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## Scientific investigations, metaphorical gestures, and the emergence of abstract scientific concepts

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### Abstract

Where anthropological and psychological studies have shown that gestures are a central feature of communication and cognition, little is known about the role of gesture in learning and instruction. Drawing from a large database on student learning, we show that when students engage in conversations in the presence of material objects, these objects provide a phenomenal ground against which students can enact metaphorical gestures that *embody* (give a body to) entities that are conceptual and abstract. In such instances, gestures are often subsequently replaced by an increasing reliance upon the verbal mode of communication. If gestures constitute a bridge between experiences in the physical world and abstract conceptual language, as we conjecture here, our study has significant implications for both learning and instruction. © 2002 Elsevier Science Ltd. All rights reserved.

### 1. Introduction

Research across culture not only shows that gestures are pervasive (Kendon, 1997) but also that they are deeply integrated with other intellectual abilities such as navigation and orientation competencies, sense of direction, language, and narrative structures (Haviland, 1993; Levinson, 1997; Widlok, 1997). That is, gestures are a deep feature of cognition that cannot be dissociated from the intellectual feats accomplished by individuals. As the following example from our research among scientists and science-related professionals shows, gestures are a central feature of

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knowing in a technological world often characterized by abstract graphical representations.

Our research on scientific cognition in everyday settings showed a deep connection between the understanding that scientists and technicians bring to their reading and interpretation of graphs, for example, and their gestures that have originated in their personal experience during data collection (Roth, 2000; Roth & Bowen, 2001). Fig. 1 provides three examples from a two-year ethnographical study among environmental activists. In this situation, a water technician working as part of the group explains a graph presented at an Open House organized by the activists. In the first line of Episode 1 (Fig. 1a), the water technician moves from pointing to the origin of the graph to a position parallel to the wall. She then lowers her body (see head position with respect to graph) and comes up with both hands positioned as though placed

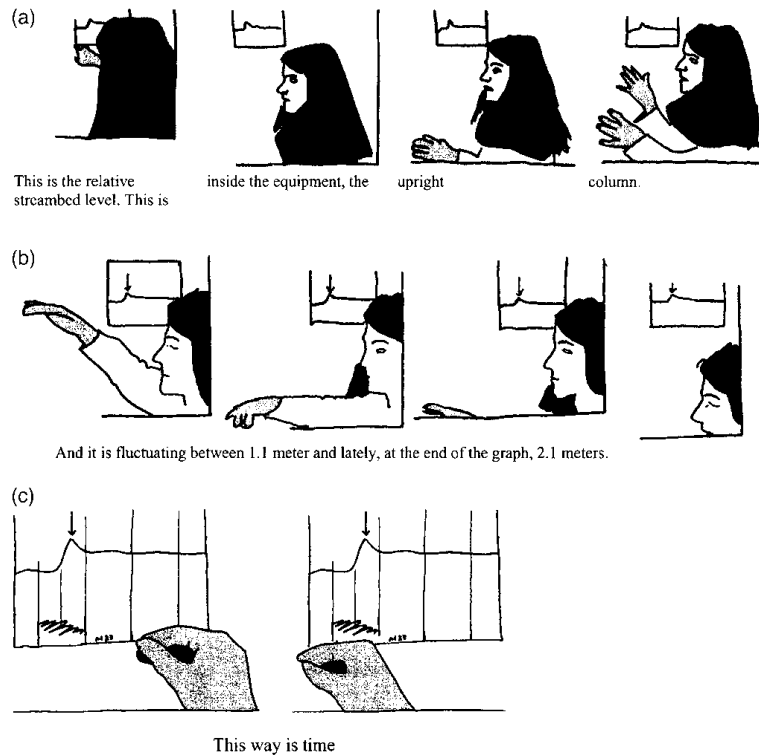


Fig. 1. Three episodes from a technician's explanation of the graphs she had collected in her work. The technician gestures three aspects of her water-level recording device: (a) a vertical drum (a); (b) pen-chart recording mechanism; (c) and movement of paper in pen chart.

on the outside of a drum or barrel. Her utterance refers us to some equipment, presumably the equipment that produced the graph. In the second line (Fig. 1b), the water technician moves up and down with her body, her hand/arm following the up-down motion slightly delayed. Her utterance tells us that the water level in the column has been fluctuating between 1.1 and 2.1 m, corresponding to the origin and the top of the graph paper. Finally, in the third strip (Fig. 1c), the technician moves her hand parallel to the chart behind her while uttering 'this way is time'.

Our ethnographic work shows that these gestures and body motions are linked to the device that records the graphs she is in the course of explaining. Thus, the water levels displayed on the graph behind her, and in fact the graph itself, are produced by a floating device moving up and down in a steel drum that reaches to the bottom of the creek and drives the pen of a chart recorder. Her gestures and enactments represent the structure of the recording device and the process of recording her body stands for the floating device, her hand for the recording pen. Seen from an observer's perspective, the hand appears to inscribe another graph onto the paper. In the third strip, the technician moves her hand in the direction that the paper moves in the recorder. Thus, her hand movement does not indicate time in the way a physicist would (from left to right), but rather in the direction that she had experienced the paper to move.

In the same way, we conducted a two-year study among ecologists during which we followed the construction of scientific knowledge, particularly scientific representations, from the early conception of research questions until the study was publicly reported. During an interview, while we asked our informant to explain the nature of an outlier data point, our informant crouched, gestured a significant belly, and then illustrated potential measurement errors related to the shape and size of the animal. Again, the understanding of the graphical representation was demonstrated through an embodied understanding of the field in general, and in this example, to the animal species in particular. This is consistent with a previous study that indicated that a central aspect of scientists' reading of graphs is their familiarity with the phenomena they represent (Roth & Bowen, 1999a).

In these examples, we can see how the gestures enacted by the person familiar with the phenomena come to play an important role in the process of explaining a graphic representation. More so, there appears to be a relationship between the topology (form) of gestures and the experiences that give rise to these gestures (Roth, 1999a, 2000; Roth & Welzel, 2001; Welzel & Roth, 2001). Given the central aspect of gestures to cognition (Iverson & Goldin-Meadow, 1998; McNeill, 1992), it therefore comes as a considerable surprise that there is very little research on the role of gestures in learning and instruction (the few exceptions are reviewed below).

A linguistic analysis of elementary to high school students' talk during laboratory investigations showed that gestures are related in form to the manipulations and observations made (Roth, 1999b, 2000). In terms of conceptual development, gestures express features of scientific concepts and relations prior to the equivalent representation in verbal discourse. That is, gestures appear to scaffold the emergence of students' observational and theoretical language about the phenomena they study. Now, the use of gestures to express phenomenally (perceptually) accessible entities

is plausible and perhaps even intuitive. However, it is not so intuitive whether and how gestures should support and scaffold the emergence of a theoretical language that largely consists of abstract conceptual terms. A core question that is yet to be answered is: “Why and how may gestures support the emergence of theoretical (conceptual) language?”

The purpose of this paper is to provide answers to this question, supported by exemplary vignettes from a large database on student learning; our interest is in describing the structure of a phenomenon rather than its prevalence, which, as we indicate later, changes during students’ development. Thus, we propose that when students engage in conversations in the presence of material objects and events, these provide a phenomenal ground against which students can enact metaphorical gestures that *embody* (give a body to) entities that are conceptual and abstract. If gestures constitute a bridge between experiences in the physical world and abstract conceptual language as we conjecture here, our study has significant implications for learning and instruction.

## 2. Gestures, knowing, and learning

Research on classroom instruction almost exclusively focuses on words, sentences, and turn-taking patterns (Lemke, 1990; Macbeth, 1994; Poole, 1994). Yet if the results of existing studies on gestures outside schools are generalizable, there exists a serious lacuna in terms of research on gestures (and other modalities of communication). This lacuna is particularly salient following two earlier studies on the relationship between discourse, spatial arrangement of speaker and focal artifacts, and the role of gesture in the development of classroom science projects. The first study shows that individuals (students, teacher) who are near the focal artifact dominate the conversation. To change the nature of the whole-class conversation, content and structure of the interactions, even the teacher had to enter a critical zone around the artifact (Roth, McGinn, Woszczyna, & Boutonné, 1999). As a result of this research, one may ask, “How does proximity between the speaker and focal artifact influence the structure and development of classroom discourse?” In response, the second study shows that immediate proximity to chalkboard diagrams allows students to use gestures that often express what could not be expressed in words and from a distance (Roth, 1996b). That is, when students are enabled to talk over and about diagrams, their discourse rapidly develops and exhibits striking similarities with scientific discourse both in content and form. These results can be interpreted as evidence for the contention that the presence of artifacts affords gesturing, which, in turn, scaffolds the emergence of scientific language. The relationship between gestures and speech during conceptual development was the focus of several studies.

Research on gesture-speech relations generally assumes that speakers know what they are talking about; in this situation, speech and gesture provide consistent information. For this reason, some authors have claimed that the gestural modality provides predominantly redundant information (Crowder, 1996; Crowder & Newman, 1993). However, gesture and speech are not always consistent. For example, Goldin-

Meadow and her colleagues have demonstrated that discrepancies can be observed between gestures and speech when children are in transitional states of their understanding (Church & Goldin-Meadow, 1986; Goldin-Meadow, Alibali, & Church, 1993; Goldin-Meadow, Wein, & Chang, 1992). These authors report that during transitional states, gestures depict new understandings, although students’ linguistic competencies have not yet developed to express the understanding in a verbal modality. The gestural and verbal modalities therefore express different types of understanding. These results find support in several studies on gestures during ‘hands-on’ science classes. When students are asked to make sense about phenomena that they did not know prior to instruction, the gestural expressions appear to precede the evolution of new verbal modes of expression (Roth, 1999b, 2001).

Much of the existing research is concerned with the relationship between gestures and phenomenal aspects of their experience. Thus, the entities that are represented by gestures are themselves accessible to the perceptual experience. However, the central question why there should be a connection between ‘hands-on’ experience (manipulating materials, objects, instruments) and conceptual language has not been answered by the existing studies and, therefore, is the focus of the present study.

## 3. Gestures

Psychological and linguistic research distinguishes the different types of gestures, which fall on what has come to be known as Kendon’s Continuum: gesticulation→language-like gestures→pantomimes→emblems→sign languages (McNeill, 1992). As we move from left to right in this continuum, the obligatory presence of speech declines, linguistic properties increase, and gestures become increasingly regulated by social conventions. In the present paper, we are concerned with gesticulation (in the literature often simply referred to as ‘gesture’): idiosyncratic and spontaneous movements of the hands and arms that accompany speech.

There are different types of gestures including beats, deictic gestures, iconic gestures, and metaphoric gestures (Kendon, 1993). Beats are gestures void of propositional content that, through their regularity, provide a temporal structure to communication and, in some theories, are said to facilitate the (lexical) search for words (McNeill, 1985; Beattie & Aboudan, 1994). Deictic gestures occur when a speaker points to actual objects that are either present, non-present, or metaphorical in nature. The technician in our first episode uses a deictic gesture as she points to the origin of the graph (Fig. 1a, frame 1). Gestures are considered iconic when they bear a perceptual relation with concrete entities and events. For example, iconic gestures depict relations in space between objects or entities, modes of action, or paths of movement. In Fig. 1b, the water technician produced iconic gestures that represented the vertical drum of the recording device and the recording mechanism (floater-pen). Finally, metaphoric gestures are similar to iconic gestures in that they have a narrative character, but the images produced relate to abstractions. In such gestures, abstract content is given form in the imagery of objects, space, movement, and so forth. For example, when the water technician moved her hand parallel to the chart

while uttering ‘this way is time’ (Fig. 1c), she uses a metaphoric gesture that indicates the flow of time (here associated with the movement of the paper in the device).

Few studies have investigated metaphoric gestures in an academic discipline. One study of two mathematicians revealed patterns that differ from normal gesturing practices (McNeill, 1992). Thus, where gestures are normally associated with verbs, both in content and in their temporal deployment, mathematicians used metaphoric gestures to signify noun words (mathematical concepts such as ‘duality’, ‘limit’, and ‘inverse limit’) in ‘imagistic’ ways. While McNeill (1992) discusses some uses of metaphorical gestures in mathematics, everyday life, and across cultures, the area of gesturing related to abstract scientific concepts is virtually unexplored. We note two studies (though gestures were not their stated purpose) that show how scientists employ gestures to articulate relationships and transitions in metaphorical spaces of computer databases and phase changes (Ochs, Gonzales, & Jacoby, 1996; Suchman & Trigg, 1993).

In this study, we therefore extend the notion of metaphoric gestures to those gestures that are used to denote abstract scientific entities (concepts) and processes that are used for explanatory purposes but are not available to perception. Concepts featured in our database include force (in and on structures or moving objects), velocity, energy, electrons, and atomic nuclei.

#### 4. Data sources and method

This study was motivated by previous research findings that gestures, in the context of laboratory investigations, may scaffold the emergence of theoretical language and abstract concepts (Roth, 1999b, 2000). That research did not provide an explanation to the question why there might be such a relation. In search of an answer, we turned to a series of videotapes collected over a 10-year period in 10 classrooms at different age levels (grade 4–5, 6, 6–7, 8, 10, 12), different content areas (architectural structures, simple machines, ecology, physics of linear motion, rotational motion, chaos theory, and static electricity) and in different countries (Australia, Canada, and Germany). That is, in this study we examine an existing database from an entirely new perspective. In these studies, groups of students were videotaped over periods ranging from 8 to 46 lessons; there were two or three cameras present in each study. Student notebooks, interviews with students, teacher curricula, artifacts, and various written questionnaires were also entered in the database. (Readers may find particulars of the extensive research efforts in the published studies on cognition and learning, e.g. Roth, 1995, 1996a,b; Roth & Duit, 1997; Roth, McGinn, Woszczyzna, & Boutonné, 1999; Roth, McRobbie, Lucas, & Boutonné, 1997)

In all these previous studies, evidence is provided for the interdependence of language, context, and cognition. However, we realized only recently that gestures might be an important aspect of the genesis of scientific cognition. For the present study, we focused on four classrooms and isolated between 40 and 100 episodes from the corresponding database. An episode consists of a communicative situation in which

a speaker uses gestures in addition to language to articulate something about the topic at hand. The beginning and end of a speaking turn usually define the beginning and end of an episode. If there were long sections in the turn without gestures, we cut the episode such that it covered all the gesturing and sufficient frames before and after to understand the context of what is being said. We digitized the episodes (from about 20 to 120 s in length) to make them available for frame-by-frame analysis. More than 90% of these episodes feature situations in which an individual (teacher, student) asks one or more students to provide observational and theoretical descriptions of a phenomenon at hand. That is, gestures were observed when students and teachers provided descriptions and, more so, when they provided explanations rather than when they talked about getting an experiment to work. In the present paper, we report on a particular structure of the gesture–context–speech relation obtained when students communicated about conceptual entities. (On the use of gestures by lecturers see Roth & Bowen, 1999b; Roth and Lawless, 2001c.) We selected the episodes from these four classrooms to show that the phenomena hold across age level, content area, and activity structure. The episodes in which students talk about the strength of bridge structures (grades 4–5), argue about pulley systems (grades 6–7), explain an investigation in static electricity (grade 10), and investigate motion phenomena in a computer-based microworld (grade 12) are included. Details of each episode are described as they are presented.

Gestures occurred frequently as a part of students’ explanations but the frequency changes with students’ competency to verbally articulate the subject matter. For example, in a typical 90-s episode near the beginning of a curricular unit, a particular individual enacted 18 gestures. Among these gestures, iconic (including metaphoric) gestures predominated (15) compared to beats (2), and deictic gestures (1). When students were fully competent and had previously articulated their ideas in writing, gestures decreased in their frequency—consistent with other studies (Roth & Lawless, 2001b; Roth & Welzel, 2001). Because of these changes, it is not meaningful to provide frequencies of metaphorical gestures because their appearance is contingent on the current understanding and familiarity with the topic and the nature of the topic itself.

In all the studies, the videotapes were transcribed on a word-by-word basis, but without pause length or overlaps. The transcriptions of episodes with apparent theoretical appeal were then enhanced in two ways. First, we included pauses, overlapping speech, stresses, and other characteristic features of speech. Second, based on the video offprints, we produced strips that coordinate transcript with gesture. (Printed video frames are traced onto transparency film, which are subsequently scanned. Shading is used to make characteristic features salient.) As the videotapes were recorded at a rate of 25 or 30 frames per second, timing of gestures and speech and the coordination between the two channels is accurate to within one frame (i.e. 0.040 and 0.033 s, respectively).

#### 5. Student investigations and metaphorical gestures

Our analysis of the data from different countries, age levels, and subject matter content reveals striking similarities across these different contexts. First, there are

three modalities of communicative acts: perception; gestures; and speech. Initially, the communication is distributed across the three modalities in such a way that the salient objects and events represent themselves (perceptible entities ‘go without saying’), leaving gestures and speech to represent abstract conceptual entities. Secondly, students begin gesturing abstract concepts using metaphoric gestures before the equivalent conceptual language evolves. The temporal gap between the metaphoric gestures and corresponding abstract conceptual language decreases until they merge. Here, we present our findings in the form of episodes from four classrooms, thereby underscoring the generality of our finding across different contexts.

### 5.1. Episode 2: forces in a bridge

This episode is taken from a study of grade 4–5 students who learn about forces, material strength, and stability by building architectural structures (bridges, towers, and domes) from household materials (straws, glue, pins, adhesive tape, Popsicle sticks, cardboard, and paper). A central criterion of their design process (including (re)-planning, building, prototyping) is to achieve maximum stability and structural strength, which students test according to their own criteria. To establish a community of design practice, the two teachers in the class planned daily whole-class meetings where students presented, critiqued, and collectively redesigned the structures. The following episode comes from one of these whole class sessions where one grade-5 student (Jeff) talked about his bridge that had carried a load of more than 350 wooden blocks. During the 16-min exchange about Jeff’s bridge, one of the questions raised by a peer pertained to the strength of this particular bridge design. In response, Jeff talked at length about how he had tested earlier versions of the bridge, and then, in successive cycles of testing, prototyping, and redesigning increased the maximum load that the bridge could carry at its center. Central to Jeff’s presentation was his explanation of forces that act in the upright pillars and in the horizontal bridge deck.

Throughout his presentation, Jeff used deictic (pointing) and iconic gestures as he talked about how his design came about. Further, Fig. 2 shows that Jeff enacted metaphoric gestures to denote forces that, in his view, exist within the structure. In fact, he argued that his design distributes the forces in the way shown by the gesture (‘it is easier for the force to go across here’). We can see that as the utterance unfolded, Jeff’s right hand moved parallel to the bridge deck from the right to the left side, returned and repeated the gesture.

We suggest that the gestures are metaphoric, as there is no precedence, no experience that would have allowed him to actually see or otherwise perceive the forces. Here, the forces in structures are abstract concepts not directly available to experience, but which are useful because they have explanatory power. The gesture itself was metaphoric, enacting the conduit metaphor (McNeill, 1992): some entity ‘goes across’ in the bridge structure. At the same time, the repetition (within 1 min, Jeff moved his hand six times across the bridge in the way shown) of the gesture also indicates a dynamic situation. Of equal importance is the temporal relation between verbal and gestural components of communication. Here, Fig. 2 shows that the ges-

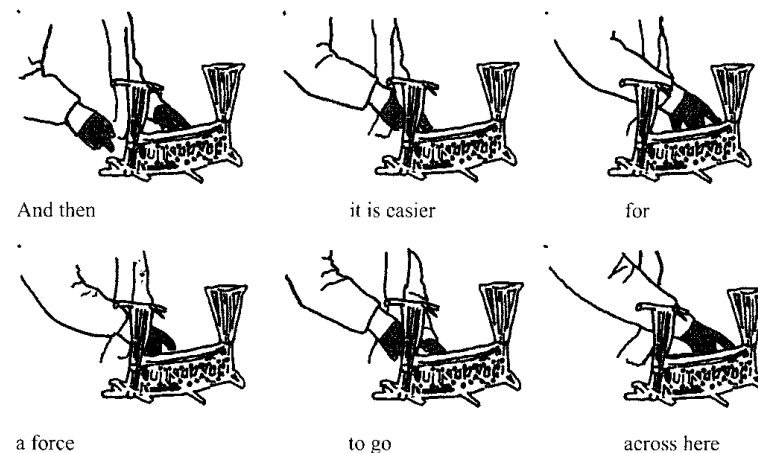


Fig. 2. A grade 5 student explains why the bridge he constructed from straws is able to hold as many as 356 wooden blocks. His gesture indicates how forces are distributed in the bridge structure.

ture denoting the force across the deck was complete before Jeff talks about forces and their action. As previous linguistic studies show, when students have not yet achieved the competence to talk about scientific phenomena, their gestural equivalent precede talk (Roth, 1999b, 2000) suggesting a developmental sequence.

This episode shows how an entity that was not available from the perspective of the audience (‘force’) is said to be present. More importantly, the gesture *enacted* an abstract concept<sup>1</sup> and provided others with a visual image of this concept. The shape of the gesture (parallel to deck) indicated the topology of the abstract phenomenon. The link between the abstract concept and the actual bridge seen by the audience was made in two ways. First, at the end of the utterance, Jeff used the indexical term ‘here’. Although terms such as ‘here’ identify specific locations close to the speaker (Hanks, 1992), the context set up by the combination of utterance (‘go across’) and gesture (extended in space) oriented the listener to the trajectory. (This is confirmed elsewhere in our database where students use the term ‘here’ in the context of gestured trajectories, despite their extension in space.)

Secondly, we note that there exists a mutually constraining relation between gesture and particular aspects of the bridge. From the speaker’s perspective, the topology of the bridge and in particular the orientation and shape of the bridge deck-motivated attention to the topology of the gesture. At the same time, and particularly from the audience perspective, the shape of the gesture motivated attention to the horizontal

<sup>1</sup> The significance of enactment is summarily discussed below. Because the activation of linguistic meaning is associated with activation in the sensory and motor cortex (Bates, 1999), such enactment may in fact provide the starting activation that supports the emergence of linguistic meaning.

bridge deck that Jeff was talking about. That is, the trajectory of the gesture makes salient the horizontal features of the bridge which then become figure against the remaining more diffuse ground of everything else. Here, then, the two communicative modalities (gesture and utterance) with abstract referents, were enacted against a perceptible bridge, the topic. In fact, because the bridge was available to all participants, the speaker did not have to refer to its physical presence or shape — ‘it goes without saying’ (Roth & Lawless, 2001b). At the same time, the copresence of abstractions and physical device in the same communicative act conflate the two.

### 5.2. Episode 3: electrons in a metal rod

The present episode is part of a video database that features a German grade-10 physics class where students learned about static electricity by exploring a variety of phenomena through their own investigations. For many investigations, the teacher provided a range of materials and encouraged students to conduct investigations of their own design. Students were asked to describe their investigations and construct explanations for the phenomena they observe. The present episode occurred as a part of a two-lesson investigation into an electrostatic induction phenomenon. In this experiment, a pith ball was suspended on a filament so that it came to rest in line with and about 1 cm away from a metal rod. When a charged object was brought to the other end of the metal rod and quickly removed, the pith ball was first attracted to the rod, touched it, and then bounced wildly for a while until it came to rest again. After having conducted the investigation repeatedly, the four students around the table engaged in constructing an explanation. Initially, they talked and gestured over (i.e. in the presence of) and about the actual apparatus. After one of the students had removed the apparatus, another student, Paul, placed a plastic rod in front of himself. His gestures and talk made it clear that the plastic rod stood for the metal rod, thereby setting up an orientation and location in space. That is, all the parts of the instrument not represented were gestured in the exact spatial relation where they would have been in relation to the rod. In a metonymic way, the plastic rod denoted the original investigation.

Just prior to the episode, Paul moved his right hand to one end of the rod and his left hand to the other end. Next he stated, “This piece that you charged pulls itself toward...” (Fig. 3, frame 1). Subsequently and without any accompanying speech, Paul moved his right hand parallel to the rod from the right to the left end. This action was repeated twice before he utters ‘pulls itself toward...’. Later in the lesson, Paul verbally explained that the bouncing pith ball was giving some charge back to the metal rod each time it touched. Consequently, the transferred charges (electrons) redistributed themselves in the rod so that the pith ball was attracted again.

We can then see that at this point the movement and redistribution of charges in the rod were not articulated by verbal means. However (and consistent with our observation across the different studies), his gestures already denoted abstract concepts 30 min before he had the verbal means to talk about them. This shift has to be seen in the context of the previous episodes presented here. In Episode 1 where the water technician talked about graphs from her work (Fig. 1) there was no tem-

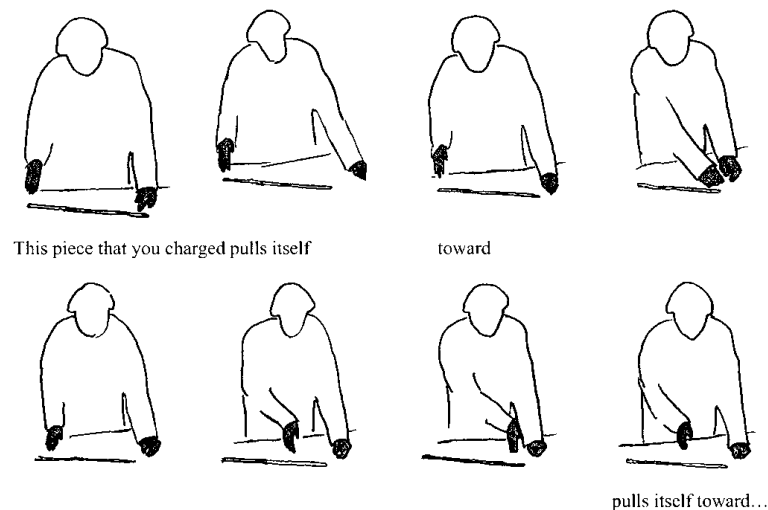


Fig. 3. A grade 10 student uses gestures to depict electrons and their movement in a metal rod to explain why a pith ball bounced in the experiment he conducted.

poral shift between words and gestures. In Episode 2 (which followed a three-week exploration of bridges during which Jeff developed great familiarity with the phenomenon) there was a delay between the gesture and the verbalization of an abstract concept is of the order of 1000 ms. Then, in developmental terms, we see Jeff and Paul at different stages in the process of evolving a theoretical language; i.e. Paul was further from verbal competence than Jeff (Roth, 2000).

There is also a similarity to Episode 2 in the repetition of the movement, which indicates transmission, process, and change (McNeill, 1992). However, in the present case, the processes concern conceptual entities, electrons and electric charges, which are never perceptually available. Consequently, the gestures are metaphorical in nature.

Finally, as in Episode 2, gestures were enacted against a material object (plastic rod) that was perceptually available to the other three students in the group. From our perspective, it is therefore not surprising that Paul did not make a reference to the object. The historical development of their interaction allowed the students in this group to establish a common ground in which the rod became a metonymy for the investigative equipment as a whole. We argued elsewhere that this common ground could therefore be regarded as part of the communication and analyzed in terms of the signs that cooperate with verbal and gestural signs (Roth & Lawless, 2001b).

### 5.3. Episode 4: force and energy related to moving objects

The episodes in Fig. 4a and b were taken from a video database recorded in a grade-12 qualitative physics course. In these lessons, students studied motion, particularly the concepts of force, acceleration, and velocity. As part of the curriculum, students conducted investigations in a computer-based Newtonian microworld (Interactive Physics™). The particular feature that allowed students to learn Newtonian physics was the copresence of objects that move in accordance with the real world (iconic relationship) and conceptual objects such as velocity and force vectors (Roth, Woszczyna, & Smith, 1996). The students in this class were asked to describe and explain phenomena that they produced by manipulating the entities in the microworld.

Episode 4a is from a lesson in which the students try to maneuver a circular object through an opening between the two vertical walls and into another opening without bouncing (clearly seen in frame 1 of Fig. 4a). From a physics perspective, this can be achieved by arranging the velocity and force vectors in such a way that the resulting parabolic trajectory falls between the openings. This episode represents part of a student's attempt to explain how force and initial velocity should be oriented in order to move the object through the two openings.

Fig. 4a shows how gestures allowed Glen to represent the complex relationship between the trajectory of an object and the force acting on it. The entire gesture

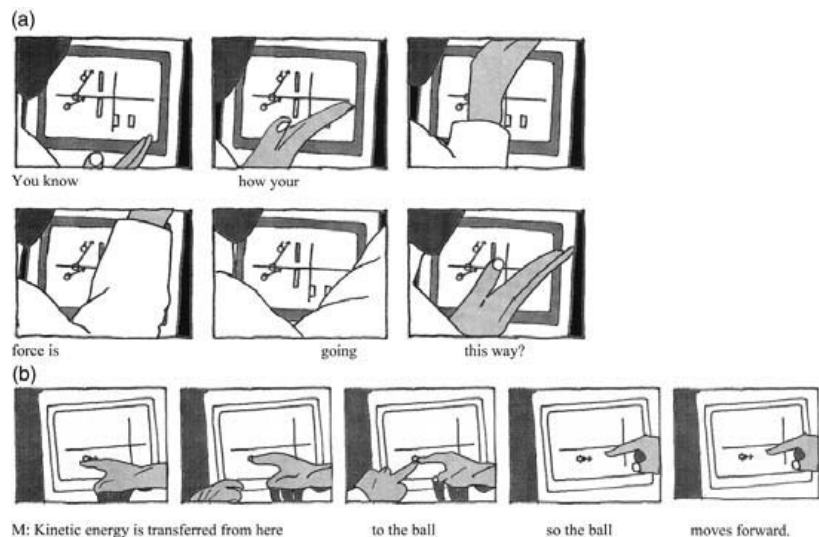


Fig. 4. Two episodes from a physics course where students used modeling software to explore motion phenomena. Gestures constitute an important element in their communicative efforts.

(frames 1–5) is curved, but the absolute orientation of the hand stayed constant (Fig. 4a). This constant orientation of the hand evoked and made reference to an observation sentence that Glen had uttered earlier: “This one [force vector] always stays straight”. Subsequent to his utterance (not represented here), Glen immediately repeated the same gesture thereby underscoring the character of the process of the phenomenon he talked about.

The episode in Fig. 4b comes from a different class in the same school and at the same grade level. The students worked on the same set of tasks. Here, Mike explained to his three peers what would happen in the situation given the particular configuration of phenomenal and conceptual entities (if they were to ‘run’ the experiment). In the first part of the communication (Frames 1–3), Mike talked about a transfer of kinetic energy from some unspecified location or object (‘here’) to the ‘ball’ while his finger moved from left to right until it came to rest over the ball. Mike continued his hypothesis by implying that the ball would move forward as a consequence, while moving his finger to the right, in line with the earlier trajectory and parallel to the horizontal coordinate axis.

Once again, an abstract concept (‘kinetic energy’) was enacted in the form of a metaphoric gesture against a ground that was perceptually available to all participants. In the present situation, this gesture was paired and causally connected with a subsequent gesture that iconically represented a potential event (forward motion) (Frames 3–5). This was also the first episode in this article where the verbal modality expressed both abstract concepts and perceptually available entities.

As in the previous episodes, the students here were in transitional stages of developing a theoretical language (abstract concepts) about motion phenomena. In this episode, Glen's gesture had already completed its trajectory when he uttered the corresponding verb ‘going this way’. (As in Episode 2, the indexical locution ‘this’ in ‘this way’ did not denote a point in space, but a collection of points commonly referred to as the trajectory.) Mike's hand had already completed the forward motion (Fig. 4b, fourth frame from the left) when it was evoked in speech (fifth frame from the left). In both cases, the abstract entities, force and kinetic energy, were depicted in gestural form against a ground of phenomenal objects and events.

### 5.4. Episode 5: forces in pulley systems

This final episode derives from a study on grade 6–7 students learning about a variety of simple machines such as pulleys, levers, and inclined planes (including the concepts of force, energy, mechanical advantage, and gear ratio). As part of the unit, students learned to use a variety of graphical means of representing physical devices. Throughout the lessons, students were encouraged to graphically render significant aspects to make salient to their audience what they were currently talking about. Episode 5 comes from a whole-class discussion that follows a tug of war lost by 20 students against their teacher, who had rigged the competition using a block and tackle. The students first constructed an explanation for the teacher's victory and then continued the discussion in order to design alternative pulley systems that

would not disadvantage the students. In this discussion, students and the teacher drew alternative designs in simplified and abstract form on the chalkboard (Roth, 1996b).

At this point in the discussion (and the lesson sequence as a whole) the student, Shaun, already has considerable competence in representing the scientific aspects of pulley systems (Fig. 5). The fixed points ('banisters') in the system and the pulley were rendered in an abstract form. However, he omitted the details of the actual block and tackle, the form of the banister, or the manner in which the rope is attached to the pulley.<sup>2</sup> The arrow in the drawing indicated where and in which direction the force acted, generated by the teacher's pull. Simultaneous with the use of the more abstract representations (no longer iconic), Shaun also enacted the force as his hand moves from the side of his body all the way toward the top of the chalkboard and parallel to the rope associated with the teacher. The gesture enacted the abstract notion in a dynamic form, via the already encountered conduit metaphor (Episode 2 above). As seen earlier, in dynamic situations, 'here' refers to the process embodied in the gesture and its referent. In the present situation, and contrasting the previous student episodes, the utterance about the force fell together with the corresponding gesture. At the same time, the perceptually available aspects of the pulley system 'go without saying' and therefore did not need to be articulated in words.

## 6. Discussion

In the preceding section, we presented episodes from different contexts that feature students at various stages in their evolution of scientific language (abstract concepts).

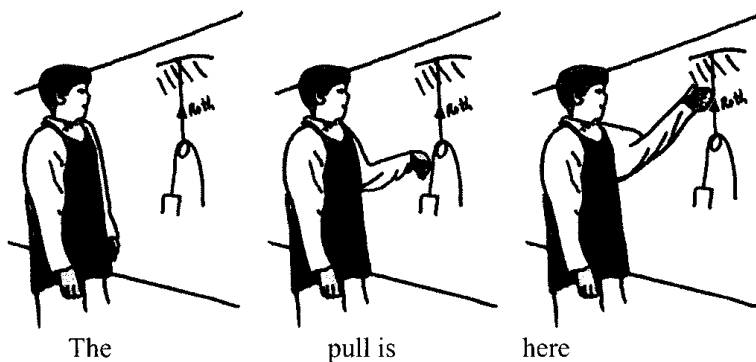


Fig. 5. A grade 7 student attempts to construct an alternative pulley arrangement in which he and 19 peers would not lose a tug of war against their teacher, who had rigged the competition using a block and tackle.

<sup>2</sup> Elsewhere we provide evidence that students develop increasingly abstract imagistic (drawn) and verbal representations and become increasingly competent in deploying these representations in descriptions and explanations of phenomena (Roth, 1996a; Roth & Lawless, 2001c).

All the episodes illustrate how students use metaphoric gestures to represent abstract concepts and processes, and a temporal lag of the verbal modality with respect to the gestural. From this we conjecture that certain gestures literally embody abstract concepts in two ways. First, in their materiality, gestures enact topological features of a conceptual entity that does not exist in object form. Secondly, the body of the speaker produces the gesture, literally embodying a signifier for the concept. Consequently, while students construct verbal expressions of abstract concepts, gestures and perceptually available entities take on a complementary representational function that adds additional dimensions to communication above and beyond isolated utterances. As such, communication is best understood as being distributed over three different modalities, thereby easing cognitive demands and freeing resources for evolving new forms of theoretical language. We end this section with recommendations for classroom practices that encourage the use of gestures and propose an agenda for research in which our conjectures are tested empirically.

### 6.1. Multimodal communication

When the objects and events talked about are not perceptually available, speakers ordinarily mark positions in space as well as arbitrary objects to stand for those abstract entities that they are going to talk about. For example, in an episode not illustrated in this paper, a student holds up one pen and then another pen and declares them to stand for plastic film. Next, she holds up a third pen, making the cap stand for electrons, the body for atomic nuclei. Finally, she illustrates how rubbing the two films creates positive and negative charges that are separated. In contrast, when equipment, objects, or materials are present, students do not have to divide the space and mark objects prior to their communication. The space becomes inherently marked in the interaction between gesture and characteristic features of the focal situation.

The gestures are enacted against a perceptual ground, from which, as part of the function of gestures, certain features become salient. Consequently, because they are salient, they do not need to be talked about. This, then, frees up resources in the production of speech which, in some theories, taxes the short-term memory required for word search and assembly of sentences (Anderson, 1985). The perceptually available entities and gestures therefore scaffold the development of scientific language because they take on representative functions while the verbal modality is able to devote itself almost entirely to the construction of new theoretical sentences.

Though they differ in many respects, both major theories on gesture–speech relations presume that speech and gesture are generated by an underlying semantic model (Hadar & Butterworth, 1997; McNeill, 1985). On these grounds, our data seem to suggest that students already have a semantic model, but their verbal competencies have not yet developed. This construction is consistent with interpretations generated in other research: there are discrepancies between gestural and verbal modalities during developmental transition periods, with gestures foreshadowing conceptually more advanced understandings (Goldin-Meadow et al., 1992). Our analysis of students perceiving and learning about phenomena that they had been



unfamiliar with suggests an alternative interpretation (Roth & Lawless, 2001a,b). Thus, gestures motivated by structures in the perceptual ground provide a basis for the subsequent development of semantic models, which also include verbal and perceptual (which Barsalou, 1999 calls ‘retinotopic’) representations.

Then, in this sense, both perceptually available structures in the material world and gestures assume part of the representation work so that new competencies can develop in the verbal modality. Of course, because of the primacy of linguistic modes of expression, schooling constitutes a force that privileges the evolution of language despite the earlier presence of other (perceptual, gestural) modalities.

### 6.2. Neurosciences

One might still ask, why should perception and gestures scaffold the emergence of more abstract language? Recent research in a variety of neurosciences (neurophysiology, neurobiology, neurobehavior) indicates that many different aspects of sensory and motor cortex are activated in language-related tasks that involve imageable stimuli (Bates, 1999). More generally, a review of the literature on neurobiological origins of language suggests that language makes use of neuronal assemblies that first developed in response to motor and sensory needs of early humans (Müller, 1996). These same neuronal assemblies were subsequently used for gestures. When language developed, the brain reused these same neuronal assemblies. Such an assemblage lends support to the conjecture that the activation of meaning involves activation of the same regions that also participated in the original experiences on which meanings are based (Bates, 1999). It therefore comes as no surprise when some researchers argue that gestures increase brain activation in these regions and thereby increase the likelihood that associated linguistic representations are activated (Butterworth & Hadar, 1989). Thus, when the students in our studies use gestures, we conjecture that the activation levels in regions of meaning increase, and thereby facilitate the production of verbal descriptions. Further, because the same neuronal assemblies are activated for perceptual and corresponding motor activities (Decety & Grèzes, 1999), both perceptual cues and accompanying gesture would scaffold the emergence of a corresponding language that encodes meaning in the verbal modality.

### 6.3. Implications for research on learning and instruction

In this article, we have presented a few examples representing a much larger database. Despite this pervasive evidence we recognize the conjectural nature of the presented work because the mechanisms by which the gestures are connected to language and how they might support its development are not yet understood. There is much to be learned about the role of gesture in conceptual development. However, the move from the conjectures we make to causal relations between gestures and conceptual understanding requires well-designed experimental studies. To test whether gestures scaffold the emergence of students’ language about abstract phenomena, controlled experiments are required that study the emergence of abstract

language in situations that foster gesture use (manipulating materials, observing manipulation) and those that do not encourage or suppress gesture use (seeing static situations, purely narrative situations). For example, the Piagetian water level task (Fig. 6), which provides a rich context for gesture use (Ackermann, 1991), requires children to predict how the water surface will be oriented when the container is tilted through different angles. We already know that children in the concrete operational stage (ages 6–12) progressively discover horizontality. To understand the relationship of talk, gesture, and context in children’s cognitive development we may attempt to answer the following questions: “What do children show through drawing, gesturing, telling?” “What do children think their drawing, gesturing, telling, once achieved, actually show?” “How do gestures in situation help children to generate and recognize horizontality?” “Under what conditions do children recognize horizontality across contexts?” Three possible conditions include: (a) children manipulating the bottles themselves; (b) children observing the experimenter manipulate the bottles; and (c) children responding to drawn images of bottles. Based on the present study, we would conjecture that children’s language development is most supported in condition (a), where motor representations are formed, followed by condition (b), which encourages perceptual (retinotopic) representations of changes, and least in condition (c), which fosters static pictorial representations. Similarly structured experiments could be conducted with older students in other physics domains where the conditions include: (a) direct manipulation; (b) observing a demonstration; and (c) reading about the phenomenon. Again, we hypothesize decreasing learning rates in the given order of condition.

Besides the described experimental work, we also encourage researchers to conduct applied research in classroom, which is another avenue to generate new knowledge about the role of gestures in learning. Research in classrooms has the advantage that it concerns itself with communication in realistic everyday settings, thereby increasing the ecological validity of the study. If there is anything to our conjectures, then our research has considerable implications for the analysis of classroom conversations. Ordinarily, researchers focus exclusively on talk (Orsolini & Pontecorvo, 1992) thereby overlooking other modalities that provide teachers and students with a means of expressing understanding. In short, most research fails to acknowledge the multimodal character of human communication (Lemke, 1998). We have shown here that the signs (representations) available in both the perceptual ground and as gestures have to be accounted for to understand communication. Our work, therefore, implies that researchers have to identify communicative representations at (minimally) three levels: perceptual, gestural, and verbal signs. From a speaker per-

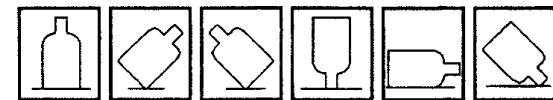


Fig. 6. The Piagetian water-level task asks children to identify the orientation of the water surface in the bottle.

spective, the three modes taken together produce communicative events; from the audience perspective, information is minimally available at the same three levels.

Additionally, we have illustrated that the perceptual ground and gestures have an important scaffolding function in students' development of scientific language, because they take on a representative function. These representations free up the verbal modality to focus on constructing new conceptual statements, which are more demanding than observational statements (Anderson, 1985). Our work implies that students should be enabled to construct descriptions and explanations of their investigations in the presence of these materials. Further, our work suggests that students should be engaged in the construction of preliminary descriptions and explanations before attempting to represent their understanding in a formal written (drawn) report. This contrasts with the traditional pattern of asking students to write laboratory reports at home.

Finally, with respect to the temporal delays between gestural and verbal means to express abstract concepts, our findings suggest that students should be given considerable time to construct their first verbal representations. The time provided needs to be sufficient for students to shift the representation of abstract concepts from the gestural to the verbal modality.

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