

From Activity to Gestures and Scientific Language

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Abstract

Gestures may provide the long sought-for bridge between laboratory experiences in science and scientific discourse about abstract entities. In this article, we present our results of analyzing students' gestures and scientific discourse by supporting three assertions about the relationship between laboratory experiences, gestures, and scientific discourse. Gestures arise from the experiences in the phenomenal world, they most frequently express scientific content before students master discourse, they allow students to construct complex explanations by lowering the cognitive load; they provide a medium on which the development of scientific discourse can piggy-back; and they provide the material that glues layers of phenomenally-accessible and abstract concepts. Our work has important implications for laboratory experiments which students should attempt to explain while still in the lab rather than afterwards and away from the materials.

Introduction

Since the 1960s, science educators around the world have placed considerable value on hands-on activities in their classrooms (Tobin, 1990). Piaget's theories makes it reasonable to expect that children learn those aspects of science that are associated with actions and operations. However, it is not clear at all why such activities should assist students to learn the discourses about more abstract concepts, that is, entities not phenomenally available. In recent years, researchers affiliated with the situated cognition paradigm suggested that hands-on activities somehow provided a concrete setting which somehow grounded the discursive in the material activities that students enacted (e.g., Roth, 1996a). However, despite careful and thick descriptions of learning in school

science laboratories, the fundamental questions how putting hands on materials leads to the understanding of abstract concepts have not been answered to any sufficient satisfaction.

More recent work which relates linguistic studies and learning in school science laboratories suggests that there may be a link between the “hands-on” activities students enact, the gestures that they develop, and the onset and emergence of their science-related discourse (e.g., Crowder & Newman, 1993; Roth, 1999a). This is the line of research which we present and extend in the present study. Central to the link between hands-on activities and discursive competence is the phenomenon of deixis, the referring function of signs used in communication.

Deictic phenomena occur in many forms. For example, verbal deixis includes the use of terms such as “this,” “that,” “he,” and “today.” The referents of these deictic terms may be entities in the world or linguistic entities; thus “he” in the sentence “The farmer plowed the field; *he* also fed the cows” refers to the farmer, another linguistic item. Gestural deixis often occurs by means of pointing to an entity using the index finger. Gestures are called iconic when their topology is structurally isomorphic with their content. Iconic gestures also have deictic function because they make salient certain aspects which are then recognized by the listeners as salient figure that stands against the ground. For example, a physics student moves her hand along a trajectory described by a quadratic function while she talks about the motion of an arrow shot at some angle to the earth’s surface; she communicates by means of an iconic gesture. Finally, in some situations, gestures have a metaphoric character; for example, a mathematician may move his right hand until it touches the spatially fixed left hand while talking about the mathematical notion of limit. In this case, the gesture is said to be a metaphorical instantiation of “limit.” Now there is evidence that gestures and deixis are deep features of human cognition.

Words, Gestures, & Cognition

There is little doubt in the scientific community that the recent human evolution is strongly correlated with the use of representations, that is, entities (sounds, gestures, objects) that stand for something else (tree, moving arrow, goats in herd). Increasingly, researchers hypothesize that early representation occurred in the form of gestures which therefore have to be considered the precursors to language more generally (Corballis, 1999). Rather than being an additional feature that accompanies language, gestural phenomena are perhaps the “unicycle” on which verbal communication later piggy-backed. Evidence from influential psychological studies provide grounds for this contention that gestures are not mere coincidental to speech but in deep ways reflect and facilitate cognition (Iverson & Goldin-Meadow, 1998); and recent neuroscientific studies suggest possible evolutionary paths for the emergence of language from manual skills via gestural communication (e.g., Arbib & Rizzolatti, 1997).

Words and gesture, should therefore be studied together because they are deep features of cognition; together they constitute multimodal presentations (Lemke, in press). Evidence from linguistic anthropology suggests that what are often considered different cognitive capacities deixis, gesture, and spatial orientation are not independent (Haviland, 1993; Levinson, 1997). Gestures are deeply integrated into systems of directional reference which is fundamentally important to understanding the cognitive background before which actions take their significance. For example, indexical reference plays an important role in accumulating spatial knowledge among the Hai||om bushpeople and is embodied in the form of topographical gossip involving terms that indicate directions (Widlok, 1997).

This interdependence clearly demonstrates that gestures and language are not simply aspects of linguistic system but of a broader communicative one. Talk and gesture are almost always co-present during communicative acts (e.g., McNeill, 1992), especially during science activities (Crowder, 1996). Although early research suggested that talk and gesture are separate components of communication (e.g., Kendon, 1983), more recent work suggests that it is more advantageous to study these features as aspects of the same event (Goodwin, 1986). We are therefore held to study the visible structure in the stream of speech as it interacts with grammatical knowledge to accomplish social action.

From a historical perspective on human development, such an hypothesis of the ontogenetic primacy of gestures to language makes sense, for there is evidence that gestures existed as representative means prior to language (Corballis, 1999). If individual human development (ontogeny) recapitulates the evolution of cognition of humanity (phylogeny) as Piaget suggested, we might expect gestures to precede discourse. Detailed demonstrations of such contentions have yet to be conducted. In such efforts, activity-oriented school science classrooms are ideal laboratories for they lend themselves to studying the relationship between activity, gesture, and the evolution of abstract discourses over relatively short periods of time.

Gestures and Science Talk

Verbal and gestural deixis provide links between language and its situative background which is taken for granted by the participants in a communicative situation. However, science and scientific language are generally praised for their context-independence. That is, we might formulate the hypothesis that there is no place for deictic phenomena in science and science education. But this hypothesis is disconfirmed by existing empirical sociological studies (normally not concerned with the role of gestures). Several ethnographic studies in scientific laboratories (also in engineering design studies) document the dependence of laboratory talk on the context (e.g., Henderson, 1991; Woolgar, 1990). Scientists and engineers apparently need visual representations to which they can point or in front of which they can move their hands in order to make themselves understood. In the absence of certain representations physical (drawings, photographs, graphs, models), the communicative efforts come to a grinding halt (Amann & Knorr-Cetina, 1990; Henderson, 1991). Talk continues only when the physical representations are available, associated with a lot of gesturing and pointing. If no representation can be fetched or drawn as facsimile, scientists and engineers often resort to gestures that render an ephemeral facsimile in the air especially when the collaborators are familiar with each other, and the topic of their collective work. We can say that scientific laboratory talk is highly indexical, occurs in the presence of the object of talk, and involves a lot of gesturing: it is literally handwork (Suchman & Trigg, 1993).

We can say that talk and gesture are *over* and *about* the entities (objects, phenomena, inscriptions) of the communication. Gestures and talk are *over* the entities because the latter serve as ground against which gesture and talk become the salient figure. They are also *about* the entities because these are the current conversational topic. The actual presence of entities therefore provide important resources to scientists when they interact in their laboratories. It has been noted that physicists may come to their understandings and interpretations of the subject matter in part through sensori-motor and symbolic reenactments of events (Ochs, Gonzales, & Jacoby, 1996). Furthermore, the availability of gesture as expressive medium provides resources to collaborative thinking-through processes in the sense that it affords the production of public and therefore witnessable and accountable events.

Recent research related to discourse and cognition in science learning intimates that gestures are a common phenomenon and may play a role as expressive medium (Crowder, 1996; Crowder & Newman, 1993). In these studies, gestures are described as playing ancillary roles in the development of discourse. When gestures are used to describe scientific models, they were typically timed with speech and provide “redundant” information. Gestures used when constructing explanations in-the-moment more frequently precede related verbal content and remedy the shortcomings of gesture-carried talk. Our own work (as reviewed in the next section and throughout the present study) suggests that gestures are more deeply integrated to cognition and play an important role during the genesis of scientific discourse in school-aged individuals.

From Activities to Scientific Discourse: Exploratory Work

In several recent studies we were able to provide some initial hints how the very nature of scientific concepts was constructed as students operated on more primitive concepts which were, in the course of their activities, assembled to more complex actions. For example, Grade 7 students began their activities with balanced levers by responding to the position of the weights along the lever

rather than, as traditional research presupposed (including the seminal studies by Inhelder and Piaget [1958] and Siegler [1976]), to the distance from fulcrum to weight (Roth, 1998). As students were provided with opportunities to move the weights along the balance beam, they began to act (discursively, practically) towards positional changes of weight. Out of this proto-distance notion, they developed a mature fulcrum-weight distance concept. During the post-test phase, students' gestures over and about drawings of the balance beam still made reference to the movement of weights along the lever arm which they had previously enacted. Their gestures were topologically identical to the original hand movement when they changed the position of weights along the beam.

In several linguistically-oriented studies of students' development of discursive competence as a function of their experience with material objects provided evidence that gestures may take an intermediate position between material activities and the representation of these activities in discourse (Roth, 1999a, 1999b). These studies suggested two possible routes to the development of discourse. First, iconic gestures can arise directly from the activity in the sense that, for the purpose of representing an action during an explanation, the hands and arms enact the same movements without materials that they had enacted with materials and tools during the activity. For example, a study of gestures and talk enacted by students as they interacted with a computer-based Newtonian microworld (Interactive Physics™) showed that students expressed the relationship between object and trajectory, force, and velocity long before they did so with words (Roth, 1996b). As students continued to interact, their initially highly variable discourse began to stabilize and verbally expressed concepts increasingly approached the earlier appearing gestures. In the end, gestures and talk coincided. Second, hands and arms may enact movements that had been observed such as when a hand iconically describes the direction and magnitude of forces in pulley systems drawn as diagrams on the chalkboard (Roth, 1996c). (Neuroscientifically, this makes sense for the same groups of neurons are involved in enacting motion oneself and recognizing the same motion in others [Decety & Grèzes, 1999].) This latter study also showed that if students have access to the drawn representation (or draw these themselves), their talk is much more and much faster scientifically correct than if they do not have this access. This can be interpreted as evidence supporting the importance of gestures in the development of scientific discourse and the importance of natural or represented entities as background against which the gestures obtain their meaning. Finally, by having their architectural models of bridges and towers present as they talked, Grade 4-5 students evolved a highly-developed conceptual discourse of static forces that explain strong and stable structures (Roth, 1999a). Students employed gestures during the discursive situation that later showed up, as in our simple machines study (Roth, 1998), in their written representations or while explaining the written explanations. Thus, in the first case, the arrows representing forces in a bridge drawing stood in an iconic relationship to the gestures the same student had employed during a presentation of his bridge project 4 weeks earlier; and the action of moving weights along a lever were iconically represented in the motion that students employed when they explained their written solutions to balance beam problems. In all situations, the gestures which were initially iconic became abstract and symbolic (had sign function). As such, they can then be replaced by words which represent the objects or events independently of the particular context in which they are used.

Research Questions

This early work provided some good starting points for understanding the relationship between activity, gestures, and the emergence of scientific discourse; but these early studies are limited in one key respect. All are concerned with domains that have strong phenomenal components and can be classified in terms of static and dynamic forces and motion phenomena. That is, static and dynamic forces (pushing, pulling), velocity, trajectories, and relationships on the balance beam could be said to constitute prime examples of physical situations that can be expressed by means of gestures. But this is not the case in physics (or chemistry) domains where the content of talk is no longer directly accessible visually such as in atomic physics or acid base reactions. If gestures do provide a link between the phenomenal laboratory activities and conceptual talk even for abstract

concepts, this would legitimate some form of hands-on activities (perhaps in some form of computer modeling) even in areas where students traditionally do not engage in such activities.

We planned the present study to test three clusters of research question that had arisen from our earlier work but in a domain that has conceptual components not easily accessible: micro-physical explanations of static electricity. Our initial questions which brought about and guided our research were:

1. What is the function of gestures in students' science talk? What are the relationships between gestures and the material activities students conduct?
2. What conceptual content is expressed by the gestures that accompany students' talk about electrostatics? How is this conceptual content expressed by means of gestures?
3. What is the temporal relationship between gestures and scientific discourse about the topic of electrostatics? Does this temporal relationship depending on students' familiarity with the entities?

Method

This study of the relationship of students' laboratory activities, gestures, and scientific discourse was conducted in a previously established data base, but with a set of research questions and hypotheses developed in a different context (age group, culture, language). Small parts of the entire data base have been the subject of one masters (Smolé, 1997) and two Ph.D. theses (Langensiepen, 1995; Welzel, 1995) unrelated to our research questions about gestures and the related cognitive development. Repeatedly, we drew on a second data base in which the same curriculum was taught to students in a different school and one year older (but same country and region) to test whether various assertions could be disconfirmed in yet another data set.

Research Participants

The data base was established as part of a study on learning in physics classroom. For a period of 6 months, the second author (Welzel) taught a unit on electricity (static electricity, electrical currents) in a Grade 10 physics course at a local academically-streamed high school (Gymnasium). A physics professor (and physics educator) was also present to interact with the students and to construct field notes on what happened in the classroom. There were 12 female and 7 male students in this class. Some observers of the videotapes and participant observation suggested that the male students may have achieved better understandings of the concepts. However, a test comparing the achievements of male versus female students in this unit on the basis of the tests and exams as simultaneous dependent measures (MANOVA) showed that there were no gender differences in the achievement as a result of this unit. This was confirmed in our qualitative assessment of the post unit interviews concerned with conceptual understandings.

The students worked in self-selected groups and according to their own seat preferences. As it happened, there was one male (4 students) and one female group (4 students) at the tables where the cameras had been focused. The students at these sites agreed to participate and therefore became the main research participants. (Written tests and examinations were available from all students. Similarly, contributions of other students to video-taped whole-class conversations were transcribed and available for analysis.)

Curriculum

For the purposes of the second author's Ph.D. research project (Welzel, 1995), all parts of her stay at the school were videotaped. For the present analysis, we used the entire 10-week unit on electrostatics. Physics was taught during two 45-minute lessons per week scheduled as one block. (In this type of German schools students are taught physics, chemistry, and biology separately, because teachers normally teach only the 2 subjects in which they took masters level subject matter course work as part of their teacher preparation. In grade 10, students therefore attend 6 lessons of science per week.)

During the 10 weeks, the (planned) curriculum contained the following topics: charging of objects by means of rubbing (which increases the contact between the materials and therefore the exchange of electrons), transfer of charges, and induction and grounding; electrostatic induction; electrical potential; capacitor and the effect of distance between plates on voltage. Throughout the course, students conducted investigations including transparency films, metal plates, pieces of wool and cotton cloth, small neon glow lamps, electroscopes, styrofoam plates and tiny spheres, and (plastic, metal, PVC) rods. Students were invited to plan and execute investigations of their own interest, but instructions for ready-made investigations were also available for those students who felt more at ease with specific instructions. Students kept notes throughout their investigations and reported back results in two forms. First, there were regularly scheduled whole-class sessions where the different groups talked about what they had done and found out. Second, students wrote more formal reports in a format provided to them.

[Insert Figure 1 about here]

The main conceptual elements of the unit relevant to the present discussions are outlined in Figure 1. We conducted elsewhere a detailed analysis of the systems involved in this unit and the cognitive complexities the multiple phenomenal and conceptual domains constitute (Roth & Welzel, in preparation). For the present purposes, it shall suffice to point out that there are both phenomenal and conceptual issues. On the phenomenal level, materials and instruments such as the electroscope can be experienced by the student; it is made of stuff (metal and plastic insulation). The electroscope can be understood as a mechanical system (conceptual ontology). As such it consists of a fixed part (ring, central suspension) and a pointer suspended from the central part. Electrically, the system also consists of two parts, but the part-whole relation is different than that of the mechanical perspective. The entire central section suspension and pointer are electrically connected (Figure 1). A plastic insulator separates this part from the outer ring and base which are also connected electrically. A final conceptual level involved is the microscopic explanation of electrical phenomena in terms of electrons. Electrical phenomena can be understood in terms of a liquid model as used, for example by electricians, which does not require electrons. We kept these two levels of description separate not in the least because they appeared differently in students' talk.

Data Construction

The entire unit was videotaped using two fixed cameras that focused on one group each, yielding a total of 30 hours of video-taped materials (2 cameras x 20 lessons/camera x 1 hour/lesson). Two microphones recorded the conversations around each of the two tables. The videotapes were transcribed also containing descriptions of the actions in which students engaged. The first author spent approximately 350 hours viewing the data base, digitizing all situations in which students or teachers used gestures, manipulated the sound track to improve audibility and transcription. (The second author, as the teacher in the study, already knew the data set.) These transcriptions were then transformed to contain images and time codes. He prepared visual representations of the episodes (as they are used throughout this article) and the initial analyses.

Students were formally tested at three points in the unit, after Lesson 8 (week 4), Lesson 20 (week 10), and Lesson 30 (week 15). These tests were copied and entered in our data base. They served to assessing students' understanding and for conducting statistical analyses.

The eight students featured on the videotapes were interviewed prior and after the unit. These interviews were transcribed and analyzed in terms of student understanding of concepts in static electricity. Furthermore, all instances where students used gestures as part of their communication were digitized to make them available for frame-by-frame analysis. The respective part of the sound track and transcript were also prepared as previously.

Analysis of Gestures

From a total of 15 video tapes of 90 minutes each (the sound quality impeded with the analysis of the other 5 tapes), we selected all those situations in which students (and teachers) used gestures and digitized the sequences (from about 20 to 120 seconds in length) to make them available to frame-by-frame analysis. Furthermore, all student activities represented on the video were

translated into a pictorial representation so that we had an easily accessible data base of the actions in which students had engaged. We isolated in this way approximately 100 episodes.

The sound track of each sequence was enhanced using Ulead® MediaStudio Pro 5.2 such as to improve the audibility and comprehensibility of the utterances. The computer program also afforded a visual representation of volume so that the onset of each speech act was easily identified as it normally corresponds to a rapid vertical increase to a peak that stands above the noise (e.g., Figure 8). Finally, the computer program allowed the timing of the onset of individual utterances to an accuracy of 0.001 seconds. These timing measures were coordinated with the visual frames which are refreshed every 40 milliseconds (frame rate is 25 images per second).

Our analysis is grounded in hermeneutic phenomenology which insists on two issues central to the present research (Ricœur, 1991). First, a researcher's interpretation of human action and its setting requires both explanation-seeking structural analysis and understanding-seeking lived experience. Second, human actions are subject to the same analytic processes as text; that is, hermeneutic phenomenological analysis is extended to ephemeral actions capture here on video-tapes.

Following the precepts of Interaction Analysis (Jordan & Henderson, 1995), we then met repeatedly to view the video clips and to discuss our emergent assertions. These assertions were tested in the entire set of episodes. We also presented our initial conceptualizations to different groups of colleagues and graduate students at the University of Bremen and at the Hanse Institute of Advanced Studies. We used our interactions with others during the presentations and discussions to validate our readings of episodes, gestures, and students' utterances. We particularly conferred with the physics professor who had participated in the lessons as an observer and incidental teacher to make sure that our interpretations were viable.

Gestures, Situations, and the Construction of Complex Explanations

In this section, we present our research findings in terms of three assertions which we support with episodes from our data base. The three assertions related to our preplanned research questions are:

1. *Gestures allow students to construct complex explanations even in the absence of scientific language. In this, gestures serve to represent aspects of the communicative content or to point to entities in the world that represent themselves.*
2. *Gestures allow the coordination of phenomenal and conceptual layers of content. The phenomenal layer (entities, actions) provide the basis on which conceptual layers can be added, but indexical and iconic gestures provide the "glue" for this layering to be successful.*
3. *The time for the situated construction of an explanation decreases and speech increasingly takes over the representational function. (a) There is a decrease in the temporal decalage between gesture and equivalent verbal representation of content; or (b) long pauses with gesture and utterance overlapping.*

In the following sections, we present case studies to elaborate each assertion. However, as this is a naturalistic study rather than a laboratory study it makes little sense to attempt generalization of frequency of occurrence in two groups to the generality of gesture use. Our analysis of the gesture talk relations are general in the sense that they the structures (a) confirm similar patterns observed in an entirely different data base and (b) that the structure was confirmed in several random checks in a second data base on learning electrostatics in a Grade 11 class in the same German city at a similar academically-oriented school. We have sufficient data to substitute the examples several times over with other examples. We chose the specific ones because they are particularly well-suited for the didactic function that any research article has in communicating a novel research area to colleagues.

Situated Sequential Construction of Complex Arguments

Assertion 1: Gestures allow students to construct complex explanations even in the absence of scientific language. In this, gestures serve to represent aspects of the communicative content or to point to entities in the world that represent themselves.

With these case studies, we illustrate (a) how gestures allow students to coordinate objects and events at multiple phenomenal levels and (b) that, once the students have coordinated and situationally produced an explanation, it can be shifted into the discursive domain during subsequent productions which, in addition, can also be assembled quicker.

Case Study 1: Constructing the Water Current Experiment

In our first situation, Jessica constructs a proposal for an experiment which can be expressed thus: a small water current running from a tap is to be deflected by an electrically charged transparency film. Whereas our statement appears trivial, it is in fact a dense statement of physical phenomena (objects, events) that are produced by means of human actions, and explanations. When Jessica first attempts to propose the experiment, she does not have available the discursive resources to produce a statement of that type, even in terms of a series of statements.

[Insert Figure 2 about here]

What we observe is that by means of gestures that make use of the materials at hand, and before the background of other materials not used, a student constructed new descriptions and explanations. Our representation of Jessica's proposal unpacks the different levels of things and actions represented and how these are coordinated in time. On the top of each "line," we present the utterances and the gestures of each hand as these are available to her peers and the analyst (cf. Figure 2). Below that we represent the phenomenal levels of the water current, transparency film, and the actions by the experimenter. Both water current and transparency film are also causal agents, that is, they can have effects on the world. These effects are presented on the respective "event" lines. Our representation of the episode shows how different aspects of Jessica's presentation make salient different entities (water current, transparency film, movement of each, action) and this in different ways (verbal [v], iconic [i], deictic [d], self [s]).

Initially, Jessica merely produces a charged transparency film by rubbing. Throughout her presentation, this transparency then stands for itself and in the state that her initial action had put it in. Jessica does not verbally refer to it as a charged film throughout her presentation; but she unmistakably (to all participants in the situation) uses it as a charged film in her gestures that enact the demonstration.

Jessica then suggests that the prepared transparency film is to be brought next to the water current. During the first time she utters this statement, she still rubs the film. However, she then repeats the statement that was accompanied by the film held in the air with her left hand while the right hand appeared next to it as she utters "water tap" ("Wasserhahn"). Our representation makes clear that there are more elements thematized in the second line than in the first (Figure 2). In this second line, she suggests that the water current can be pulled with the (charged) film. Her left hand moves the film away from the right (water) hand (Figure 3.a).

[Insert Figure 3 about here]

At this point then, it may still be unclear what exactly happens to the water. As Figure 3.b shows, the right hand then moves away from the film and upward into a vertical position as if indicating the (inverse) water flow. Thus, not only water but also its flow are thematized by the right hand, increasing the number of elements present. In the final stage, then, Jessica begins her description again by thematizing water, its downward flow, the movement of the charged film, and the action of pulling (Figure 2, line 3; Figure 3.c). The charging does not have to be rethematized for this is already silently at hand in the film that stands for itself. That is, although our representation merely shows the film, it is actually a film that has already been prepared and therefore represents (qua sign) a more complex situation than the film by itself.

There are therefore four parts to the entire episode, the first referring to the preparation of a charged transparency (not represented here) and three parts in which the experiment is constructed. In the first part, the left hand enacts the movement of the transparency film whereas the hand representing water stays still (Figure 2.a). In the second part, the water hand gestures the lateral and vertical directions in which the water moves (Figure 2.b), although in the reverse way in both instances. It is then in the third part that Jessica coordinates the two movements, assembling the results of her earlier cognitive action. The water current moves vertically down and, as a result of the movement of the charged film, is deflected sideward (Figure 2.c).

An inspection of the three lines of transcript gives evidence for the increasing complexity of the situation presented. The assembly, having occurred a first time, was assembled in real time taking about 19 seconds. Jessica subsequently provides another description of this proposal after group mate absent during the first presentation had returned to the table. In this new presentation, the number of gestures dramatically decreases, more of the situation changes modality and is represented in discourse (rather than gesture), and the total time of the explanation decreases to about 11 seconds. For example, at this time she only gestures the movement of the film and subsequently briefly indicates the vertical downward motion of the water current. That is, more of the description of what she wants the group to investigate moves into the discursive presentation. This then makes the gestures coincidental when they appear, presenting redundant information, perhaps making the gestures ultimately unnecessary (which is what Crowder [1996] found). But the important thing to retain is that after she assembles the description to a coherent whole, while drawing on the materials present and gestures, these resources obtain a lesser importance to subsequent presentations when more and more of the ideas are represented in the discursive domain.

Case Study 2: Constructing an Atomic Explanation of Contact Electricity

In this episode which occurs toward the end of Lesson 2, the teacher asks the group of young women to explain static electricity. At this point, students have spent nearly two lessons investigating charging of materials. In her presentation, Jessica draws on gestures and objects she picks up to instantiate an explanation (Figure 4). First, she picks up a pen to stand for the transparency film (Figure 4.a.left). She then raises her right hand to gesture rubbing the “transparency film” with her index finger standing for “atomic shell” (Figure 4.a.center), but then picks up another pen to stand in for the “atomic shell” (Figure 4.a.right). In the final part of the episode, Jessica points out clearly that there are negative charges on the material represented by the right hand pen (Figure 4.b.left). By means of a sweeping gesture away from the current focal area coinciding with her utterance of “positive charge” (Figure 4.b.right) she unambiguously communicates the electric status of the material represented by the pen cap in her left hand.

[Insert Figure 4 about here]

In this excerpt, Jessica explains the relationship between the text that they have just read and the investigations that they have completed during the previous and the present lesson. (Dropped are the back and forth about who is to explain.) Thus, at first, Jessica raises her left hand indicating that it stands for the plastic film. This is a direct link to the investigations during which they extensively rubbed films. In the following sequence, she presents the atomic shell. Given that her hands are, at this point, next to each other (see first frame), it would not have been clear which hand coordinates with the atomic shell. Here, her right arm and hand move up and return. This gesture (length 18 frames or 720 ms) coinciding with uttering the word atomic shell thus coordinates hand and corresponding utterance. Here, the student is marking the hand that is to represent the atomic shell. The hand beats the tact, shows others where and how to coordinate gesture and talk. The hand is moving as she pronounces the word, so that the word and hand come to stand one for the other.

In the next video frames, she then indicates how the film is rubbed at the atomic shell in the other material. However, there is an gap as she co-presents objects from two worlds, an epistemic and a phenomenal. The atoms, their shells, electrons, and positive and negative charges are not what they experienced during the investigations. Rather, their experience involved materials. Thus, it does not appear surprising to see a second gesture in which she picks up a pen that—though this is not made

explicit—that stands for the rods that they had also used extensively. The following line re-enacts the rubbing. Here, then, we have a coming together of elements from two categories, a phenomenal that is re-enacted in the gestures, and a discursive world that has to be coordinated with the other world, because it is said to explain the first.

From an experiential perspective, the gestures have a direct relation to the earlier investigations. Additional objects (e.g., pens) are used to bring in further distinctions and re-presentations). The rubbing is re-enacted and therefore links directly to the sensori-motor experiences. In the absence of the actual material, Jessica seeks recourse to other materials that stand in for the original equipment. Recall that when the actual materials were present, students actually picked up these materials and used them in their gestures. Here, the original materials are replaced by other materials, in this case the pens that they had available in front of them. One might ask why film was not re-presented in the form of a sheet. This might have been done with a piece of paper. On the other hand, the materials themselves, the PVC and other plastics find, of course, their re-presentation in the plastic material of the pen which they did hold. Furthermore, in some instances, they did in fact rub two rods such as the PVC and clear plastic ones.

So at this point, Jessica rubbed the two materials. In the next two frames, she then talks about the consequences of this rubbing. Here she shifts into the explanatory mode, and at the same time, from the phenomenal to the discursive domain. In this discursive domain, there are electrical charges, positive and negative ones. At the same time, Jessica explains that these are separated in and after the rubbing. She therefore, in the following frames, separates the effect both discursively—negative and positive charges—and in gestural space by locating one set of charges (negative) in front of her on the table, the other one at a substantial distance (see left hand motion in Figure 4). In both cases, additional emphases are used to coordinate the discourse with the utterance. This emphasizes the distinction and difference between the two types of charges. The separation that is such a crucial aspect of the phenomenon comes out of this explanatory demonstration very clearly.

Section Discussion

In these episodes, we see that gestures play a central role in the representation of that which is to be communicated. However, equally important is the role of the objects at hand which are used to represent themselves (Case Study 1) or objects that are used to represent other objects and materials (Case Study 2). Sometimes a body part takes such representational function. Thus, in the first case study, Jessica's right hand instantiated the water first in symbolic form (hand with palm sideways thereby emphasizing vertical dimension) then in iconic form with hand following the trajectory that an actual water current would follow. We also intimated that such gesturing and use of materials decreased as students became more familiar with the things they talked about (Case Study 1). Thus, it is apparent that the gestures take on the function of representing entities talked about especially in the early stages of learning. Furthermore, objects also take part in the representing and gesturing process.

Hints to lead us toward an understanding the importance of gestures and objects come from domains unrelated to linguistic research on gestures. First, cognitive scientific research on games and everyday activities such as cooking shows that cognition becomes more efficient and faster if part of it is unloaded onto the environment (e.g., Agre & Horswill, 1997; Kirsh, 1995); that is, when aspects of memory and representation are left outside the human agent and are used whenever they are necessary. Second, the brain itself uses indexes (pointers) to keep track of things in the environment which essentially stand for themselves or, in turn, point to some other thing (Ballard et al., 1997). These indexes are much more space saving and therefore allow people to enact more complex cognition than if they were to build a complete mental representation of the situation and its explanation. As students become familiar with the new constructions, they enact them more rapidly leading (a) to faster overall performance and (b) to smaller lag between gesture and the associated lexical item. We return to present further evidence for and discussion of the temporal aspect of the gesture-speech relation in the third subsection.

Coordination of Multiple Conceptual Dimensions

Assertion: Gestures not only serve to coordinate phenomenal entities as in Case Studies 1 and 2, but more importantly, to enact and coordinate conceptual entities together with, and over and about the phenomenal entities. Gestures allow the coordination of phenomenal and conceptual layers of content. The phenomenal layer (entities, actions) provide the basis on which conceptual layers can be added, but indexical and iconic gestures provide the “glue” for this layering to be successful.

Case Study 3: Phil Explains Induction

In this episode, Phil constructs a first explanation of the phenomenon of induction on the electroscope. In his explanation, he approaches a charged transparency film to the top plate of the electroscope which thereby attracts as many electrons as possible to the top of the electroscope. As a result, the pointer deflects. However, he proposes that in the process, the charges come to balance on the transparency film, but there is an over-concentration of charges on the top of the electroscope which are (because of the balancing on the sheet) pulled back onto the central part of the needle suspension.

We again represent utterances and gestures on the one hand, and the contents of the presentation on the other (see Figure 5). In this presentation, besides the transparency film and the electroscope as phenomenal (material) objects which represent themselves ([s]), there exists an additional layer in the explanation concerned with entities and events at the atomic level. We therefore include in our representation these new layers in which the electrons in both the electroscope and film are thematized. The film has been charged earlier and therefore stands for itself as well as for the electrons which, represent themselves qua objectified conceptual entities. The electrons on the electroscope do not come into play until that moment where Phil points with his right hand to the pointer and its suspension ([d]) and then moves his index finger upward, thereby instantiating the movement of the electrons ([i]) discursively thematized ([v]) only later in the utterance. Because Phil holds the film above the electroscope in the same way he had done earlier when he actually conducted the investigation, the action represents itself in addition to being indicated verbally (“put . . . onto”).

[Insert Figure 5 about here]

In the excerpt represented here, Phil initially refers to the charging of the transparency which is then brought near the electroscope. The utterance “you put here something onto” is somewhat ambiguous because it could refer to the charging of the transparency or to the fact that the charged film is held on top of the electroscope. His left hand, which has been resting in his lap below the table moves up points to the needle and continues upward to end at the film which is the current topic of talk. He changes the position of his left hand pointing when he reiterated that the part which pulls is the film. The upward movement of the left hand along the suspension gestures the motion of the electrons which are attracted to the top of the electroscope. This movement is indicated long before Phil actually verbalizes this conceptual content (2.69 s).

Figure 5 shows how the explanation is assembled and how it layers objects in the world, phenomenal descriptions, and conceptual entities. As Phil holds the film above the electroscope, these two, as material entities, represent themselves (s) and do not have to be thematized, they “go without saying.” They constitute a stable background available to all participants. Furthermore, the electroscope is also charged (deflected needle) a fact that is available to those present and does not have to be thematized. In the same way, the film has been previously charged, a fact that does not have to be further thematized but is understood as such by the participants in the conversation. With this in the background and available to all, Phil’s construction of an explanation can run its course. He presents the electrons and their movement in deictic and iconic gestures and by discursive means. The electrons are evoked as something physical (pointed to, something that moves); this evocation occurs against the electroscope and film which constitute the ground to the presentation. The conceptual entity is therefore associated with the phenomenal ground, and therefore attributed to it as a constitutive element. Thus, although electrons are never phenomenally available, they

become entities that reasonably account for the phenomena at hand, and therefore acquire the characteristic of something “real.”

One can see, for example, that Phil thematizes the movement of the electrons before he actually refers to them in the process of pointing to the film that is approached to the electroscope. Because he approaches the film while uttering “you are packing something onto here” (“man packt ja hier was rauf”), approaching is both thematized, and a gesture which is also part of the actual experiment and therefore represents itself. Figure 5 shows that the movement of the electrons upward in the electroscope is made available in the gesture that demonstrably moves up on the suspension before ending in pointing to the film that is charged (“ungleiches Verhältnis”), but is not made available by verbal means.

Our way of representing the explanation embodies the metaphor of layering which occurs and which we have used in an analogous way to understand why it is easier to learn Newtonian mechanics from computer microworlds that make phenomenal and conceptual issues copresent by drawing both objects and the physical concepts onto the same screen (Roth, Woszczyna, & Smith, 1996). Here, the objects are present and serve as background against which the phenomena are enacted, that is, as figure against the ground. Gestures enact part of the experiment (e.g., rubbing the film, approaching the film) or the resulting events on the physical level (Phil deflects the pointer, moves it into a new position with less deflection) or microscopic conceptual level (gestures movement of electrons in the central part of the electroscope). He also uses deictic gestures as a way to point to that entity that he currently talks about “**here** you produce something unequal,” “now **this part** is pulling,” “then **it here** deflects,” “at a certain point, **that one here**,” “but **here** it is,” and “so **it** is attracting again.”¹ Of course, this layering is not unlike constructing a multimodal presentation in other domains such as mathematics that include gestures, pictures, signs, and words (e.g., Lemke, in press).

Case Study 4: Teacher Explains Dis/Charging of Double Plate

Teachers, too, use gestures as part of their explanations and interactions with students. In part, these gestures are the same ones found again in the explanations of students. The present episode is part of an explanation in which the teacher Stefan attempts to help students understand why the neon lamp was glowing on opposite sides (different charges) when they tested the separated plates after they have been charged by the process of “induction and separation.”

This is a difficult process for students to learn initially, for the movements have to be coordinated appropriately in time and space. (Even the grade 11 students in the reference data set experience difficulties in producing the phenomenon and explaining it.) The process involves the following steps. Two plates are placed so that they touch each other. A charged object is brought close to one of the two plates. They are then separated. Finally, the charged object is removed again. According to the scientific explanation, charges opposite to those on the charged objects are attracted near the latter leading to an unequal distribution of charges on the two plates. When they are separated, the unequal distribution is “locked in” and therefore remains when the charged object is removed again. The teacher Stefan explains:

In this situation, there are too many electrons on one side, too few on the other. The electrons have to go in one direction onto the other side. And when you discharge them individually, when you discharge it individually, then there are here for example too many electrons that have to leave. And how is it here? So they have to go there this way. Here they have to leave this way. Here they have to get to thus.

Our representation of the last part of the episode (Figure 6) shows how conceptual layers are enacted by drawing on gestures both as part of the explanation and against a stable phenomenal ground. Because the conversation is about the plates as being charged by a process, both represent

¹ The original German expressions uttered by the students are: “man macht ja **hier** ein ungleiches...,” “man packt ja **hier** was rauf,” “nun zieht **das Teil**. . .,” “dann schlägt **der hier**. . .,” “am bestimmten Zeitpunkt hat **der hier**. . .,” “und **hier** ist aber. . .,” and “also zieht **er** jetzt wieder an.”

themselves qua charged objects. This charge which is phenomenally available by means of a test, the neon bulb which glows at different ends when brought to each plate separately, is explained by drawing on entities not phenomenally available: electrons. The gestures of the hand moving from the plate toward the ground and from the ground toward the right plate confers a material quality to these entities. In this, the gestures are metaphorical. But the gestures also have iconic quality in instantiating something like a trajectory, if not for the electrons, so for the electrical current said to move to or from the plate from and to the ground and in the process, making the lamp glow.

Our depiction of the episode makes it evident that there is much more communicated in the entire presentation than what is being verbalized. There are several lines in Figure 6 that are present (represent themselves) even when they are not referred to in talk or gesture. Those entities evidently available to everyone in the situation are in most cases not enunciated with their lexical affiliate but pointed to or made salient through a gesture that enacts some conceptual content against it.

[Insert Figure 6 about here]

In this example, Stefan actually layers three explanations—possibly misleading students to misconceptions on the students' part: plates qua object which are grounded by means of the gestured process with the (here, the plates are present, but the lamp is not used as resource in the explanation) and the ground also salient in the gesture which is brought far underneath the table surface. Second, there is talk about electrons that are moving from one plate toward the ground, or from the ground to the other plate. Finally, there is an electrical picture of “stuff” flowing from or to plates. The gestures appear to suggest that the electrons are, qua objects, actually moving from the plate and onto the ground, each electron that is removed making the entire journey. Though in the physicists' explanation, it is more like a fixed fluid which as a whole moves a bit until charge equilibrium is reached.

Section Discussion

In this section, we showed how conceptual talk and gestures embodying conceptual entities are layered on top of a world phenomenally available to all those present in the interaction. Our way of representing the presentation keeps track of those things not evoked in the utterances, but are present to the participants. Furthermore, the gestures enact actions that have occurred as part of the investigation and thereby represent themselves, and they render salient aspects of the devices when they emerge from the ground because of the topological similarity. Thus, when Phil points to the suspension of the pointer and then moves his hand upward toward the transparency, he gestures the movement of the electrons *and* highlights the needle suspension itself.

Electrons are considered here as entities of a conceptual layer. Yet both Stefan and Phil attribute to them material quality in pointing, using a hand, moving their hands along imaginary trajectories which these conceptual entities take. In this, these conceptual entities obtain material qualities. These, when layered against the phenomenally available world, are said to explain what everyone can see, although the conceptual entities are never seen. This layering is more complex with the things present, and because of the gesture, than these students could do with words alone. In the latter case, the demands on the memory capacities would be tremendous, whereas in the former case, a lot of representing goes on in different modalities (talk, gesture, objects). Our way of representing the presentation in multiple layers and gestures makes salient all those aspects of communicative acts that are not available when only words are transcribed. At the same time, our way of representing shows that cognition in communication is more complex than uttering and attending to words and propositional statements more general.

Decreasing Decalage between Gesture and Talk

Assertion: The time for the situated construction of an explanation decreases and speech increasingly takes over the representational function. (a) There is a decrease in the temporal decalage between gesture and equivalent verbal representation of content; or (b) long pauses with gesture and utterance overlapping.

We have already shown that Jessica's proposal for an experiment is enacted more quickly and with less gestures when she repeats it for the benefit of another student. Our data base shows this as a general trend. As students become more familiar with the explanations, the initially existing *decalage* between gestures and talk decreases. (Piaget used the notion of "decalage" to describe that the various abilities to enact conservation do not emerge at the same time in children's cognitive development.) Furthermore, the amount of gesturing also decreases in the presence of materials. (Perhaps because the discourse participants are so familiar that they know what the other is talking about?)

Case Study 5: Phil explains Induction

In Phil's case explaining how induction works on the electroscope, the action verbs and nouns follow significantly (400 ms to 1440 ms) the corresponding gesture. Figure 7 shows two situations from an explanation Phil was asked to give in front of the class for the phenomenon of induction on the electroscope. The two examples show different duration. In both instances, the gesture *appears* to "jog" the production of the corresponding lexical item.

[Insert Figure 7 about here]

During the posttest interview, Phil is asked to explain the attraction of small styrofoam balls to a charged PVC rod. Phil uses the materials to enact the investigation. In the subsequent explanation, he also uses gestures. These gestures are coordinated with the talk such that they fall within 40 milliseconds (the frame rate) of the corresponding lexical item. Thus, in situations that correspond to those represented in Figure 7, his discourse and gestures coincide thereby contrasting his first explanation of induction on the electroscope. In the latter case, there are clear instances of *decalage*. In his case, the lexical items temporally follow the corresponding gestures.

Rather than thinking in terms of gestures that jog the production of lexical items, it may be more appropriate to understand the phenomenon in terms of the topological similarity of the iconic gestures with the content and the translation (and search) required to find lexical items in memory which, because of the arbitrariness of signs (language) and their referents (things in the world), may take longer. This then makes it plausible that with increasing familiarity, lexical items are produced more and more rapidly, coincide in increasing ways with the gestures. Later, because of the economy and context independence of words, and because of the traditional forms of written forms of testing, they become increasingly important to the expressive competence.

Case Study 6: Inga Explains the Roller Blind

In this episode, the teacher guides students personified by Inga with whom she conducts the exchange, through the phenomenon: When the rolling capacitor is charged, the connected electroscope deflects. (The capacitor is built by mounting a long section of aluminum foil onto the mechanism of a rolling blind thereby creating a capacitor in which the charge density can be changed by allowing the foil to wind up.) When the capacitor is rolled back, the electroscope deflects even more. The teacher then asks students to explain, and because no one else indicates willingness to contribute, Inga is called upon again (Figure 8).

[Insert Figure 8 about here]

In this case, long pauses are followed by the coinciding word and gesture of the same meaning. In the entire 90-second episode covering the responses to the two teacher questions (describing what happened, explaining what happened), Inga uses a total of 18 gestures (2 beats, 1 deictic, and 15 iconic). Only one of these gestures is ahead of the word corresponding to it. (In other episodes, Inga's gestures follow the same pattern that gestures and words coincide.) Here, the rolling expressed by her hand precedes the word "rolling up" by 2.12 s. In the second case where she explains that the charges are concentrated when the blind is rolled up, the gesture for "rolling" coincides exactly with the word.

In cases represented by Inga, there may be long pauses and drawn out preceding words until the subsequent gesture and concept word are expressed simultaneously. There is a drawn-out “so” followed by a pause which together take 680 milliseconds before the onset of the word “distributed” (“verteilt”) falls together with the onset of the swiping gesture away from the body that is read as a gestural instantiation of “distributed.” There are two instances of very long latencies between the moment that the end of a meaning unit should fall and the moment it actually falls. The latencies are 2007 and 2220 ms.

In Figure 8, we see the deictic gesture to the electroscope standing in front of the classroom next to the teacher; (b) the iconic gesture to express concentrated (the German word “geballt” evokes the making of balls, for example, snow balls. Inga’s gesture embodies the movements required to make a snow ball); and (c) the iconic gesture to express the distribution of something (here the charges). In this particular instance, the materials and material set up that Inga talks about is not next to her. She is therefore, compared to all the other situations presented in this article “handicapped” for she has to do additional work to represent in word and gesture what she wants to express. Her gestures do not coincide topologically with the devices and materials. Rather, as we can see in Figure 8, the word “concentrated” (“geballt”) can be said to have metaphoric dimensions and the direction of the movement related to the rolling of the blind. In contrast, Phil’s gesture is enacted over and about the electroscope maintained the topology of the worldly and corresponding conceptual domains (e.g., up down are maintained for the motion of transparency and electrons).

Section Discussion

In this section, we described the temporal decalage between gesture and speech which occurs when students first attempt to describe and explain phenomena in a new domain. Our data show that this decalage decreases over time until the gestures and corresponding lexical items overlap. At the same time, as we showed in the first subsection (Jessica and her water tap experiment), the overall time for constructing an explanation decreased over time as speech encoded more and more of the information communicated with decreasing reliance on the materials and on gestures.

Discussion

This study shows how gestures may arise from laboratory activities and, because they are used to signify, have a transitional function which links activity to discourse in a rather continuous way. In addition, we show how the materials and equipment have a representational function that carry information for the listeners which is not communicated in the verbal modality. Thus, if our findings are confirmed in further studies that gestures have a bridging function between hands-on activity and language, laboratory work takes on new significance in the work of science educators. In the following, we discuss our work in greater detail and subsequently project possible implications and extensions of the new area of research we presented here.

We can understand the entities present in the laboratory context as a stable background which does not have to be represented in talk. Deictic gestures and verbal deictic expressions can pick them out whenever necessary. Iconic gestures, or gestures that are part of the action that would be conducted in the “real” situation animate the situation but do not have to be represented in talk. They run and go without saying, visibly available to all. Against these elements as a stable ground, the conceptual level explanation can take shape. However, the conceptual level events also have to accompany that which happens in the phenomenal world so that coordination work has to be conducted. Gestures and deictic expression allow this coordination across multiple levels that is, as our Figures 1 and 3 show, multiple phenomenal and conceptual entities and their causes and effects.

Figure and Ground: Gesture, Talk, and Being-in-the-lab

Gestures are intimately tied to having a body that integrates our experiences in the world. The gestural aspects of cognition cannot be understood other than by means of the connection of cognition to perception and action. It is in this connection to experience that gestures provide a link

between students' laboratory activities and the (abstract) scientific discourses that they learn to converse about the objects and events encountered in the science classroom.

For one, the phenomenally available objects and events do not have to be expressed in language, an abstract system of representation which does not have to share properties (structure, topology, sound) with the things it refers to. Rather, these entities can simply be referenced by pointing to them (deictic gestures) whenever they are needed in the communication. The utterance then uses deictic words such as "this," "that," or "it" accompanied by some gesture to index what it is that is being talked about. Similarly, our participants indicated events such as the movement of pointers, the trajectories of electric currents, or the actions that accompany some investigation by means of iconic gestures and utterances of the type "you do this," "it moves this way," or "they have to go this way." In both type of gestures, the gestures "ground" the indexical verbal tokens to the things in the world which can be said to represent themselves. These observations are supported by recent theoretical developments according to which important aspects of cognition are modeled not in terms of concepts that are stored in memory (Ballard, Hayhoe, Pook, & Rao, 1997); rather, these new theories—that merge the best of situated cognition approaches with those of traditional approaches to cognition—use pointers (indexes) which allow the human agents to keep track of things in the world and then to find them when they are necessary for continuing in the current activity (problem, conversational contribution, etc.). Thus, when our students rub some transparency film or charged a metal plate, these objects with their properties do not need to be stored in memory. These objects represent themselves and only some system of pointers needs to keep track of them. In a similar way, these entities do not need to be referenced in speech. Rather, gestures pick them out of the things in the world to which the conversation participants have shared access. This works in conversation because of the well-known phenomenon that human communicators do not express what they assume that is shared with the others. That which goes without saying is not expressed in words.

This discussion of cognitive load is important, for the representational function of gesture and the objects in the world allow participants to enact more complex cognition because these other modalities take on what would otherwise be information to be attended to during the construction of an explanation. In the light of neo-Piagetian analyses that related task complexity to the availability of short term memory (e.g., Case, 1985; Roth, 1990) the current findings are significant. Our work presented here allows us to suggest that when students have opportunities to draw on additional representational modalities, they can construct more complex explanation that would be predicted for purely verbal tasks on the basis of their short term memory availability.

Of course, there is the potential for communicative trouble because not everyone has kept track of the same things in the world, or cuts the world in the same way. But in this case, the conversation participants will engage in conversational repair as soon as they discover the trouble. Against the background of the world as it exists and has been constituted as setting of the conversation, the participants can enact iconic and iconic-metaphoric gestures in which conceptual entities are embodied in the way physical entities are. Thus, our participants gestured the motion of electrons or positive and negative charges against the ground constituted by the materials at hand. Some gestures were used to show in which parts (and therefore direction) of the device the electrons were moving in the electroscope.

Our notion of layering was born not in the least because of this nature of discourse as occurring against the background of the items talked about. Thus, talk about electrons occurred with the electroscope both as topic of talk and as phenomenally-available but unthematized background. The electron-based explanation was layered on top of that which was available to all other participants in an interaction, and therefore available to being expressed by means of deictic, iconic, and metaphoric gestures. This layering was especially important for understanding the cognitive complexity involved in understanding the electroscope. Here, the device has to be articulated into a different mechanical and electrical part-whole structures (device is differently articulated mechanically and electrically). However, gestures allowed students (such as Phil, Marcel) to discover and enact these different articulation by drawing on the devices and on gestures as entities that glued the different articulations.

Gestures therefore have a double function. They serve as an additional means for expressing conceptual content or indexing things in the world that represent themselves; language can be thought to piggy-back on the (earlier appearing) gestures. Gestures also serve as a glue for tying together different conceptual levels of the talk about devices at hand.

In informal conversations about their research in school laboratories, science educators often deplore the lack of “conceptual” talk. Our research makes it clear that students’ experiences in the laboratory when it comes to “abstract” entities cannot be to discover these entities. Rather, in our study, the experiences with static electricity provided a phenomenal background against and on top which new discursive layers could be placed. The presence of the materials allowed students to communicate about these before they were able to represent them in discourse, but merely by using gestures to index or enact them. Having experiences in the laboratory and talking about them when they are actually present then affords students to develop new discourse(s). Though students are ultimately responsible for layering these explanations on top of their phenomenal experience, the lexical items themselves are probably best supplied through the teacher or textbook.

Gesture and Genesis of Scientific Discourse

Talking and doing science may be considered to be activities of different logical type. Considered as social practices, however, they are both of the same type. At the practices level, there are no distinctions, for the discursive actions and the practical actions come together in and through the experience of the speaker. They are also mapped into networks of significance in that the phenomenal experience and the discourse mutually co-constitute each other, include each other in networks of significance, co-embed each other.

Because the entities present in the situation or made present again by means of gestures do not require the same load on the cognitive system but stand for themselves, complex explanations can be assembled situationally. It is for that reason that the presence of materials and already completed actions in laboratory experiments are important to the conceptual development of students. It is against these materials as ground (and with these as scaffolds) that the conceptual layers that must be represented in talk or gesture. They are not themselves physically instantiated and available; they cannot stand for themselves. However, gestures can represent these entities or their causes and effects against the background of a materially present world that can also be made to change such as to coordinate micro and macro events.

Our case studies show that the gestures allow students to construct complex explanation through a succession of actions that constitute objects with new properties, or through the coordination of multiple causally connected events. Thus, Jessica draws on gestures to show what she expects to happen when she brings a charged transparency film next to a water running from a tap. (In three attempts, she does not succeed to get this to happen in the way she describes; the water is not deflected.) In the first part of the presentation, she charges a film which, from that point, stands for itself with the property of being charged. In the next section of the episode, she illustrates the movement of the charged film with the water current only indicated by the hand. In the subsequent episode, the film is fixed whereas the right hand enacts the lateral movement and vertical direction of the water current. Only in the final part of the episode are all the movements (water current down, film sideways, water current following). The entire description of an experiment is situationally constructed using gestures (with iconic, deictic, and functions) as the central representative medium.

The experiential ground therefore provides a basis (layer) onto which further layers can be grafted that do not come from the experiential domain but are discursive. In Jessica’s explanation of the water tap experiment (Case Study 1), the presentation in talk and gesture constitute phenomenal objects and events. There are no invented conceptual entities (charges, electrons) that would explain her phenomenon of a water current affected by the charged transparency film just a “raw” phenomenon. Now this presentation occurred during the first lesson when the students were provided with the opportunity to explore electrostatic phenomena and conduct investigations of their own design. Nevertheless, it is on top of such a presentation that we can think the discursive layers

to be grafted. Gestures that enact all or part of the phenomenal ground “to be explained” therefore pull these layers together, they ground the discourse in the phenomenally-accessible world.

Such grafting can be seen in other episode. For example, when the teacher Stefan explains the different (intensity, side) ways a neon lamp lights up when held to a pair of aluminum plates electrically-charged by means of induction and separation, aspects of the phenomenal world necessary in the experiment is present. His presentation—mostly gestures and deictic words—layers an microscopic explanation on top of the event that the students had seen earlier. Cognitively, however, they have to keep the experiment present so that they can understand what Stefan’s presentation is all about.

Here we can also see what the presence of the material does in cognitive terms. They represent themselves such that this aspect of the load does not have to be held in memory. Similar to the pad on which someone scribbles two numbers to be added, and then notes all the intermediate results. Here too, the numbers 35, 17, or the intermediate calculations and results and do not have to be attended to represent themselves on the paper.

$$\begin{array}{ccccccc}
 32 & \rightarrow & 32 & \rightarrow & \overset{I}{32} & \rightarrow & \overset{I}{32} \\
 & & \underline{11} & & \underline{11} & & \underline{11} \\
 & & & & 5 & & 25
 \end{array}$$

All of this is quite complex, however, for there are many layers. Only few entities and processes are salient in the presentation. The others must obtain their properties and then keep them as the presentation continues in time. That is, in Stefan’s presentation, the plates are not just plates but plates that have previously been charged. His explanation does not make sense unless the charges are presumed to exist. If, from a student perspective, the plates represent only themselves, but not the charged plates, the explanation of what is going on is no longer meaningful.

It is interesting that students in their tests and examinations often used drawings as a representative medium to accompany their texts (e.g., Figure 9). These drawings share with the gestures that they are entities that can be pointed to or expressed in terms of their influences and changes in space, and metaphorically, in time. The worldly and dynamic quality of phenomena in the world are more easily represented in the drawings. In a project considering discourse and gestures of Grade 4-5 students learning about static forces through the construction of architectural artifacts, there were a considerable number of instances where students’ drawings expressed what their gestures had enacted earlier in the unit (Roth, 1999a, 1999b).

[Insert Figure 9 about here]

It is in such complex layering that we expect students “to get lost.” For even though the teacher presented enacted the charging process earlier on, unless students treat the plates as charged plates, following the initial presentation, they will not be able to understand the relationship between utterances, gestures, and objects that are enacted. It is only before the particular ground of objects and events build up so far that the presentation gains its sense (because sense arises when things said can be associated with—in semiotic terms, have referents and interpretants—other signs in an existing network of significance).

In this, we have a link between the discursive domain and the phenomenal domain. The experience of rubbing is re-enacted here. But what is not entirely clear is how and why the transition should occur from the rubbing to the charge separation and from there to the hypothesized underlying structure linking positive and negative charges via the atomic model.

Embodiment may be thought to exist in the phenomenal re-enactment, the rubbing. Jessica has a personal phenomenal experience which she re-describes in terms of the discourse. What is in the body is the integration between the phenomenal and discursive experience. The separations that she

enacts are metaphorical distances. As such, the origins of the relations that make these significant are to be sought in the historical development Jessica has undergone.

In all of this gesturing over and about artifacts, these aspects of the world are said to represent themselves. Deictic gestures pick them out from the background and make them (in addition to words) salient against the ground. Iconic gestures pick out salient parts, or re-enact particular sequences. Iconic gestures also exist at the various conceptual levels. Here, too, the iconic gestures provide the glue in layering the conceptual against that which is phenomenally available to the participants. Furthermore, on the metaphoric level, the entities described at the discursive level (abstract) acquire through the connotations of physical entities. Thus, when Stefan moves his hands from the plate to the ground, and from ground to plate, the entities that are the referents of this gestures, are imbued with a physical nature though they are conceptual entities. In this way, electrons and other conceptual entities (forces, ...) are naturalized (domesticated) into the realm of the physical.

A second important feature of our work is the fact that students' discourse increasingly "takes over" and represents what previously represented itself or was represented by gestures. That is, our work suggests that students move into more and more verbal modes of expression as they become familiar with the explanations that they construct with the aid of the materials present and the gestures that run the micro-events against the stable background.

Gestures can be Treacherous

Gestures that embody conceptual entities can, because of their inherently phenomenal, iconic, metaphoric qualities, lead to inferences and images that are not scientific at all. Scientists who already know may adapt their presentations (utterances and gestures) to the requirements of the conversation so that the "essential" aspects are represented "correctly." Thus, when Stefan explains the discharging of the two plates via the neon lamp, he uses a gesture in which the hand moved from the plate to the ground while talking about "them" ("sie"), presumably the notion of electron that becomes the explanans for the charged plate. Now, the gesture apparently indicates something that moves from the plate to the ground. Yet physicists do not model what happens in terms of electrons that move along a trajectory from the plate to the ground. Rather, there is a current from the plate to the ground, but the individual electrons only move a little way along the conducting path metaphorically enacted by the gesture. That is, the gesture can be interpreted—especially by the non-initiate—as saying that each surplus electron on the plate moves all the way to the ground (or vice versa, each electron hole is filled by an electron from the ground). That is, the teacher enacts a model in conflict with the one that is to be developed a few weeks later in the part of the unit on electrical currents. The particle model as enacted here where the electrons move along a conducting path from some source to some sink of electrons is incompatible with the model of current electricity.

On the other hand, a person familiar with the field would read the gesture end points as deictic instantiation of source and sink, and the intermediate part as an instantiation of the topology of the conductor. When asked about the actual movement of the electron, the physicist then draws on the standard model similar to the water pipe where each particle does not have to move along the entire connection, but in the way of the liquid column as a whole. That is, gestures obtain additional interpretive flexibility; when interpreted in words (translated into another signifying medium), there is a greater flexibility than when the semiotic process remains in the same medium (word to word) of the same culture.

Implications

We observed that almost all incidence of gestures occurred when students (and teachers) attempted to produce descriptions and explanations; during the experimental phase in the laboratory, there were no gestures. On the other hand, the gestures often reenacted those actions that constituted part of the investigations (e.g., bringing transparency film close to electroscope). It would therefore be important to enact curriculum such that students have many opportunities to have such experiences

that can later lead to gestures. Furthermore, if gestures are a medium on which language can piggy-back in its development, students should have the opportunity to engage in explanations with all the materials still present to be indexed. These materials should not just be present in the room, but available directly to the person currently attempting to construct an explanation. There exists at least one study that showed that the proximity to the visual representations about which the Grade 6/7 students conversed was related to the complexity and quality of scientific talk about simple machines (Roth, 1996c).

It is common for science educators both in schools and at the university level to have students conduct their experiments and investigations in the laboratory and then have the reports in which students explain the phenomena completed at home. Our research suggests that this might be sub-optimal, for at home, the material environment that gave rise to the observations and data (numbers) are no longer available. If, however, these materials can provide a support during the assembly of first explanations, it would appear of utmost necessity to require students to provide explanations while they are still in the laboratory. This would allow students to construct complex explanations that can later, for example at home while writing up their research, more easily and more quickly be reassembled. Working in the laboratory and constructing first explanations provides a scaffold against which more complex conceptual issues can be layered and coordinated.

Our conceptualization of discourses as constituting different layers that are coordinated with the phenomenal world by means of gestures could be shared with students. Here, then, the phenomenal world is presented as something that can be accessed and described by all conversation participants. On the basis of this shared experience, their theoretical discourses to be negotiated and developed are considered as layers that are to explain the world. In this way, students can more easily understand scientific knowledge not as a system of truth, but simply as one of different possible layers that can be placed over and on top of the phenomenal world. If needed, the theoretical layer is replaced to better account for the phenomenal world. The relationship between the two can be explained to be one of viability rather than of truth.

Despite the evidence that gestures are central to cognition and have their origin in our experience in the world, they have yet to become a topic of research in science education. Our research raises many new and interesting questions about learning in science. To date, there exists research which shows the important role of gestures to learning scientific discourses when students conduct investigations in Newtonian physics (motion, forces), static forces, and static electricity; gestures also play an important role when students discourse over and about visual representations. At this point, science educators do not know the answer to the question, "What the role of gestures might be in domains that are concerned with entities too small (atomic and nuclear theories, chemical processes) or too large (ecological systems, interplanetary processes) to be investigated by students." Furthermore, we may ask "What would appropriate experiences look like that provide a suitable background for developing scientific discourse through piggy-backing on gesture?" and "What are the (differences in) learning pathways when students' gestures occur against the background of computer models versus experiences with real objects?" Finally, if the presence of and access to the entities being talked about is so important, we may ask "How close do students have to be to the things talked about?" and "What are is the ideal size for the things (which represent themselves) being talked about?"

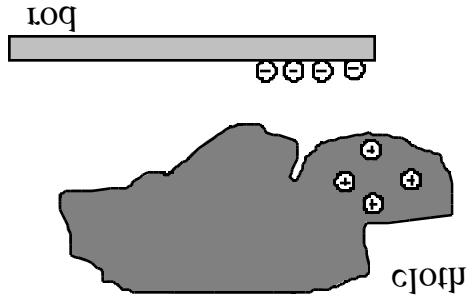
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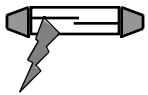
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Key Concepts in Static Electricity Covered in the Unit

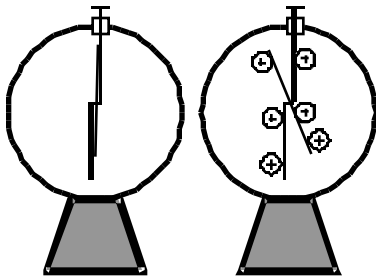


1. Charging objects. Static electricity can be produced by rubbing two objects of the same or different material (transparency film, PVC rod, plastic rod, metal plate, wool cloth [& sweater], cotton cloth [& jeans]). Charging is understood in terms of the following model. By means of rubbing, the materials are brought in very close contact. Here, electrons are accepted by one of the two materials leading to a surplus of electrons but leaving holes (lack of electrons) on the other.

2. Presence of charges. The presence of static electricity can be tested using (a) a ruler or (p) an electroscope

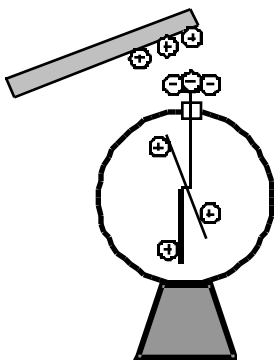


2.a. Ruler. The side on which the ruler glows indicates the location of electron surplus.



2.p. Electroscope. Electroscope uncharged (left) and charged (right)

2.c. Charging of electroscope. An electroscope can be charged by (a) induction and grounding, (p) transfer of charges from an already charged object, or (c) as one of materials as in 1.



2.g. Induction. If a positively charged rod is brought close to the plate of the electroscope, the pointer will deflect. This can be modeled in terms of elementary charges, electrons and holes. The electrons are drawn to the upper part of the electroscope leaving holes on the surface of the bottom part of the suspension. As a mechanical system, the pointer can move freely. As both pointer and suspension are charged in the same way, the former will deflect (until the gravitational restoring force and the electrical repelling force are in equilibrium).

Figure 1. Key concepts to be constructed by students during the unit in as far as they are pertinent to this article.

g'
Presentation
 L: Wann kann's so machen' so: Das haben wir schon mal gemacht. Dann heißt es an den
 You can also do it like this: We have done it before. Then you hold it under
 C: IH [----- holdes FHM ----->
 C: rH [----- rupa FHM ----->
Content
 H₂O: OP! [----->
 H₂O: EL [----->
 FHM: OP! [----->
 FHM: EL [----->
 Action [----->

p'
Presentation
 L: Wasserbahn. Dann heißt es an den Wasserbahn. Und dann kommt du ihn damit wegzubringen
 L: Water tap. Then you hold it to the water tap. And then you can buy it away with it
 C: IH [----- holdes FHM FHM] [-----] [- moves FHM -----]
 C: rH [-----] [-----] [----->
Content
 H₂O: OP! [----->
 H₂O: EL [----->
 FHM: OP! [----->
 FHM: EL [----->
 Action [----->

c'
Presentation
 L: Und geht das Wasser. Und wenn das Wasser so geht Dann geht das Wasser nach da hin
 L: Und the water goes. And when the water goes thus Then the water goes in this way
 C: IH [----- holdes FHM FHM] [-----] [----->
 C: rH [- moves rHward -] [- rH index downward --] [----->
Content
 H₂O: OP! [----->
 H₂O: EL [----->
 FHM: OP! [----->
 FHM: EL [----->
 Action [----->

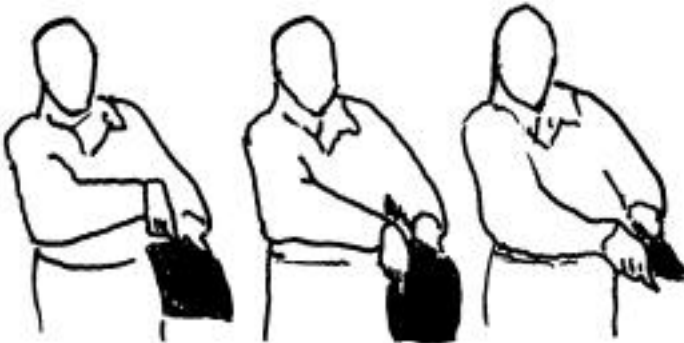
Figure 2. Presentation and content of Jessica's proposal for an experiment. The representation of her presentation contains a verbal and two gestural lines (one for each hand). The content is represented separately for the water current and transparency film. Water current and transparency are thematized as entities or as events (cause, effect). On the bottom line, we represent human agency. Entities are indicated as either deictic (d), iconically (i), or verbally (v) or they represent themselves (s). We can see an increasing complexity of the content represented as the explanation proceeds from a. through c.



a. You can pull it away with this one.



b. And then the water goes like this



c. And when the water goes like this, then the water goes perhaps like this.

Figure 3. By means of a layering of entities and processes, Jessica achieves to construct a complex explanation (c) from simpler components. a. The left hand enacts the motion of the charged transparency whereas the vertically-oriented right hand (water) stays motionless. b. The right hand moves down and away from the transparency, then vertically up thereby indicating the two independent movements of water (though in each case in the reverse direction relative to the transparency). c. Both motions are coordinated and in the proper direction respective to each other. The water current movement is enacted as down, and its deflection by means of a horizontal pendulum like motion.

a. This here is a transparency film (left), and this here is the atomic shell (center). When we now rub them [gets pen] (right)

b. Then a negative charge is created here (left) and we get here a positive charge (right).

Figure 4. Jessica constructs an explanation of macroscopic phenomena (electrically charged bodies) using a microscopic discourse (atoms, electrons). The objects, once labeled are present in the situation and do not have to be actively attended to. They serve in the same way as a written note or calculations on a note pad. Also, the distancing of negative charges (electrons) from the positive charges is made clear in the (exaggerated) gesture of distancing.

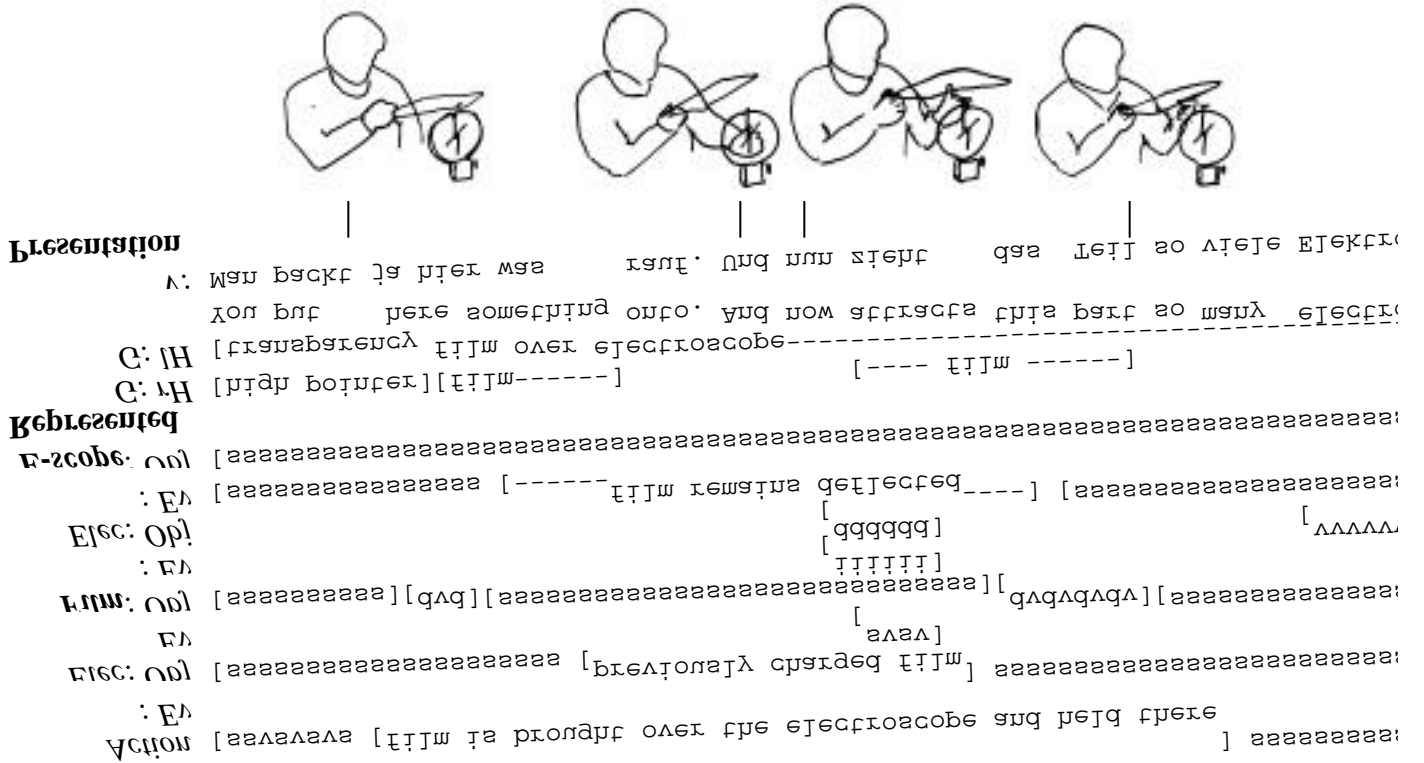


Figure 5. Phil explains how the electroscope is affected by the electrostatic induction from a charged transparency film represent themselves and have the function of figure and ground. Phil's gestures cover various levels of representations.

a.

Da ist hier noch 'ne (0.42)
There is here also an

Anziehung
attraction

b.

Da haben wir jetzt da (1.44) oben drauf n'
Mangel, There we now have there on top a
deficit,

ja da werden die jetzt angezogen.
yes they are now attracted there.

Dann werden hier jetzt Elektronen angezogen
Then the electrons are attracted here.

Figure 7. Phil explains induction on the electroscope. In both instances, the gesture occurs during the pause in the utterance, expressing the direction of the phenomenon.

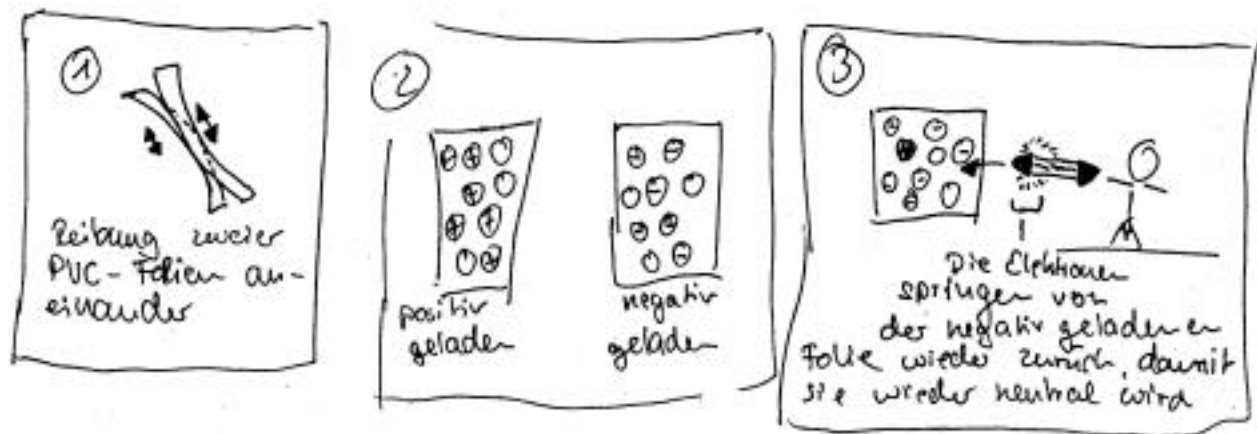


Figure 9. One student's partial answer to the question how he would show that a transparency film is charged negatively. Here, the movements and gestures from his laboratory experiences are represented in a new modality (1). The conceptual entities are layered onto the phenomenally accessible transparency film (2). Finally, the phenomenal world and the conceptual world are layered (3) such that the electrons explain the phenomenon of the bulb lighting on the left hand side of the neon light bulb.