excerpts illustrate the importance of treating what people do and say as integral parts of a situation. What might be seen as the development of a misconception in the end of the second excerpt below (lines 127–131), gets a significantly different meaning when considered in connection to the whole learning experience.

106	Fred:	But, what's that one [glass wall] doing there, it's got to be there because, to kind of stop these
107		from mixing basically. It's only supposed to let through, a tiny tiny amount, so that only kind
108		of electrons or some kind of ion can get through.
109	Eddie:	But it, it should be. . .

Fred is noticing the general gap of what role the glass wall has for the functioning of the electrochemical cell (line 106), while at the same time touching upon misconception 2e (line 108; Table 1), in noticing the additional gap of whether it is electrons or ions moving through the wall (lines 107 and 108). A bit further on, they fill the second gap in favor of the ions:

110	Fred:	Yes, because I mean if not, if not these [sulfate ions] had been able to move through [the
111		glass wall], then the electrons hadn't been able to move anywhere.
112	Eddie:	No.
113	Fred:	Right? But then it has to become, more and more... magne..., magnesium sulfate on that, on
114		that side [magnesium side].
115	Eddie:	Yes. The sulfate ions should disappear from there [copper side].
116	Fred:	Yes.
117	Eddie:	And the copper ions are settling here [on the copper foil].
118	Fred:	Yeah exactly.
119	Eddie:	Perhaps that's why it won't, perhaps, well... If we let this stand by itself for a while... a rather
120		long while, it ought to stop working altogether.
121	Fred:	Yeah.
122	Eddie:	Then [2 words missing] recharge it again, by adding... new electrons, and restore the solution.
123	Fred:	But, yeah... So, after a while the copper sulfate like, will be entirely neu..., entirely gone.
124	Eddie:	Cause all copper will anyway, if it is the way we think, then all sulfate ions will...
125	Fred:	And then there'll be only, pure copper... and magnesium sulfate left.
126	Eddie:	Yes
127	Fred:	<u>So that, that filter down there, it has to let through these, uhm...</u>
128	Eddie:	<u>the sulfate solution</u>
129	Fred:	<u>Yeah, negat...</u>
130	Eddie:	<u>Yes</u>
131	Fred:	<u>Yes, negative. Negative ions.</u>

Seen in isolation, lines 127–131 indicate that these students are on the verge of forming misconception 10f (Table 1). But considering the entire course of their reasoning in this excerpt, such an interpretation is at least inadequate as an account of the significance of this learning experience. There are two reasons for also interpreting these relations as positive contributions to, rather than problems for, the students' learning. First, through the relation "that filter—lets through—negative ions" (lines 127 and 131), the gap concerning whether electrons or ions are moving through the wall is filled in a way that is leading in the right direction. Thus, these relations can be viewed as contributing to leading their reasoning in the right direction concerning misconception 2e, that is, away from talking about electrons moving through the solutions and the glass wall. Second, this excerpt shows how they are beginning to make sense of a lot of things about the electrochemical cell, such as (a) charge being built up as a result of the flow of electrons and the formation of magnesium ions (lines 110–115), (b) the glass wall letting through sulfate ions thus compensating for this buildup (lines 110 and 127), as well as (c) the overall fate of the cell in relation to these processes (lines 119–126). They even establish relations to the recharging of the cell and the restoration of the solutions, by adding "new electrons" (line 122). Seen as part of an experience, that is, as a continuous meaning making rather than a final outcome, the relations that they establish in lines 127–131 are leading in the right direction as to the purpose of understanding the role of the glass wall, and more generally, the function of the cell as a whole. In fact, the negative ions are not primarily considered as part of a discussion about current, but about compensating for the unequal buildup of charge or ions on one side. This implies that introducing a corresponding movement of positive charge may not constitute a conceptual problem for these students. Consequently, the relation "that filter—lets through—negative ions" (lines 127 and 131), rather than representing an obstacle for their future learning about electrochemical cells, could be seen as constituting a most functional point of departure for it.

DISCUSSION

In this study, common misconceptions in electrochemistry did not acquire the central role for learning ascribed to them in previous studies (Garnett & Treagust, 1992a, 1992b; Huddle et al., 2000; Sanger & Greenbowe, 1997b). Particularly, encounters with known misconceptions in electrochemistry did not constrain the ways students established relations to fill gaps noticed during the practical, neither from the point of view of their being able to continue the learning activity nor, more importantly, from the point of view of how their reasoning developed in relation to the purpose of the task. Instead, there was a variety of other, contingent encounters—with the electrochemical cell and with relations established during the conversation—which either interfered with or promoted the students' learning. Furthermore, statements including "misconceptual" content were tentative and were framed as questions or alternatives rather than as positions being maintained and defended. This preliminary character made some of the encounters with misconceptions contribute to the development of the students' reasoning, in that they provided material for additional reflection.

The discrepant conclusions concerning the role of common misconceptions for learning electrochemistry between this and previous studies merit a closer inspection, though. We note that in these earlier studies the empirical concern was with the existence of the misconceptions, whereas their interference with learning constituted a basic premise (Garnett & Treagust, 1992a; Sanger & Greenbowe, 1997a; Taber, 2006a) that has generally been supported more by argument than by empirical evidence (diSessa, 2006; Driver & Erickson, 1983; Smith et al., 1993). Here, we turned this basic premise into an empirical question of how the various encounters experienced in a learning situation—misconceptions being among them—enter into that learning. In other words, we changed the empirical concern from investigating the nature and incidence of misconceptions in electrochemistry (Garnett & Treagust, 1992b; Sanger & Greenbowe, 1997a), as well as their persistence after instruction (Huddle et al., 2000; Sanger & Greenbowe, 1997b), to how they enter into students' reasoning during the learning process. In that respect, our study should be seen as complementary to earlier studies, in that it examines the scope and role of the recorded misconceptions in electrochemistry. So, the results should not be interpreted as challenging the finding that students express these misconceptions in interviews and paper-and-pencil tests, nor that in these settings the misconceptions may restrict their reasoning. But our results may be considered to represent an anomaly to the premise that the same misconceptions automatically interfere with learning the subject matter in other contexts, because our findings show that in another kind of setting, and when studied in relation to all the contingencies of an ordinary learning situation, these misconceptions may have a significantly less prominent role.

The results from this study are in line with other studies indicating a more balanced interpretation of the results on students' misconceptions in science. As such, they imply that we cannot take the negative impact of misconceptions on learning science as a matter of course, even if they have been carefully demonstrated within a subject area. We also have to check what part they play in different contexts, whether those contexts constitute different activities (Greeno, 2006; Schoultz et al., 2001) or subtle variations in application context for the scientific concepts used by the students (diSessa et al., 2004; Smith et al., 1993; Taber, 2000). Particularly, our results may contribute to a discussion about how to interpret what constitute resources and difficulties for students' reasoning, and how these relate to contextual contingencies in a learning situation. Hammer (2000) noted that we are still a long way from understanding and modeling how conceptual resources are activated in various situations. Schoultz et al. (2001) nicely demonstrated how a sociocultural tool functioned as a resource for the students' reasoning about the earth, but in their study there were no traces of the previously recorded misconceptions whatsoever. Magnusson et al. (1997) saw students readily change their nonscientific ideas during the conversation with the researcher, but could not determine the factors influencing momentary changes toward or away from accurate conceptions. In our study, we were able to see both how our students' reasoning readily changed, and how it changed in response to encounters becoming apparent in the discourse. Moreover, we were indeed able to spot traces of misconceptions during the discourse, even though our students reasoning was primarily influenced by other kinds of encounters. At the same time, by describing encounters with misconceptions discursively and on the same level as all the other encounters making up the learning experience, we could show their importance relative to those other encounters without the need to further clarify their status as conceptual entities in individual learners.

In all empirical studies, there is a discrepancy between what we want to observe and our methods for making the observations, and that applies to this study as well. Of course, our findings are localized to a specific topic and a specific situation. Moreover, we do not claim that our operationalization of learning captures all aspects of the learning process, nor that we were observing either misconceptions, cognitive resources, or sociocultural tools in the same detail as has been done in other studies. But we do think that the results generated in this study indicate that taking a situative and pragmatist perspective on learning can provide important insight into some of the common questions about students' misconceptions, and more generally about the difficulties and possibilities connected to learning science. In addition to contributing to a clarification of questions about whether conceptions are stable or transient, correct or alternative (cf. Taber, 2000), it may provide a way of demonstrating in what kinds of situations misconceptions really become important, and in what circumstances they constitute problems or resources for learning, respectively. Such studies could even be extended to consider how the variation in the nature of misconceptions recorded in different topics (diSessa, 2006) affects the ways they enter into students' learning in authentic settings. If, on the other hand, the contingencies of a specific situation are demonstrated to be such important aspects of learning as is indicated in this study (see also Taber, 2006b), still other questions may be formulated and examined from this perspective. For example, in what ways do contingent encounters form part of, or could be made to form part of, science learning in various situations? And what about contingent encounters drawing students' attention from the intended focus of instruction, or threatening to confuse the learning experience? Could such events constitute important aspects of learning anyway? To the extent that they are significant, in what ways do they influence the learning experience? Could teachers benefit from such contingencies in helping students to understand science in the classroom (Hamza & Wickman, manuscript in preparation)? And what would such "contingency teaching" look like?

Often, results generated within one perspective are not seriously considered by those subscribing to other views. But our study indicates that the same issues of science education can indeed be tackled from different perspectives. Having similar results generated from different perspectives should strengthen the conclusions that can be drawn, as well as modifying them and making them more balanced. Furthermore, new questions may yield new results that may inform and clarify old and possibly taken-for-granted truths. We hope that the results from this study contribute to a clarification of the role that misconceptions can play in a certain setting, as well as informing discussions about how the various encounters in an activity may enter into students' learning of a science subject matter.

We wish to thank Per Sund at Mälardalen University, who conducted a preliminary study.

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