Review of Educational Research
Fall 2001, Vol. 71, No. 3, pp. 365–392

Gestures: Their Role in Teaching and Learning

Wolff-Michael Roth
University of Victoria

Gestures are central to human cognition and constitute a pervasive element of human communication across cultures; even congenitally blind individuals use gestures when they talk. Yet there exists virtually no educational research that focuses on the role of gestures in knowing and learning and the implications they have for designing and evaluating learning environments. The purpose of this article is to provide a review of the existing literature in anthropology, linguistics, psychology, and education and, in the context of several concrete analyses of gesture use, to articulate potential focus questions that are relevant to educational research of knowing, learning, and teaching.

Gestures constitute a central feature of human development, knowing, learning, and communication across cultures (Kendon, 1997; Levinson, 1997); even congenitally blind individuals gesture when they communicate (Iverson & Goldin-Meadow, 1998). Not only is gesture a central feature in cognition but there is evidence that it is deeply integrated with other cognitive capacities (Haviland, 1998; Widlok, 1997); this integration begins early and develops throughout childhood (Alibali & DiRusso, 1999; Goldin-Meadow, 1998; Namy & Waxman, 1998). It is curious, then, that there exists very little educational research concerned with the role of gestures in learning and teaching, particularly in the subject areas that have been characterized as dealing with abstract matters such as science and mathematics. The few existing studies that focus on gesture in an education context, often appearing in journals whose primary focus is not educational research, suggest that such research might be of tremendous importance in helping to understand better the role of gestures in knowing and learning science (e.g., Crowder & Newman, 1993; Lemke, 1999b; Roth, 2000). Framing potential areas of educational research on gestures, based on a review of studies on the role of gestures in knowing and learning, is the topic of this article. As a way of introducing key issues in a non-technical way, I present the following example from high school physics, where students have begun a unit on motion but have not yet mastered the appropriate physics discourse. The presence of visual artifacts and the availability of gestures enable students to communicate even prior to their initiation in standard physics discourse.

The episode takes place in a junior-year, introductory physics course that focuses on the qualitative aspects of physics. As part of their unit on motion, students use modeling software (Interactive Physics™) to simulate motion phenomena and coordinate the phenomena with their corresponding mathematical representations (e.g., velocity and acceleration vectors; position-, speed-, and acceleration-time graphs). Four students sit around the computer, working on a task that requires them to set the velocity and acceleration vectors (arrows) attached to a circular object in order to move it through a wall opening into a specified location (Figure 1). Nick attempts to explain the task to his three peers—Edward to the right of him, the others hidden from view. (Pseudonyms are used throughout the article.) He attempts to explain that the velocity and acceleration of the circular object on the screen—visible as arrows (i.e., "vectors")—have to be set in such a way that the object, once started, moves through the first opening into the second one. At this point, he still lacks the appropriate physics language including "vector," "velocity," and "acceleration." Yet, drawing on the visual display and gestures as resources, he is able to communicate in a way that his peers understand.

Nick's finger, which previously had touched the object, moves along a trajectory that simulates, on the surface of the monitor, the hypothesized trajectory of the circle, which his audience has to imagine lying behind the finger. As the finger moves between the two blocks, the utterance describes the movement as "through here." The trajectory of the finger is visible against the ground, and so the utterance is a description of what is perceptually available. The second part of Nick's utterance, "without hitting these two," is a clause that modifies the first part. What "these two" refers to is made available to the listeners by the gesture that points first at the lower block (frame 2), then at the upper block (frame 3). The gesture makes salient the entities (the rectangular blocks) that are required by the narrative, but "two" provides an additional clue as to what is salient, because it constrains the audience to perceptually isolate two, likely similar objects.

If one considered only what Nick said in words, as is typical in written communication, it would be impossible to know what he is talking about. If the computer screen is subsequently added as an aspect of communication (i.e., as a "sign") available to Nick's partners, at least the general topic of his utterances becomes clear. When his gesture is considered in the analysis as yet another communicative modality, then the content of Nick's talk becomes even clearer. Here, Nick uses two types of gestures. First, he points and therefore makes use of a *deictic* gesture. But Nick also moves his finger in front of the screen, simulating a hypothesized trajectory; this gesture is classified as *iconic* because it has a visual resemblance with the trajectory it stands for. This gesture does not point *to* an aspect on the screen but occurs with the screen as ground—it occurs as figure *over* or against the ground. In this example, we therefore observe a conversation (gestures and talk) as being over and about the objects and events on the monitor. The monitor serves as ground against which the words become salient. Moreover, the gestures and words themselves become salient (take specific meanings) only in their interaction with those structures perceptually salient to the observer. (Goodwin, 2000, calls these structures semiotic resources in the environment.)

This example shows that gestures are not merely ancillary, but central features of communication. Gestures have both narrative (iconic gesture) and grounding functions (deictic gestures) connecting the gestural and verbal narratives to the pictorial background. Communication is therefore distributed over three modes of expression, the perceptual ground, gestures, and utterances. Because communicating is an aspect of knowing, thinking here is partially shifted into the world—it occurs right before the eyes of listeners rather than only in the head of the speaker (see also Koschmann & LeBaron, 2001). The finger moving along the surface constitutes a hypothesized trajectory. This trajectory is available to others to register

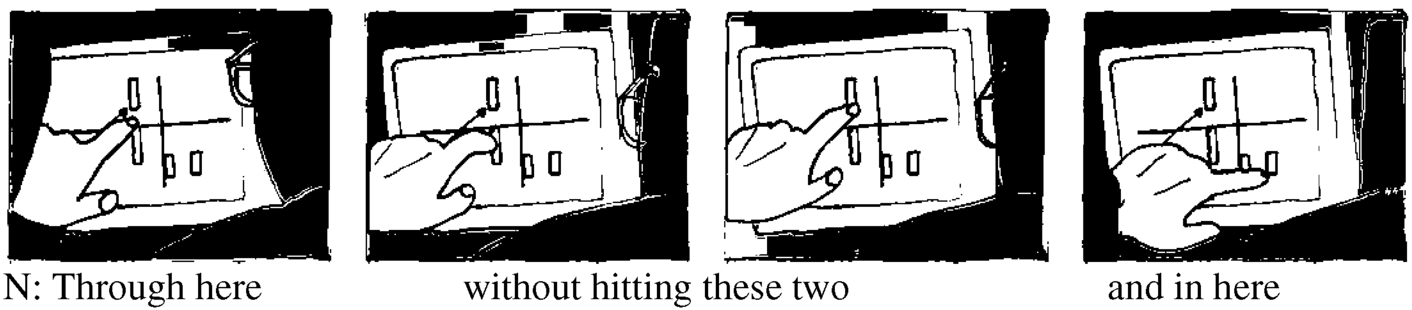


FIGURE 1. *Nick (left) explains to Edward (right) and two other students the task: Setting the two vectors (arrows) on the circular object, here hidden from view by his hand, so that the object moves through the hole in the wall and into another opening.*

it, then accept, critique, augment it, and so on. Thus, even though the students in this episode do not yet have a language to describe and theorize the events in appropriate form, the perceptual (semiotic) resources on the monitor together with the gestures allow complex communication. Several studies conducted in different content domains of science and mathematics have shown that more mature forms of verbal communication in science and mathematics develop from these early distributed communicative forms (Alibali, 1999; Roth & Welzel, 2001).[1]

The purpose of this article is to make an argument for the importance of studying gesture and its relation to speech in educational settings. I begin by reviewing the research literature as it has evolved in linguistics, anthropology, and psychology to frame the nature of gestural phenomena of potential interest to educators. In the subsequent section, I provide a review of gestures in learning and development among school-aged students, focusing both on experimental and naturalistic studies. I then provide several examples of gesture use in educational settings as starting points for framing important research questions.

Beyond Words

Gestures have often been relegated to subordinate status in communicative research (e.g., Kendon, 1984; McNeill, 1998). However, researchers have begun to extend their analyses beyond categorical features of language to include what are held by some to be the embodied expression of human experience (McNeill, 1992; Nunez & Freeman, 2000). One of the reasons for this shift towards expressions of embodied understanding is the attempt by various strands of research to address insights from both phenomenology and pragmatics (Lemke, 1999a). The result is a trend in communication research that includes multi-modality approaches that reflect the complex interactions that characterize human communication (Cassell, 1999).

Scope of Review

"Gesture" is sometimes used to refer to any of a variety of movements—including movement of hands and arms, adjustment of posture, the touching of oneself (e.g., stroking one's hair), various (nervous) ticks, and other fiddling movements—that people use while talking (Kendon, 1996). However, when research subjects were asked to view films of others in interaction, they reported only on speech and hand/arm movements as part of what persons in the film were trying to communicate and treated other types of movements as background (Kendon, 1985). The notion of "body language," common in everyday language, is not a useful concept here because body movements and positions are neither structured nor used like language. At the same time, as this review will show, many hand gestures are clearly understood as meaningful in their own right and able to communicate specific content. The self-identified community of scholars with interest in gesture research (International Society for Gesture Studies) therefore limits itself to the study of hand and arm movements that are interpreted by others as part of what a person says. Therefore, in this article I review studies that focus on hand gestures clearly identified (by researchers and research subjects) as communicative foreground. Furthermore, I do not attempt to review the entire body of research but limit myself to the research that appears to have considerable implications for research in classrooms. I therefore have excluded studies that focus on the role of nonverbal communication in determining social impressions (e.g., DePaulo, 1992); on the role of gesture as regulating mechanism through back-channeling or gaze-direction (e.g., Bavelas, Chovil, Coates & Roe, 1995; Dittman & Llewellyn, 1968; Duncan, 1972; Kendon, 1967); and on the contribution to communication by proxemics and paralanguage. (For a review of related educational practices see Woolfolk & Brooks, 1983.) I also have excluded studies that focus primarily on development of sign language, influence of neurological damage, speech disfluency, or evolution of language (Gibson & Ingold, 1993; Iverson & Goldin-Meadow, 1998; Messing & Campbell, 1999).

Gestures Defined

Gestures are, for the most part, a speaker's phenomenon (Schegloff, 1984), though there are some studies that focus on the role of gestures in making interactions work (e.g., Bavelas & Chovil, 2000; Goodwin, 1996; Koschmann & LeBaron, 2001). Furthermore, whereas all gestures are hand movements, not all hand movements are gestures. Gestures can be distinguished from other movements (such as posturing or grooming movements) by four characteristics (Kendon, 1980, 1996). First, gestures begin from a position of rest, move away from this position, and then return to rest. Second, gestures have a *peak* structure, also referred to as the *stroke,* which is generally recognized as a moment of accented movement to denote the function of meaning of a movement. Third, the stroke phase is preceded by a *preparation* phase and succeeded by a *recovery* phase in which the hand and arm move back to their rest position. Consequently, gestures have a clear beginning and ending. Fourth, gestures are often symmetrical (and, for instance, would therefore be difficult to use as a basis for deciding whether videotape is run forward or backward). In Figure 1, only the stroke phase of the gesture articulating the hypothesized trajectory is visible, interrupted by two pointing gestures, which nevertheless begin and end at the stroke trajectory of the main gesture.

A useful distinction can be made between various classifications of gestures that differentiate movements in terms of a continuum ranging from idiosyncratic, spontaneous movements that accompany speech (gesticulations) to fully developed linguistic systems such as American Sign Language (Kendon, 1988). Between these two extremes, movements become increasingly independent of speech in forming language-like gestures, pantomimes or emblems:

gesticulation → language-like gestures → pantomime →
emblems → sign language

Because gestures potentially play an important role in the emergence of language, even among high school students (Roth & Welzel, 2001), my interest lies with non-conventional gestures (gesticulations and language-like gestures) that accompany, and even require, speech with which they form an integrated whole (McNeill, 1998). For this article, I reviewed the gesture literature concerned with gesticulations, which actually constitutes the bulk of the available research.

Taxonomy of Gestures

Researchers have developed different taxonomies of gestures (e.g., Efron, 1941/1972; Ekman & Friesen, 1969; Kendon, 1988; McNeill, 1992; Rimé & Schiaratura, 1991; Wundt, 1973). Their classifications of gestures are based on particular functions of gestures or on models of gesture production (e.g., Bavelas et al., 1995; Butterworth & Beattie, 1978; Feyereisen, 1987; Hadar & Butterworth, 1997; Krauss & Hadar, 1999; McNeill, 1985). Most researchers, particularly those concerned with educational issues, now base their work on the taxonomy proposed in the seminal *Hand and Mind: What Gestures Reveal About Thought* (McNeill, 1992), according to which there are four basic types of gestures: beat, deictic, iconic, and metaphoric gestures. This taxonomy is used as a framework throughout this review.

Beats, also referred to as *batons* (Efron, 1972) or *speech primacy movement* (Freedman, 1977), are gestures that are void of propositional or topical content yet lend a temporal or emphatic structure to communication. Typically, beats are simple, non-pictorial gestures that can include the up and down flick of a hand, or the tapping motions used to emphasize certain utterances. Beats function as interactive gestures, which serve to regulate the coordination of speaking turns, to seek or request a response, or to acknowledge understanding (Bavelas et al., 1995).

Deictic gestures are used in concrete or abstract pointing. Concrete pointing is one of the first gestures to develop, appearing around ten months of age (Bates, 1976). Infants begin to gesture by extending objects and by open-hand reaching and then by pointing (Masur, 1983). These gestures are context dependent. Deictic gestures are used during the early phases of language development to combine with speech in order to name objects, indicating a developmentally early correspondence between word and gesture (Goldin-Meadow, 1998). At about ten years of age abstract pointing develops to indicate an abstract or non-present referent (McNeill, 1992). *Deictic* terms, such as *here, there, I, you, this, that,* derive part of their interpretation from the context in which the listener-speaker interaction takes place. While terms such as *I* and *here* remain unambiguous because they are self-referential, other deictic terms (*this, that, there*) remain indeterminate unless the speaker makes some sort of gesturing motion such as a head nod, a change in eye gaze, or a pointing motion to indicate an appropriate referent. Deictic gestures, coupled with deictic utterances, can play an important role during classroom interactions because they establish a distinction between figure (topic) and ground (Hanks, 1992; Roth & Lawless, in press-e). For example, Nick (Figure 1) used both abstract and concrete deixis by saying "these two" (abstract) and by putting his finger on the two blocks (concrete).

Iconic gestures, also referred to as *representational* gestures (Kendon, 1988) and covered by *lexical* gestures (Krauss & Hadar 1999), include those hand/arm movements that bear a perceptual relation with concrete entities and events. They draw their communicative strength from being perceptually similar to the phenomenon that is being talked about (McNeill, 1985). Thus, Nick used an iconic gesture when he traced an ephemeral trajectory similar to those that he and his peers had earlier observed. Iconic gestures are therefore said to have a transparent relationship to the idea they convey, particularly within a narrative event in which they depict concrete objects and events (McNeill, 1992). Compared to the ordinarily linear beats, iconic gestures often involve two or three dimensions and have greater amplitude (Hadar, 1989). Nick's gesture of the proposed trajectory extended both in vertical and in horizontal dimensions.

Metaphoric gestures are similar to iconic gestures in that they make reference to a visual image; however, the images to which they refer pertain to abstractions.

In such gestures, abstract content is given form in the imagery of objects, space, movement, and so forth. For example, a mathematician holding steady one hand while she moves the other hand toward it until the two palms touch as she discusses the concept of "approaching the limit" (McNeill, 1992) is using a metaphorical gesture, as is a student modeling a mathematics speed problem by the use of his hands (Hall, 1996). This form of gestures frequently appears in technical discussions involving abstract content, particularly in areas such as mathematics or physics (Roth & Welzel, 2001). Nick's gesture was classified as iconic because he had previously seen images where consecutive positions of the circular object were presented simultaneously, giving an image of a parabolic trajectory. However, not all gestures that stand for a trajectory are iconic. One study described the trajectories gestured by physicists to articulate movement in an abstract "phase space" (Ochs, Gonzales, & Jacoby, 1996; Ochs, Jacoby, & Gonzales, 1994). Here, the physicists' travels through graphic space, and thus their gestures, are metaphoric in nature.

Gestures are pervasive but the four types are not equally represented in particular speech events. There is evidence that during narration iconic gestures more often appear as references to story events while deictic and metaphoric gestures and beats appear in references to story structure (Cassell & McNeill, 1991). However, gesture phenomena are not yet well understood. In part, the relative frequency of the different types of gestures may depend on the presence and type of artifacts that can be pointed to or serve as ground against which gestures serve as figure (Roth & Lawless, in press-e). There have also been occasions marked by the complete absence of gestures when primary school children told a story they recently heard or wrote (Riseborough, 1982).

Competing Models of Gesture Production

Two theories about the nature and function of hand gestures accompanying speech dominate the current scientific literature (Beattie & Shovelton, 1999). One of these theories suggests that gestures convey no semantic information beyond that of the linguistic utterances that accompany them (Butterworth & Hadar, 1989; Hadar & Butterworth, 1997). In this theory, gestures are epiphenomenal to linguistic expression, which itself arises from preexisting semantic models underlying the talk. When the speaker searches for an appropriate word, there will be pauses that increase with the unfamiliarity of the word (and, possibly, the speaker's topical domain). In such cases, utterances are delayed with respect to the corresponding gestures. In this theory, gestures may have one or more of four distinct functions. Thus, gestures may act as an interruption suppression signal indicating that the speaker has not completed his or her turn. Gestures may increase the overall neuronal activation potential, helping to prime a word's firing potential more quickly when the activation for the word is too low and too slow. Third, the production of an iconic gesture may facilitate word search by exploiting a different route to the phonological lexicon. This process would require a translation of the semantic model into a perceptual model. Finally, gestures may "leak through" (Hadar and Butterworth's expression), although the corresponding selected words have been censored and suppressed for some reason before they had been uttered. In this theory, therefore, iconic gestures are epiphenomenal; they can be attributed to different aspects of word search and retrieval.

The second theory is based on the assumption that gestures and speech share a computational stage and are therefore part of the same psychological structure (McNeill, 1985, 1992). This shared stage is also referred to as the "semantic model." Because speech and gesture are driven by the semantic model, they constitute alternate modalities for expressing semantic content (meaning). Alternative avenues are particularly important when there are gaps in the speaker's lexicon (McNeill, 1992) or when gestures, because they are better at expressing spatially extended features, are a more appropriate expressive modality (Goldin-Meadow, 1999; Lemke, 1999b). In my opening example, an iconic gesture allowed Nick to communicate to his peers the particulars of trajectory, even though he did not have access to the vocabulary of standard physics discourse. Here, the gesture filled a logical gap by covering a "situation in which there is the movement of a particular shape of thing" (McNeill, 1992, p. 129) and therefore expressed both manner and cause of movement not covered by common English verbs. Whereas speech and gesture develop out of the same psychological structure, iconic gestures, because of their similarity relation, require less transformation. They reflect the content of the semantic model more faithfully. It is therefore possible to catch a glimpse of students' understanding of a given concept in the gestures they adopt even when having difficulty articulating their understanding (Church & Goldin-Meadow, 1986). Recently, this gesture-speech mismatch has become the focus of several educational researchers whose results are discussed below.

To this day, empirical studies have not been able to eliminate one theory in favor of another. On the one hand, some research reports delays between the onset of gestures and corresponding words of up to 3.75 seconds (Morrel-Samuels & Krauss, 1992; Roth, in press; Schegloff, 1984), thereby challenging the gesture-speech synchrony that underlies McNeill's theory. On the other hand, the facilitation of lexical access that forms the core of the Butterworth and Hadar model also has been challenged repeatedly on the following grounds. First, there is no significant decrease in gesture frequency when individuals are asked to retell a story up to six times (Beattie & Coughlan, 1998). Second, research subjects whose gestures were inhibited recalled more low frequency words, a result that is inconsistent with the theory of lexical facilitation (Beattie & Coughlan, 1999). Both findings undermine Butterworth and Hadar's theory, which would have predicted decreases in (a) gesture frequency, because unfamiliar words have become more familiar and (b) occurrence of low frequency words, because facilitative moment of gestures was inhibited. Two alternative theories have recently been proposed but have yet to be tested empirically. The first theory extends McNeill's (1992) claim that gesture is involved in the conceptual planning of an utterance by suggesting that gesture helps speakers "package" spatial information into units appropriate for speech expression (Kita, 2000). Based on detailed studies in naturalistic contexts, the second theory does away with the notion of a semantic model in situations where individuals are unfamiliar with a context (Roth & Lawless, in press-d), claiming instead that the semantic model is the outcome of learners' verbal and gestural interactions with the material and social world.

There is strong evidence that deictic gestures serve a communicative function (Goodwin, 1986; Hanks, 1992; Haviland, 1993; Levinson, 1997) but the value of iconic and metaphoric gestures remains contested. Whereas many researchers accept that gesture and speech have a common origin, there remains little consensus as to whether or not listeners glean any semantic information from iconic gestures that is not conveyed by speech. In short, if gestures do not communicate anything then it is possible that they merely serve the speaker. On the other hand, if they do communicate information, they become an important resource in discourse interactions, as is suggested by some research findings that listeners do attend to the gestures of others. (Cassell, McNeill, & McCullough, 1999; McNeill, Cassell & McCullough, 1994). Despite their differences, most current theories (e.g., Hadar & Butterworth, 1997; Krauss & Hadar, 1999; McNeill, 1999) suggest that iconic gestures emulate from a visual cognitive component that is semantically related to a concept or unit of discourse that corresponds to the gesture. It is this idea that remains paramount to most educational research on gestures because it suggests that gestures might actually provide some insight into the mind of the speaker.

Gestures in Development and Learning

Gestures play an important role in learning, development, and communication of children (Piaget, 1959). Early research showed that almost all the rules children verbalize while explaining a board game to an adult are accompanied by gestures; the gestures provide cognitive support when children attempt to talk about difficult tasks (Evans & Rubin, 1979). Recently, a small number of researchers have begun to study the role of gesture in knowing, learning, and problem solving on Piagetian tasks (e.g., Church & Goldin-Meadow, 1986; Goldin-Meadow, Alibali, & Church, 1993), in mathematics (e.g., Alibali, 1999; Garber, Alibali, & Goldin-Meadow, 1998), and in science/medicine (Crowder, 1996; Lemke, 1999b; Roth, 2000).

Experimental Studies

The bulk of the existing experimental gesture studies was conducted at the University of Chicago by Susan Goldin-Meadow and her associates (for a summative review see Goldin-Meadow, 1999). As a whole, these studies make four core claims: First, gestures reveal knowledge that is not expressed in speech. Second, gestures reveal implicit or emergent knowledge that is expressed in speech only at some later point; gestures can be said to constitute the "leading edge" in children's cognitive development. Third, the mismatch between gestures and speech is an indication of the readiness to learn. Fourth, the changes in the gesture-speech relationship can be interpreted as reflecting a path of knowledge change.

With respect to the first and second claims, several studies show that for particular concepts, students can be found in one of three stages (Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988). First, children (usually younger) express an incorrect conceptual understanding in both speech and gestural modalities. Second, other children gesturally express correct conceptual understanding, whereas their speech still expresses incorrect conceptual understanding. Finally, some children (usually older or instructed) correctly express the concept by both gestural and verbal means. Subsequent studies also showed that it is possible to distinguish discordance between gesture and utterance from inconsistency in verbal explanations as a predictor for transition. Children who are in transition with respect to a particular concept can be identified on the basis of the inconsistency in the information conveyed in speech versus gesture—rather than inconsistency in the information conveyed in speech alone (Perry et al., 1988).

In a follow-up study, children were examined in a rating task that did not involve gesture (Garber, Alibali, & Goldin-Meadow, 1998). The children rated solutions derived from procedures they conveyed uniquely in gesture higher than solutions derived from procedures they did not convey at all. Thus, gesture was deemed to be a vehicle through which children sometimes uniquely express their knowledge that may be accessible to a different modality in other tasks. When gesture reinforced the representation expressed in the spoken description, students were likely to solve the problem using a strategy compatible with that representation—much more likely than when gesture did not reinforce the spoken description (Alibali, Bassok, Olseth-Solomon, Syc, & Goldin-Meadow, 1999). The results indicated that gesture and speech together provide a better index of mental representation than speech alone.

On the basis of these studies, it was hypothesized that as children move through transitional states, they attempt to employ multiple procedures, suggested by a mismatch between procedures indicated through gesture and procedures indicated through speech, which is used as evidence for the existence of (dual) multiple representations. As the child's explanations move towards a single correct procedure, gesture and speech coordinate once again into a single correct procedure and an appropriately correct state of concordance is observed.

In their early work, Goldin-Meadow and her associates hypothesized that gesture-speech discordance is a general characteristic of individuals grappling with a particular concept, which they understand only partially, but for which they are ready to receive training (Church & Goldin-Meadow, 1986; Perry et al., 1988). Gesture-speech discordance, as expressed in the third claim, is therefore an indication of readiness for instruction. With respect to a particular concept, those children who provide discordant understanding by gestural and verbal means should therefore draw greater benefit from instruction than children who provide concordant but incorrect conceptual understanding. Using children who had not yet mastered a concept, these studies showed that those whose gestures and talk were discordant were in fact more likely to benefit from instruction than those who were concordant.

The fourth major claim arising from the experimental studies pertains to the path of knowledge change as it can be inferred from changing speech-gesture relationships. For example, the relationship between gesture and speech was monitored over a series of mathematics tasks among fourth graders (Alibali & Goldin-Meadow, 1993). The majority of children who learned to solve equivalence problems correctly did so by adhering to the following trajectory: First, they produced a single, incorrect procedure that, when they entered a discordant state, was accompanied by a second procedure in the gestural modality. Finally, these children again produced a single but correct procedure.

The studies in the Goldin-Meadow group generally hypothesize the existence of definite parallel cognitive states during developmental transition states (e.g., Alibali & Goldin-Meadow, 1993; Goldin-Meadow, Nusbaum, Garber, & Church, 1993). Such research leaves open questions about the nature of the mechanisms by means of which different cognitive states (or cognitive strategies) come about and the nature of the path between these states. Alibali (1999) studied the changes children instructed on mathematical equivalence problems undergo between pretest and posttest. The results show that knowledge changes gradually and unevenly; knowledge variability manifested itself in mismatches between gestural and verbal expressions in children's problem explanations. Completely consistent states do exist but they are rare and short lived; variable knowledge states, even when they persist, are strikingly dynamic.

Summarizing the results of her research group's extensive work on gesturing and learning, Goldin-Meadow (1997) suggested that gesture is indeed a window to the mind. Gesture-speech mismatches indicate readiness for learning a concept. During the learning process, gesture serves as a window into what a learner is thinking particularly if she or he uses dual strategies. Information conveyed in gesture is not tied to the hands. Goldin-Meadow concluded that gesture might contribute to the learning process not only by providing a unique view of the learner's thoughts, useful to experimenters and communication partners alike, but perhaps by stimulating those thoughts as well.

Classroom Studies of Gestures in Science

A very small number of studies, some of which do not even focus on gestures per se, provide evidence for the important role gestures play in the face-to-face meetings of scientists (Goodwin, 1995; Ochs, Gonzales, & Jacoby, 1996; Ochs, Jacoby, & Gonzales, 1994; Suchman & Trigg, 1993; Woolgar, 1990). All of these studies included descriptions of how deictic gestures allow scientists to orient each other to particular entities salient to one but not to others or to coordinate talk about highly abstract concepts, on the one hand, and visual displays, on the other. Furthermore, because iconic and metaphorical gestures are of a topological nature, they are used by scientists to depict phenomena and concepts that are much more difficult to describe in words, which are of typological nature (Lemke, 1999b). A number of studies in science classrooms underscore the importance of gestures in science talk (Crowder, 1996; Roth, 1999b, 2000). In contrast to the studies in the previous subsection, all of the studies reviewed here worked in the tradition of anthropological (Haviland, 2000; Kendon, 1994; Widlok, 1997) and linguistic research on gestures and therefore employed ethnographic and discourse-analytic methods.

When students and scientists are observed in their everyday settings, high frequencies of deictic, iconic, and metaphorical gestures become salient. These gestures have to be seen not only with respect to the talk that accompanies them but also with respect to the perceptual ground (e.g., Hall & Stevens, 1995). That is, in these situations, individuals not only point to specific items in their settings—a piece of equipment, a feature of an inscription—or to abstract items and locations in space, but they also use iconic gestures whose shapes are motivated by particular objects or events. Gestures are particularly frequent when students construct an explanation of a phenomenon in the moment and they appear to help students to predict, revise, and coordinate elements in a model (Crowder, 1996; Roth, 2001). Therefore, when the classroom context supports the use of gestures students may develop scientific modes of discourse much more rapidly than when the context does not support the use of gestures (Roth, 1996). In this situation, gestures often precede their verbal equivalent initially by weeks and subsequently on the order of several seconds; once students are familiar with a topic, their gestures coincide with the verbal equivalent (Crowder, 1996).

Several studies attempted to understand gestures in situations where students made scientific arguments over and about (a) drawn (still) graphical models, (b) computer-based "runable" graphical models, and (c) three-dimensional models of architectural structures (Roth, 2000, in press; Roth & Welzel, 2001). First, in the absence of scientifically appropriate discourse, students' gestures already pick out, describe, and explain scientific phenomena in ways that are consistent with scientific explanations. There may be a delay of several weeks before agreement, from a scientific perspective, is achieved between the two modalities. Second, during the initial appearance of appropriate scientific expressions, deictic and iconic gestures precede the associated utterances. The delay decreases with increasing correctness. Third, as students' familiarity with a domain increases, scientific talk takes on greater importance and gestures begin to coincide with the talk.

To arrive at socially shared perceptions two individuals have to witness two consecutive scenes and experience them as perceptually similar, communicate that they experienced them as such, and integrate the different resources (materials, gestures, writing) available in the situation (Ford, 1999; Roth & Lawless, in press-b, in press-d). Signals (verbal, gestural) are merely part of the perceptual salience that gets correlated with other signals and with situations. Because they face novel situations, students in real classrooms provide ad hoc explanations and descriptions, involving speech and gestures, that lack the coherence usually associated with scientific discourse. We call this form of talk *muddle* (Roth, 1996) because it is characterized by hesitations, restarts, mumbles, silences, malaproprisms, disfluencies, tics, colloquial speech, self-repair, other-repair, and many other characteristics of mundane or everyday communication (Koschmann & LeBaron, 2001; Rorty, 1989). Beginning with muddle, the trajectory then moves from observation sentences to observation categoricals, and to the simplest forms of explanation (theory) that generalize correlations across situations (e.g., "Whenever there is a force, there is acceleration"). In these changes, gestures appear to play a crucial role in the emergence of students' coherent theory talk.

Students make salient particular entities in their environment by means of utterances and different types of gestures; entities and events at the three levels of significance, that is, objects, gestures, and words are coordinated with each other (Roth & Lawless, in press-d). The difficulty arises in part from the fact that the gestures and words can be shifted during periods of transition. What the videotapes of science learning in many different contexts reveal is a multi-level process (Roth, 2000, 2001; Roth & Lawless, in press-b, in press-c; Roth & Welzel, 2001). First, there are processes of shaping the content (what language and gestures are referring to) and expression continua (the media such as gesture and language that are used for referring and representing). Second, there are the processes by means of which expression continua are correlated with their possible content. Finally, there are the processes by means of which signs get connected to the segmentations of the content continuum. More abstract forms of communication (writing, abstract symbols) are used competently only later in the emerging communicative patterns.

In a developmental sequence of communicative action, gestures, which are initially similar to action sequences, substantially shorten and represent actions in metonymic form (Roth & Lawless, in press-a). In another process, action sequences are based on kinesthetic schemata that themselves find their metaphoric expression in language. Again, gestures enact kinesthetic schemata that are correlated with verbal expressions.

In summary, there are three main results from this research. First, gesturing in the presence of the objects and events that are the content of students' expressions allows students to construct complex explanations by lowering the cognitive load.

Second, gestures provide a medium on which the development of scientific discourse can piggyback. Third, gestures provide the material that "glues" layers of perceptually accessible entities and abstract concepts (Roth & Welzel, 2001). When students enter conversations in the presence of material objects, these objects provide a phenomenal ground against which students can enact metaphorical gestures that em*body* (give a body to) entities that are conceptual and abstract (Roth & Lawless, in press-c).

Role of Gestures in Teaching

Gestures can be regarded as mediating devices that link the social and the psychological (Vygotsky, 1978). Yet there is little research on the role gestures might take in teacher-students interactions. It is possible to deduce two possible functions of gestures in teaching. On the one hand, they might serve teachers as information to assess a student's current understanding of a topic; on the other, students might be able to use the teachers' gestures as additional resources for making sense of teacher talk, for example, by presenting novel perspectives on the lecture content (Corts & Pollio, 1999). After being shown videotapes of children articulating the same or different strategies in verbal and gestural modality, children, undergraduate students, and teachers exhibited similar sensitivity to gestures, frequently describing strategies that children had only expressed gesturally (Alibali, Flevares, & Goldin-Meadow, 1997; Kelly & Church, 1998).[2] Therefore, gestures are actively interpreted by listeners (Kelly, Barr, Church, & Lynch, 1999), and even without training children and adults alike are able to interpret children's words and gestures from videotapes appropriately (Goldin-Meadow, Wein, & Chang, 1992) and in live settings (Goldin-Meadow & Sandhofer, 1999).

In lectures and other forms of teacher presentations, iconic gestures may be more easily appropriated than language because they are encoded in the form of images and therefore do not require a translation (Roth & Lawless, in press-d). Thus, children were less likely to reiterate teacher speech if there was no gesture than if it was accompanied by a matching gesture; they were even less likely to reiterate teacher speech if it was accompanied by a mismatching gesture (Goldin-Meadow, Kim, & Singer, 1999). A study in a university-level architecture course showed that students rapidly used gestures highly similar to those earlier employed by the professor (LeBaron & Streeck, 2000). In conjunction with the lecturer's body position, gestures can orient students to aspects of a visual representation that the lecturer can point to and highlight by tracing, or to visual aspects of a representation not available in the room (Roth & Lawless, in press-e). However, because of their physical nature, a teachers' gestures may also lead students into non-scientific understanding when they interpret their teacher's gestures as iconic rather than as metaphoric representations, especially when gestures embody conceptual entities such as "electrons" (Roth & Welzel, 2001). The difficulty in comprehending lectures appears to increase when the lecturer's gestures are shifted temporally or conceptually with respect to their verbal equivalents (Bowen & Roth, 1998; Roth & Bowen, 1999).

In summary, then, because teachers (as other speakers) make available considerable gestural resources important for understanding a concept, students must attend to gestures as well as to speech to access all the information presented in a lesson (Flevares & Perry, 2001). Understanding the role and function of gestures in the relationship between teachers and student, therefore, ought to be an important aspect of educational research. In the following section, I attempt to chart an agenda for research interesting to educators and educational researchers.

Toward an Educational Research Agenda on Gestures and Gesturing

To the best of my knowledge, the previous section covers the existing research on the role of gestures in knowing and learning scientific and mathematical concepts in school-aged children. Despite these existing studies, the role of gestures in scientific and mathematical discourse remains largely unexplored in educational research (Lemke, 1998). Therefore, there is considerable potential in beginning a fruitful and implication-rich research agenda to elucidate different dimensions of gesturing in the learning of science and mathematics. Long-term training studies in young children show that encouraging the use of iconic gestures facilitates language acquisition (Goodwyn & Acredolo, 1998); furthermore, gestures provide second-language learners with support during transitional stages of language competencies (Gullberg, 1997). If the results of the qualitative studies of gesturing in science hold up in future studies, gestures may afford similar enhancements in the acquisition of science discourse. In this section, I provide specific gesture examples and interpretations as a way of introducing relevant issues and formulating research questions.

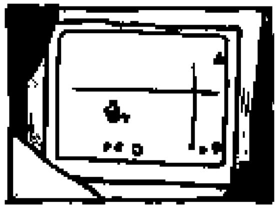
Mutual Orientation and Learning

The perception of physical and social objects and events is often taken for granted by educators. However, isolating entities from a perceptual ground is not an easy task and has played an important role in differentiating the learning abilities of people in, for example, the Group Embedded Figures Test (Witkin & Goodenough, 1981). Furthermore, research shows that students observing the same physics demonstrations make quite contradictory statements about what occurred (Roth, McRobbie, Lucas, & Boutonné, 1997). Because the physical entities are present in the communicative situation, interaction will be facilitated when the participants have the opportunity to use deictic or iconic gestures to enhance the salience of particular material configurations and events (Glenberg & Robertson, 1999; Koschmann & LeBaron, 1998). Gestures may therefore constitute an important resource in collaborative student activity for coordinating interactions, talk, and writing (Ford, 1999).

Episode 1. The following transcript was obtained from the same junior-level physics course as the introductory episode. Glenn, Elizabeth, and Ryan had not yet developed a language in which they used “vector,” “velocity,” or “acceleration” to distinguish the different arrows that appeared on the screen. Because there were six additional arrow-shaped tools available on the computer interface, students confused each other by referring to each of these eight entities as “arrow.” One such situation of confusion is illustrated in this episode (Figure 2).

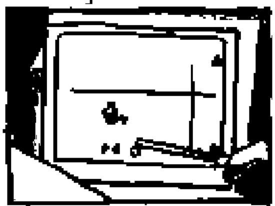
In this episode, one can see how gestures are used to identify particular features in the background that students had difficulty identifying by language alone. Here, Glenn wanted to “shift” one of the arrows near the center of the screen. Until that point, the students had manipulated only the two arrows that are objects in the microworld rather than objects surrounding and designed for manipulating the microworld.

01 G: Do you know how to shift the arrow thing the other way?

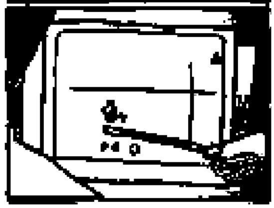


02 E: Was it this little arrow thing?
03 G: No, the big arrow, you know how it was… [cursor circles on screen]

04 E: Try these arrows

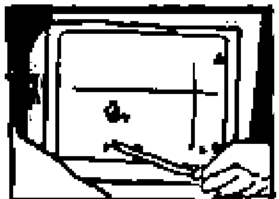


05 down there.



06 R: No, those will shift the screen.
07 E: No, not that one.

08 E: Like those two



09 arrows.

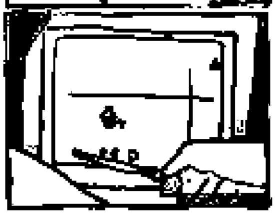


FIGURE 2. *Transcript including utterances, gestures, and indexical ground. When students are unfamiliar with a topic, deictic and iconic gestures prevail over mature descriptive and explanatory speech.*

Elizabeth's question, "Was it this little arrow thing?" (line 02), indicates that she did not know which arrow Glenn had talked about. Glenn specified the object as the "big arrow." Elizabeth then proposed that they "try these arrows down here," simultaneously pointing to two different places at the lower left of the monitor. Ryan suggested that these were not the appropriate arrows because they shifted the screen. There is then a difference in what he understood and what Glenn and Elizabeth were saying. Elizabeth interpreted Glenn as referring to different arrows than those that she had wanted to make salient and then engaged in a repair sequence by bringing the pointing pencil tip closer to the screen (lines 08–09).

My interpretation runs like this. In the first three lines, Elizabeth and Glenn have to settle on which arrow they are talking about, before Elizabeth introduces two arrows that were not salient before. Ryan's contribution indicated a difference between the shifting Ryan is trying to achieve and the shifting that is achieved when one clicks on the arrows indicated by Elizabeth. However, Elizabeth understood Ryan as referring to arrows different from those she had pointed to earlier (line 02). She engaged in another conversational repair by pointing again to two objects in the lower left of the screen. We can understand talk (using words) as making objects in the world salient. Here, students used the word "arrows" to make salient different entities appearing on the interface. But it is not clear which arrows were salient for each of the speakers. In this case, Elizabeth's gesture picked out two of these. Despite the pointing, however, Elizabeth perceived Ryan as having misinterpreted her earlier pointing and reiterated the pointing to the objects that she really meant.

Elizabeth's deictic gesture identified the "arrow" that she hypothesized the talk to be about and provided students with an opportunity to align each other perceptually to a particular object. However, because of the different and shifting referents of "big arrow," linguistic alignment was not achieved. Full perceptual alignment, requiring a consistent sign-referent relationship, was only achieved toward the end of the lessons when students perceived objects in the same way and consistently used the same words to refer to the objects that they isolated from the perceptual ground.

This episode provides an example of how people deal with the ambiguity of verbal deixis in praxis. In this situation, there was a potential for alternate referents given that there were two arrows. Here, Glenn engaged in a conversational repair because it was not clear which object was being referred to. Using the cursor, Glenn pointed to one of the arrows and asked "this one?" Elizabeth confirmed, thereby allowing Glenn to continue with the investigation. Because there are only two arrows, even a negative answer would have allowed Glenn to continue, this time by manipulating the other arrow.

Questions. The first episode raises a number of questions that future studies need to address. How do gestures (iconic, deictic, and beat) function in the coordination of collaborative activity? Of particular interest are the inconsistencies and temporal delays that are apparent during learning and development; both inconsistencies (Goldin-Meadow & Sandhofer, 1999) and delays (Bowen & Roth, 1998) may cause difficulties for the audience. If there are inconsistencies in the verbal and speech modalities during learning, one might ask, How do these inconsistencies mediate coordination and understanding within groups of learners? Furthermore, if temporal delays between gestures and corresponding speech by lecturers lead to comprehension problems, one might ask, How do temporal shifts mediate the communication comprehension in student-centered activity?

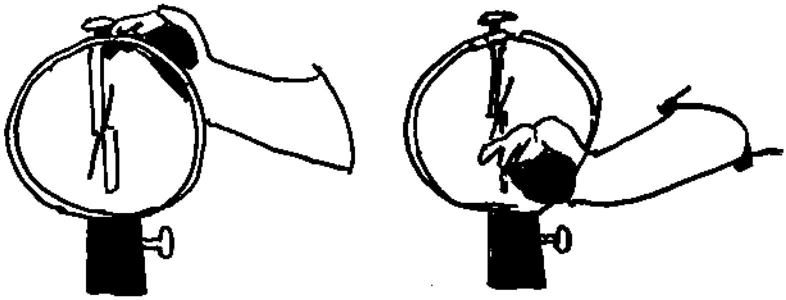
Whereas considerable research has focused on the way children express conceptual understandings in verbal form, very little is known about the role of gestures in expressing abstract mathematical and scientific knowledge. With the few exceptions cited in this review, very little is known about the relationship between gesture and speech when students learn the different abstract concepts that they encounter in school. We therefore need to determine, for instance, the nature of mathematical and scientific knowledge that students express in their words and gestures. Some of my own research reviewed here raises the possibility that the very fact of producing gestures, because it externalizes thinking, reflexively affects the student who produces the gestures. That is, externalization may forge links between embodied and abstract or symbolic forms of thinking. This raises the further question, Does the action of producing gestures influence student thinking, and if so, how?

Although there are indications that iconic gestures might arise from earlier manipulations (ergotic hand movements) and sensing (epistemic) movements (Hadar & Krauss, 1999; Roth, in press), very little is actually known about the extent to which symbolic gestures are related to physical activity. We therefore need to know, What is the relation between the manipulation of objects during "hands-on" activity and iconic gestures? Research would allow us to know more about the extent that "hands-on" activities allow children to develop abstract discourse. Furthermore, previous research produced the hypothesis that gesturing in the presence of concrete objects allows students to distribute their communication and cognition across the material setting (Roth & Lawless, in press-d). Does gesturing have consequences for learning abstract content? Empirical and experimental research has yet to be conducted to confirm or disconfirm this hypothesis.

There is already some evidence that gestures assist students in coordinating their interactions (Koschmann & LeBaron, 2001), but it has not yet been shown how gestures, coordination, and interaction are related to the types of knowledge students develop. It is important to know what function the different types of gestures serve in student-student communicative process and, ultimately, in the social and individual knowledge constructed by students in activity.

Metaphorical Gestures and "Abstract" Concepts

Metaphorical gestures, because they exploit the human capacity for visual imagery and the cognitive advantages of embodied metaphors (Johnson, 1987; Lakoff, 1987, 1998), may turn out to have particular relevance in the learning of traditionally difficult ("abstract") subject matter. Both metaphor and visual imagery allow a student's lived experiences to enter an otherwise unfamiliar domain, such as the physics discourse about static electricity. The following example was drawn from an eleventh-grade physics course in an academically streamed German school (*Gymnasium*). The students in this course had been studying a variety of concepts related to static electricity. However, static electricity is a difficult topic in part because the entities that populate the conceptual domains (electrons, atoms, nuclei, or atomic shells, charges) are not perceptually available. Thus, the discourse about atomic entities appears to be disconnected from the phenomenon, such as the changes in the needle position on an electroscope (Figure 3). In this



M: They are repelled and then are down here

FIGURE 3. *The teacher used a gesture to indicate the movement of electrons. Because electrons are conceptual rather than material entities, the gesture is a metaphorical one. The presence of the physical device allows students to coordinate material and associated conceptual entities.*

episode, the teacher used metaphoric gestures in the vicinity of the electroscope to illustrate the movement of electrons.

Episode 2. The teacher, Marion, and four students sat around an electroscope, a device that is used in physics to register electrostatic charges. When a charged object is brought close to the top knob, or a charged body is rubbed against the knob, the needle begins to deflect, indicating the presence of charges. The teacher wanted the students approaching the electroscope to learn a theoretical discourse that explains the deflection of the needle.

Prior to this episode, the teacher had told students that there were equal numbers of fixed positive and moveable negative charges in the device. When a negatively charged object is brought close "they [negative charges] are repelled and then are down here." Against this conversational history and the electroscope at hand, Marion modeled with her right hand the manner in which negative charges move downward. Given the geometry of the device, it is clear that the movement and the vertical central part mutually make each other salient. The movement of the negative charges cannot be but in the central part.

In these gestures, electrons come alive as material objects that move around in the material. This is not a universal description; physicists also talk about electrons in material bodies in terms of waves. In physics, "electrons" are diffused rather than strongly localized phenomena (like a ball). The students were already familiar with the phenomenon physically available to them. The gesture layers onto the phenomenal entities conceptual entities new to the students that would explain what can be seen. The conceptual entities are not simply fixed objects, but they are animated. The geometry of the movements is set against the geometry of the objects at hand. Whether or not it is reasonable to regard charges (electrons) as material bodies, like macroscopic entities, the gesture in fact portrays these conceptual entities as material ones. The equipment functions as common ground against which students and teachers can make sense of each other's talk.

This situation can be interpreted as one in which the world provides a stable ground against which conceptual (metaphorical) entities are mapped or a (common) ground to which the conceptual entities are anchored. Metaphorical gestures literally allow the embodiment of theoretical entities never available to perception. To put it another way, they "package" sensori-motor information suitable for linguistic expression (Alibali, Kita, & Young, 2000). Here, these entities are embodied in two ways. First, they are represented by a body part that signifies the entity. Second, the speaker's gestures enact the entity. When these gestures are in the presence of physical devices we get a layering of two different classes of entities. Objects and events that are perceptually at hand for all those present can also serve as background to the theoretical entities that appear against the perceived world as the ground. The theoretical explanation of the objects and events rides on top of the phenomenal description.

Questions. My review showed that metaphorical gestures might have a potential in assisting students to learn concepts that do not have experiential equivalents. The frequent engagement of children and high school students in hands-on activities raises questions about the relationship between hands-on activity, gestures, and abstract understandings. One might ask, How do metaphorical gestures relate to aspects of the hands-on activities within which they arise? How do learners bring metaphorical gestures, which have conceptual referents, and material objects and events into relationships?

On the surface, iconic and metaphorical gestures are indistinguishable; the differences between them arise from differences in their referents—for the former, structures in material objects and events, for the latter, abstract concepts. This poses the question, Do students distinguish between iconic and metaphorical gestures? Students are often unfamiliar not only with the scientific theories they are to learn but also with those structures in the material objects and events that are relevant to scientific theorizing. Even if no relationships were found between hands-on activity and metaphorical gestures, there might still be a role for the latter in the interaction between students and teachers. One may therefore be interested in posing and answering questions such as, How do teachers' metaphoric gestures mediate students' appropriation of abstract knowledge?

Gestures in Instructional Talk

Instructional talk is replete with gestures, allowing speakers to make salient specific aspects of texts and diagrams on the chalkboard, on overhead transparencies, or on slides. Although they appear to constitute a significant resource in meaning-making—because they underscore conceptual distinctions (Roth & Tobin, 1996), make salient relevant features (Koschmann & LeBaron, 2001), or orient the audience to different types of features (Roth & Lawless, in press-e)—the lecturer's ephemeral gestures (and body motion) are less likely to be recorded in student notes than his or her talk.

Episode 3. In this episode, an invited speaker talked to a class of seventh grade students who were studying the ecological health of a watershed. The teacher had asked, among others, a trained biologist and environmental activist (Mindy) to introduce the students to a variety of issues plaguing the watershed. In this episode, the lecturer used gestures to identify the confluence of two creeks (Figure 4.a, lines

a. b.

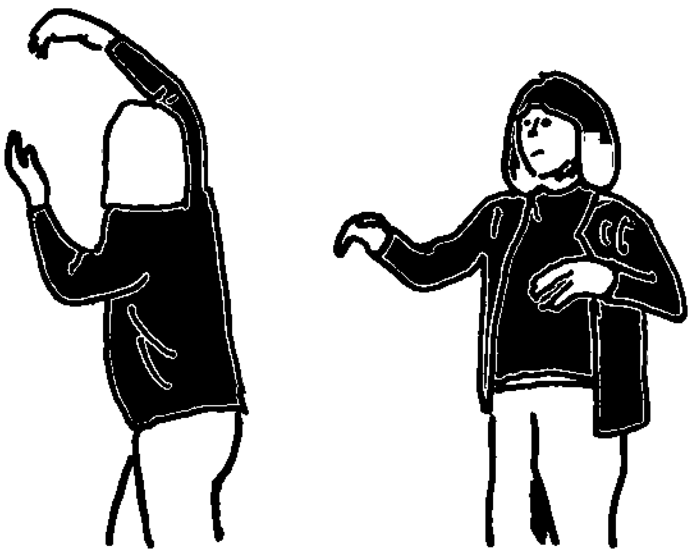


FIGURE 4. *Teachers employ gestures that may assist students in identifying salient features in a diagram, picture, or other representation, such as the confluence of two creeks on a map (a). Iconic and metaphoric gestures may assist in making salient topological features not easily communicated in words, such as the notion of "watershed" (b).*

01–04) and to provide a visual image of the concept of watershed (Figure 4.b, lines 05–07). In the first part, Mindy turned to the map behind her and talked about how and where the tributaries Goodwin Creek and Henderson Creek come together to form the main stem of Henderson Creek.

01 It has at that point * two parts that are draining into what's *
Gesture of two tributaries, Figure 4.a
02 called the main stem . . . * And this is basically *
Points to main stem
03 * the area where the creeks * are coming . . . Goodwin is coming this
Gesture of two tributaries, Figure 4.a
04 way and Henderson is coming down that way. . . .
Follows each tributary with finger in extended pointing gesture

This episode is part of the presentation where Mindy wanted to explain to the students what a watershed is. She did this in pointing to all the creeks that empty into the same main stem. Mindy used the same gesture three times to show the coming together of the two tributary creeks (lines 01, 02, 03) separated by deictic gestures to other features. The gesture is oriented to the graphic, the hands making salient the creeks on the map behind her.

After having pointed to and outlined the tributary creeks, their confluence, and the main stem on the map, Mindy visibly rotated her body to face the audience. She produced a gesture that articulated two tributaries again that eventually come together (shown in the joining of her two hands) and continuing as one creek (two hands, moving away from her).

05 * So this is basically a drainage area that is collecting all
Body and arm position as in Figure 4.b, but slight 'pumping'
06 water that is coming down * and it is all funneling down
motion of both arms, hands are approaching and touching
07 through the streams and ultimately into Sandwich inlet.
Hands joined move forward and away from speaker's body.

The accompanying gesture (Figure 4.b) helped establish that a watershed is a drainage area. She then brought the two hands together in a downward and forward motion as if showing two creeks that flow downward, near each other and eventually join to continue together (lines 06–07). Thus, Mindy set up a narrative space where the heights forming a watershed transform into the two arms of a creek until they combine into one. The three-dimensional nature of the gesture allowed her to articulate the topology of "coming down" and "funneling," which cannot easily be articulated in words.

Questions. This example, like the previous ones, raises a number of questions to be addressed in future educational research. Because two previous research studies showed that teachers' gestures can both assist and hinder student learning (Flevares & Perry, 2001; Roth & Bowen, 1999), it is important to ask, How do instructors' gestures mediate students' understanding in science and mathematics? To better understand how temporal shifts hinder comprehension, we need to better understand whether a listener's familiarity with the topic decreases his or her sensitivity to discrepant information due to temporal and conceptual shifts. We need to understand in particular whether or not students use a lecturer's body orientation and gestures as resources in making sense of the talk and, if they do, how they use this information.

Conclusion

It should be clear that the study of gesture in education constitutes an open field and raises many important questions. Research into these questions has the potential to shed light on knowing and learning in everyday school settings. In my view, two types of research would be especially helpful in engaging in the important questions raised throughout this article: quantitative hypothesis testing and qualitative hypothesis generating. Both types of research can lead to very similar conclusions. The two lead articles in a recent issue of *Discourse Processes,* one using experimental manipulation, the other a qualitative discourse analysis perspective, have underscored this point (Glenberg & Robertson, 1999; Roth, 1999a). Both studies showed the role of gestural and verbal deixis in learning new skills from instructions and learning physical concepts through hands-on activities and both arrived at the same conclusions about the role of deixis in knowing and learning.

Nevertheless, the qualitative and quantitative approaches differ. Hypothesis testing requires theories, which therefore limit what a researcher will look for. Thus, the researchers in the laboratories led by Goldin-Meadow and Alibali, respectively, assume that children begin with one conceptual model, hold two, sometimes contradictory models during conceptual transition, and then hold a single better model after development is completed. These researchers and their associates therefore identify one or two different conceptual positions from their transcripts. On the other hand, researchers who move frame by frame through video material are more likely to notice the continuous variation that discourse and gestures undergo at those moments when students have not yet obtained a semantic model (their talk resembles "muddle"). Mature forms of communication emerge out of an increasing coordination of discursive and gestural elements. Thus, this type of research is suited to generate theories concerned with the formation of semantic models; the transition between two consecutive models that a learner might adhere to; and the moment-to-moment coordination of speech, gesture, and salient aspects in the setting in the production of communication, and, ultimately, in the construction of scientific and mathematical knowledge.

Finally, there is at least one study that showed how the identification of pre- and post-instructional conceptual models can be integrated with frame-by-frame studies of language emergence (Duit, Roth, Komorek, & Wilbers, 2001). However, gesture studies should be driven by the questions we ask rather than by one or the other research methodology.

Acknowledgments

The writing was made possible in part by Grant 410-99-0021 from the Social Sciences and Humanities Research Council of Canada (SSHRC) and by a SSHRC internal grant administered by the University of Victoria. I am grateful to my student Daniel V. Lawless who contributed to establishing the database for this review. I thank Professor Dr. Manuela Welzel for access to her database from which the example in Episode 2 was taken. Finally, the comments and questions raised by three anonymous reviewers allowed me to improve on an earlier version.

Notes

[1] More mature, because of the primacy that is attributed to words in scientific and scholarly discourse.

[2] To reiterate, listeners never or seldom use other body movements on their own to make inferences about what the speaker wanted to say, although these other body movements are additional resources in identifying the real content of an utterance.

References

Alibali, M. W. (1999). How children change their minds: Strategy change can be gradual or abrupt. *Developmental Psychology, 35,* 127–145.

Alibali, M. W., Bassok, M., Olseth-Solomon, K., Syc, S. E., & Goldin-Meadow, S. (1999). Illuminating mental representations through speech and gesture. *Psychological Science, 10,* 327–333.

Alibali, M. W., & DiRusso, A. A. (1999). The function of gesture in learning to count: More than keeping track. *Cognitive Development, 14,* 37–56.

Alibali, M. W., Flevares, L. M., & Goldin-Meadow, S. (1997). Assessing knowledge conveyed in gesture: Do teachers have the upper hand? *Journal of Educational Psychology, 89,* 183–193.

Alibali, M. W., & Goldin-Meadow, S. (1993). Gesture-speech mismatch and mechanisms of learning: What the hands reveal about a child's state of mind. *Cognitive Psychology, 25,* 468–523.

Alibali, M. W., Kita, S., & Young, A. J. (2000). Gesture and the process of speech production: We think, therefore we gesture. *Language and Cognitive Processes, 15,* 593–613.

Bates, E. (1976). *Language and context: The acquisition of pragmatics.* New York: Academic Press.

Bavelas, J. B., & Chovil, N. (2000). Visible acts of meaning: An integrated message model of language in face-to-face dialogue. *Journal of Language and Social Psychology, 19,* 163–194.

Bavelas, J. B., Chovil, N., Coates, L., & Roe, L. (1995). Gestures specialized for dialogue. *Personality and Social Psychology Bulletin, 21,* 394–405.

Beattie, G., & Coughlan, J. (1998). Do iconic gestures have a functional role in lexical access? An experimental study of the effects of repeating a verbal message on gesture production. *Semiotica, 119,* 221–249.

Beattie, G., & Coughlan, J. (1999). An experimental investigation of the role of iconic gestures in lexical access using the tip-of-the-tongue phenomenon. *British Journal of Psychology, 90,* 35–56.

Beattie, G., & Shovelton, H. (1999). Do iconic hand gestures really contribute anything to the semantic information conveyed by speech? An experimental investigation. *Semiotica, 123,* 1–30.

Bowen, G. M., & Roth, W.-M. (1998). Lecturing graphing: What features of lectures contribute to student difficulties in learning to interpret graphs? *Research in Science Education, 28,* 77–90.

Butterworth, B., & Beattie, G. (1978). Gesture and silence as indicators of planning in speech. In R. N. Campbell & P. T. Smith (Eds.), *Recent advances in the psychology of language* (pp. 347–360). New York: Plenum.

Butterworth, B., & Hadar, U. (1989). Gesture, speech, and computational stages: A reply to McNeill. *Psychological Review, 96,* 168–174.

Cassell, J. (1999). Embodied conversational agents: A new paradigm for the study of gesture and for human-computer interface. In L. S. Messing & R. Campbell (Eds.), *Gesture, speech, and sign* (pp. 203–222). New York: Oxford University Press.

Cassell, J., & McNeill, D. (1991). Gesture and the poetics of prose. *Poetics Today, 12,* 375–404.

Cassell, J., McNeill, D., & McCullough, K. (1999). Speech-gesture mismatches: Evidence for one underlying representation of linguistic & nonlinguistic information. *Pragmatics & Cognition, 7,* 1–33.

Church, R. B., & Goldin-Meadow, S. (1986). Using the relationship between gesture and speech to capture transitions in learning. *Cognition, 23,* 43–71.

Corts, D. P., & Pollio, H. R. (1999). Spontaneous production of figurative language and gesture in college lectures. *Metaphor and Symbol, 14,* 81–100.

Crowder, E. M. (1996). Gestures at work in sense-making science talk. *The Journal of the Learning Sciences, 5,* 173–208.

Crowder, E. M., & Newman, D. (1993). Telling what they know: The role of gestures and language in children's science explanations. *Pragmatics & Cognition, 1,* 341–376.

DePaulo, B. M. (1992). Nonverbal behavior and self-presentation. *Psychological Review, 111,* 203–243.

Dittman, A. T., & Llewellyn, L. G. (1968). Relationship between vocalizations and head nods as listener responses. *Journal of Personality and Social Psychology, 9,* 79–84.

Duit, R., Roth, W.-M., Komorek, M., & Wilbers, J. (2001). Fostering conceptual change by analogies: Between Scylla and Charybdis. *Learning and Instruction, 11,* 283–303.

Duncan, S., Jr. (1972). Some signals and rules for taking speaking turns in conversations. *Journal of Personality and Social Psychology, 23,* 283–292.

Efron, D. (1972). *Gesture, race and culture.* The Hague, Netherlands: Mouton. (Originally published in 1941 as *Gesture and environment,* New York: King's Crown Press.)

Ekman, P., & Friesen, W. V. (1969). The repertoire of nonverbal behavior: Categories, origins, usage, and coding. *Semiotica, 1,* 49–98.

Evans, M. A., & Rubin, K. H. (1979). Hand gestures as a communicative mode in school-aged children. *The Journal of Genetic Psychology, 135,* 189–196.

Feyereisen, P. (1987). Gestures and speech, interactions and separations: A reply to McNeill (1985). *Psychological Review, 94,* 493–498.

Flevares, L. M., & Perry, M. (2001). How many do you see? The use of nonspoken representations in first-grade mathematics lessons. *Journal of Educational Psychology, 93,* 330–345.

Ford, C. E. (1999). Collaborative construction of task activity: Coordinating multiple resources in a high school physics lab. *Research on Language and Social Interaction, 32,* 369–408.

Freedman, N. (1977). Hands, words, and mind: On the structuralization of body movement during discourse and the capacity for verbal presentation. In N. Freedman & S. Grand (Eds.), *Communicative structures and psychic structures* (pp. 109–132). New York: Plenum Press.

Garber, P., Alibali, M. W., & Goldin-Meadow, S. (1998). Knowledge conveyed in gesture is not tied to the hands. *Child Development, 69,* 75–84.

Gibson, K. R., & Ingold, T. (Eds.). (1993). *Tools, language and cognition in human evolution.* New York: Cambridge University Press.

Glenberg, A. M., & Robertson, D. A. (1999). Indexical understanding of instructions. *Discourse Processes, 28,* 1–26.

Goldin-Meadow, S. (1997). When gestures and words speak differently. *Current Directions in Psychological Science, 6,* 138–143.

Goldin-Meadow, S. (1998). The development of gesture and speech as an integrated system. *New Directions for Child Development, 79,* 29–42.

Goldin-Meadow, S. (1999). The role of gesture in communication and thinking. *Trends in Cognitive Sciences, 11,* 419–429.

Goldin-Meadow, S., Alibali, M. W., & Church, R. B. (1993). Transitions in concept acquisition: Using the hand to read the mind. *Psychological Review, 100,* 279–297.

Goldin-Meadow, S., Kim, S., & Singer, M. (1999). What the teacher's hands tell the student's mind about math. *Journal of Educational Psychology, 91,* 720–730.

Goldin-Meadow, S., Nusbaum, H., Garber, P., & Church, R. B. (1993). Transitions in learning: Evidence for simultaneously activated hypotheses. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1–16.

Goldin-Meadow, S., & Sandhofer, C. M. (1999). Gesture conveys substantive information to ordinary listeners. *Developmental Science, 2,* 67–74.

Goldin-Meadow, S., Wein, D., & Chang, C. (1992). Assessing knowledge through gesture: Using children's hands to read minds. *Cognition and Instruction, 9,* 201–219.

Goodwin, C. (1986). Gestures as a resource for the organization of mutual orientation. *Semiotica, 62,* 29–49.

Goodwin, C. (1995). Seeing in depth. *Social Studies of Science, 25,* 237–274.

Goodwin, C. (1996). Practices of color classification. *Ninchi Kagaku (Cognitive Studies: Bulletin of the Japanese Cognitive Science Society), 3*(2), 62–82.

Goodwin, C. (2000). Action and embodiment within situated human interaction. *Journal of Pragmatics, 32,* 1489–1522.

Goodwyn, S. W., & Acredolo, L. P. (1998). Encouraging Symbolic Gestures: A New Perspective on the Relationship between Gesture and Speech. *New Directions for Child Development, 79,* 61–73.

Gullberg, M. (1997). Gesture as a communication strategy in second language discourse: A study of learners of French and Swedish. *Travaux de l'Institut de Linguistique de Lund, 35,* 9–253.

Hadar, U. (1989). Two types of gesture and their role in speech production. *Journal of Language and Social Psychology, 8,* 221–228.

Hadar, U., & Butterworth, B. (1997). Iconic gestures, imagery, and word retrieval in speech. *Semiotica, 115,* 147–172.

Hadar, U., & Krauss, R. K. (1999). Iconic gestures: The grammatical categories of lexical. *Journal of Neurolinguistics, 12,* 1–12.

Hall, R. (1996). Representation as shared activity: Situated cognition and Dewey's cartography of experience. *The Journal of the Learning Sciences, 5,* 209–238.

Hall, R., & Stevens, R. (1995). Making space: A comparison of mathematical work in school and professional design practices. In S. L. Star (Ed.), *The cultures of computing* (pp. 118–145). Oxford, England: Blackwell.

Hanks, W. F. (1992). The indexical ground of deictic reference. In A. Duranti & C. Goodwin (Eds.), *Rethinking context: Language as an interactive phenomenon* (pp. 43–76). New York: Cambridge University Press.

Haviland, J. B. (1993). Anchoring, iconicity, and orientation in Guugu Yimithirr pointing gestures. *Journal of Linguistic Anthropology, 3,* 3–45.

Haviland, J. B. (1998). Early pointing gestures in Zinacantan. *Journal of Linguistic Anthropology, 8,* 162–196.

Haviland, J. B. (2000). Pointing, gesture spaces, and mental maps. In D. McNeill (Ed.), Language and gesture: Window into thought and action (pp. 13–46). Cambridge: Cambridge University Press.

Iverson, J. M., & Goldin-Meadow, S. (1998). Why people gesture when they speak. *Nature, 396,* 228.

Johnson, M. (1987). *The body in the mind: The bodily basis of imagination, reason, and meaning.* Chicago: Chicago University Press.

Kelly, S. D., & Church, R. B. (1998). A comparison between children's and adults' ability to detect conceptual information conveyed through representational gestures. *Child Development, 69,* 85–93.

Kelly, S. D., Barr, D. J., Church, R. B., & Lynch, K. (1999). Offering a hand to pragmatic understanding: The role of speech and gesture in comprehension and memory. *Journal of Memory and Language, 40,* 577–592.

Kendon, A. (1967). Some functions of gaze-direction and social interaction. *Acta Psychologica, 26,* 22–63.

Kendon, A. (1980). Gesticulation and speech: Two aspects of the process of utterance. In M. R. Key (Ed.), *The relationship of verbal and nonverbal communication* (pp. 207–227). The Hague, Netherlands: Mouton Publishers.

Kendon, A. (1984). Did gesture have the happiness to escape the curse at the confusion of Babel? In A. Wolfgang (Ed.), *Nonverbal behavior: Perspectives, applications, cultural insights* (pp. 75–114). Lewiston, NY: Hogrefe.

Kendon, A. (1985). Behavioural foundations for the process of frame attunement in face-to-face interaction. In G. P. Ginsburg, M. Brenner, & M. von Cranach (Eds.), *Discovery strategies in the psychology of action* (pp. 229–253). London: Academic Press.

Kendon, A. (1988). How gestures can become like words. In F. Poyatos (Ed.), *Cross-cultural perspectives in nonverbal communication* (pp. 131–141). New York: Hogrefe.

Kendon, A. (1994). Do gestures communicate? A review. *Research on Language and Social Interaction, 27,* 175–200.

Kendon, A. (1996). An agenda for gesture studies. *Semiotic Review of Books, 7,* 8–12.
Kendon, A. (1997). Gesture. *Annual Review of Anthropology, 26,* 109–128.
Kita, S. (2000). How representational gestures help speaking. In D. McNeill (Ed.), *Language and gesture* (pp. 162–185). Cambridge: Cambridge University Press.
Koschmann, T., & LeBaron, C. (1998, August). *The complementarity of speech and gesticulation in learner articulation.* Paper presented at the Eighth Annual Meeting of the Society for Text & Discourse, Madison, WI.
Koschmann, T., & LeBaron, C. (2001). Learner articulation as interactive jointing: Studying gesture conversationally. Retrieved January 30, 2001, from *http://edaff.siumed.edu/tk/articles/gestures*
Krauss, R. M., & Hadar, U. (1999). The role of speech-related arm/hand gestures in word retrieval. In L. S. Messing & R. Campbell (Eds.), *Gesture, speech, and sign* (pp. 93–116). New York: Oxford University Press.
Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago Press.
Lakoff, G. (1998). The metaphorical conception of events and causes: Some implications of cognitive science for philosophy. In X. Arrazola, K. Kepa, & F. J. Pelletier (Eds.), *Discourse, interaction and communication: Proceedings of the Fourth International Colloquium on Cognitive Science* (pp. 49–83). Dordrecht, Netherlands: Kluwer.
LeBaron, C. D., & Streeck, J. (2000). Gestures, knowledge, and the world. In D. McNeill (Ed.), *Gestures in action, language, and culture* (pp. 118–140). Cambridge: Cambridge University Press.
Lemke, J. L. (1998). Multiplying meaning: Visual and verbal semiotics in scientific text. In J. R. Martin & R. Veel (Eds.), *Reading science* (pp. 87–113). London: Routledge.
Lemke, J. L. (1999a). Meaning-making in the conversation: Head spinning, heart winning, and everything in between. *Human Development, 42,* 87–91.
Lemke, J. L. (1999b). Typological and topological meaning in diagnostic discourse. *Discourse Processes, 27,* 173–185.
Levinson, S. (1997). Language and cognition: The cognitive consequences of spatial description in Guugu Yimithirr. *Journal of Linguistic Anthropology, 7,* 98–131.
Masur, E. F. (1983). Gestural development, dual-directional signaling, and the transition to words. *Journal of Psycholinguistic Research, 12,* 93–109.
McNeill, D. (1985). So you think gestures are nonverbal? *Psychological Review, 92,* 350–371.
McNeill, D. (1992). *Hand and mind: What gestures reveal about thought.* Chicago: The University of Chicago Press.
McNeill, D. (1998). Speech and gesture integration. *New Directions for Child Development, 79,* 11–27.
McNeill, D. (1999). Triangulating the growth point—arriving at consciousness. In L. S. Messing & R. Campbell (Eds.), *Gesture, speech, and sign* (pp. 77–92). New York: Oxford University Press.
McNeill, D., Cassell, J., & McCullough, K. (1994). Communicative effects of speech-mismatched gestures. *Research on Language and Social Interaction, 27,* 223–237.
Messing, L. S., & Campbell, R. (Ed.). (1999). *Gesture, speech, and sign.* New York: Oxford University Press.
Morrel-Samuels, P., & Krauss, R. M. (1992). Word familiarity predicts temporal asynchrony of hand gestures and speech. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 615–622.
Namy, L. L., & Waxman, S. R. (1998). Words and gestures: Infants' interpretations of different forms of symbolic reference. *Child Development, 69,* 295–308.

Nunez, R., & Freeman, W. J. (Eds.). (2000). *Reclaiming cognition: The primacy of action, intention and emotion.* Thorverton, England: Imprint Academic.

Ochs, E., Gonzales, P., & Jacoby, S. (1996). "When I come down I'm in the domain state": Grammar and graphic representation in the interpretive activity of physicists. In E. Ochs, E. A. Schegloff, & S. A. Thompson (Eds.), *Interaction and grammar* (pp. 328–369). New York: Cambridge University Press.

Ochs, E., Jacoby, S., & Gonzales, P. (1994). Interpretive journeys: How physicists talk and travel through graphic space. *Configurations, 2,* 151–171.

Perry, M., Church, R. B., & Goldin-Meadow, S. (1988). Transitional knowledge in the acquisition of concepts. *Cognitive Development, 3,* 359–400.

Piaget, J. (1959). *The language and thought of the child.* London: Routledge & Kegan Paul.

Rimé, B., & Schiaratura, L. (1991). Gesture and speech. In R. S. Feldman & B. Rimé (Eds.), *Fundamentals of nonverbal behavior.* New York: Press Syndicate of the University of Cambridge.

Riseborough, M. G. (1982). Meaning in movement: An investigation into the interrelationship of physiographic gestures and speech in seven-year-olds. *British Journal of Psychology, 73,* 497–503.

Rorty, R. (1989). *Contingency, irony, and solidarity.* Cambridge: Cambridge University Press.

Roth, W.-M. (1996). Thinking with hands, eyes, and signs: Multimodal science talk in a grade 6/7 unit on simple machines. *Interactive Learning Environments, 4,* 170–187.

Roth, W.-M. (1999a). Discourse and agency in school science laboratories. *Discourse Processes, 28,* 27–60.

Roth, W.-M. (1999b). The evolution of umwelt and communication. *Cybernetics and Human Knowing, 6* (4), 5–23.

Roth, W.-M. (2000). From gesture to scientific language. *Journal of Pragmatics, 32,* 1683–1714.

Roth, W.-M. (2001). Situating cognition. *The Journal of the Learning Sciences, 10,* 27–61.

Roth, W.-M. (in press). From epistemic (ergotic) actions to scientific discourse: The bridging function of gestures. *Pragmatics & Cognition.*

Roth, W.-M., & Bowen, G. M. (1999). Decalages in talk and gesture: Visual and verbal semiotics of ecology lectures. *Linguistics & Education, 10,* 335–358.

Roth, W.-M., & Lawless, D. (in press-a). How does the body get into the mind. *Human Studies.*

Roth, W.-M., & Lawless, D. (in press-b). Science, culture, and the emergence of language. *Science Education.*

Roth, W.-M., & Lawless, D. (in press-c). Scientific investigations, metaphorical gestures, and the emergence of abstract scientific concepts. *Learning and Instruction.*

Roth, W.-M., & Lawless, D. (in press-d). Signs, deixis, and the emergence of scientific explanations. *Semiotica.*

Roth, W.-M., & Lawless, D. (in press-e). When up is down and down is up: Body orientation, proximity and gestures as resources for listeners. *Language in Society.*

Roth, W.-M., McRobbie, C., Lucas, K. B., & Boutonné, S. (1997). Why do students fail to learn from demonstrations? A social practice perspective on learning in physics. *Journal of Research in Science Teaching, 34,* 509–533.

Roth, W.-M., & Tobin, K. (1996). Aristotle and natural observation versus Galileo and scientific experiment: An analysis of lectures in physics for elementary teachers in terms of discourse and inscriptions. *Journal of Research in Science Teaching, 33,* 135–157.

Roth, W.-M., & Welzel, M. (2001). From activity to gestures and scientific language. *Journal of Research in Science Teaching, 38,* 103–136.

Schegloff, E. A. (1984). On some gestures' relation to talk. In M. Atkinson & J. Heritage (Eds.), *Structures of social action: Studies in conversational analysis* (pp. 266–296). Cambridge: Cambridge University Press.

Suchman, L. A., & Trigg, R. H. (1993). Artificial intelligence as craftwork. In S. Chaiklin & J. Lave (Eds.), *Understanding practice: Perspectives on activity and context* (pp. 144–178). Cambridge: Cambridge University Press.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press.

Widlok, T. (1997). Orientation in the wild: The shared cognition of Hai||om bushpeople. *Journal of the Royal Anthropological Institute, 3,* 317–332.

Witkin, H. A., & Goodenough, D. R. (1981). *Cognitive styles: Essence and origin.* New York: International University Press.

Woolfolk, A. E., & Brooks, D. M. (1983). Nonverbal communication in teaching. In E. W. Gordon (Ed.), *Review of Research in Education, 10,* 103–149.

Woolgar, S. (1990). Time and documents in researcher interaction: Some ways of making out what is happening in experimental science. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 123–152). Cambridge, MA: MIT Press.

Wundt, W. (1973). *The language of gestures.* The Hague, Netherlands: Mouton.

Author

WOLFF-MICHAEL ROTH is Lansdowne Professor of Applied Cognitive Science, MacLaurin Building, University of Victoria, Victoria, BC, Canada V8W 3N4; mroth@uvic.ca. His research interests include ethnography of scientific practice, science education in and for the community, mathematical representations, and praxis perspectives on teacher knowledge. His recent books include *Re/Constructing Elementary Science, At the Elbow of Another: Learning to Teach by Coteaching,* and *Science Education as/for Sociopolitical Action.*