The Role of Gesture in Meaning Construction

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Abstract

This paper examines the role of gesture in the shared meaning-making processes of a group of 6th grade students studying plate tectonics using a geographic information system (GIS) data visualization tool. Students’ verbal and gestural characterizations of key concepts of plate motions (i.e., subduction, rift, and buckling) were transcribed and coded across episodes of small-group work over the course of the unit, tracking emergent concepts and their subsequent refinements. The emergence histories of these concepts showed that they were initiated in gesture before they were conveyed in speech. Once they appeared in speech, speech and gesture figured prominently in further co-construction (elaboration, modification, and refinement) of the meaning of the key concepts. Gestures were found to afford an interaction space for meaning negotiation processes among group members through manual manipulation, imitation, and correction of each others’ gestures. These interactions furthered the group’s shared understanding of plate tectonics, and mediated individual student learning. The findings suggest that explicit attention to gesture in instruction and assessment holds great potential for furthering our understanding of the development of domain understandings in science investigations.
The Role of Gestures in Meaning Construction

INTRODUCTION

This paper brings together analytic perspectives on discourse and gesture to examine the processes of meaning construction during an inquiry project in earth science. During this project, small groups of students worked together to make sense of complex visual data presented in an interactive computer-based geographic information system (GIS). Even casual observations of the interactions that occurred in this learning environment made clear that students employ a rich array of interactional processes – interactions with the materials and each other. During these interactions, students put forth, shared, exchanged, and reasoned about information through multiple modes of communication, including visual, verbal, and gestural forms. Accordingly, understanding meaning construction in this context required that we use analytic lenses that are sensitive to and allow us to capture these multiple forms of information representation, their interconnections, and their role in reasoning processes and meaning construction.

Multimodal Means of Communication

A growing body of research indicates that hand gesture plays an important role in mathematical and scientific reasoning. A number of studies report that students and teachers use gesture when they talk about science (Crowder & Newman, 1993; Crowder, 1996; Goodwin, 1986; Roth, 2001; Roth & Lawless, 2002; Roth & Welzel, 2001; Rasmussen, Stephan, & Allen, 2004). Other research indicates that gesture shapes mathematical conversations in certain learning environments, often leading to new or more accurate task understanding (Church, Ayman-Nolley & Mahootian, 2004; Goldin-Meadow & Singer, 2004; Singer & Goldin-Meadow, 2005). As well, researchers have used spontaneous hand gestures to assess children’s problem-
solving strategies in math and science (Church & Goldin-Meadow, 1986; Crowder & Newman, 1993; Perry, Church, & Goldin-Meadow, 1988; Roschelle, 1992; Roth, 1999; Roth & Welzel, 2001). Although the research indicates that in many instances gestural and verbal modes reinforce one another, there are also a number of situations in which gestures provide information not accessible through speech alone. Indeed, gesture has sometimes revealed problem-solving strategies that were not evident at all in speech (Church 1999; Church & Goldin-Meadow, 1986; Perry et, 1988).

In science domains that are complex, and/or not directly observable in space and time (e.g., earth’s orbit, seasonal change, tectonic plate motions, etc.), gestures may play a particularly important role in constructing meaning. Gesture may make it possible for students to concretize and make visible phenomena that they cannot see and ideas that are difficult to capture in their speech alone. By way of illustration, consider the response of a 6th-grade student to her teacher’s question about how plate movements might create earthquakes. The student’s spoken answer is: “When the plates are moving in the same direction.” The words alone are ambiguous: is she envisioning vertical, horizontal, or circular motion? Are the plates moving in parallel, or toward one another? However, the student’s hand gestures provide disambiguating information: both hands are flat with palms facing down; she moves her hands toward each other, and when the fingertips meet the palms move vertically, creating a mountain shape. Her gestures convey to both the teacher and other students information beyond that which is visible in speech alone: she is describing two plates converging, colliding, and rising.

The 6th grade student’s gesture is an example of what is referred to as an iconic or representational gesture (McNeill, 1992) and is the type of gesture on which this paper focuses. We focus on representational gestures because they are a means of expressing conceptual
information (Crowder, 1993; Goldin-Meadow, Alibali & Church, 1993). They use iconic imagery to express information about people, objects and events (McNeill, 1992). Indeed, researchers have found that when adults and children talk about difficult to conceptualize information about spatial objects and events, they often produce gestures that bear close resemblance to the image they are describing (Crowder & Newman, 1993; Kita, 2000; Hostetter, Alibali, & Kita, 2006; McNeill, 1992; Roth, 2003). For example, Crowder and Newman (1993) found that elementary students produced representational gestures when they were actively constructing knowledge about abstract scientific phenomena (seasonal change), and they did so despite their lack of scientific vocabulary. In other words, the students’ gestures conveyed scientific ideas that they could not articulate in their speech (Crowder & Newman, 1993).

In the present research we were interested in examining how students worked together to construct the meanings of abstract scientific concepts in the domain of plate tectonics. Because of the iconicity of representational gestures we expected that students would be able to describe, explain, elaborate, or provide new information in gestures even when they appeared not to have the domain language in speech. By focusing on their representational gestures, we intended to closely examine how students copied, manipulated, and added to each other’s gestures as they co-constructed the meanings of these abstract concepts during small group work. Our data suggest that gestures were a crucial aspect of the “representational practices” (Greeno, 2006) the group relied on to interpret, represent, and share their thinking with each other.

In addition to representational gestures, points and traces are two other kinds of gestures that play important roles in knowledge construction processes. Points and traces have a referential function in that they often are used to establish common ground and focus attention on particular referents (Clark, 2005; McNeill, 1992). Especially when working with others,
ensuring that group members share referents is a prerequisite for effective co-construction of meaning. However, detailed analyses of the role that points and traces play in this process is beyond the scope of this paper. We are focusing on points and traces in other papers currently in progress (e.g., Radinsky, Singer, & Goldman, in preparation) in which we are concerned with shared reasoning about visual data patterns, a process in which points and traces figure prominently. In the present paper, we instead focus on the role of representational gestures in constructing shared understanding of the abstract domain concepts central to plate tectonics.

*The Interaction Situation: a plate tectonics investigation using GIS*

Geographic information systems (GIS) are a class of computer-based data visualization tools that can offer students access to studying complex scientific phenomena at otherwise unobservable scales of space and time (Audett & Abegg, 1996; Edelson & Gordin, 1998). For example, in the domain of plate tectonics, this tool makes visible elevation, earthquake and volcano data over many years’ time span and at a global geographic scale. The GIS makes it possible for students to reason about visual data, and study complex phenomena and abstract science concepts in ways consistent with the practices of scientists. That is, the GIS provides students with increased opportunity to describe what they see in the data, develop coherent explanations, link their explanations to the data, understand someone else’s explanation, and compare, contrast, debate, and evaluate different possible interpretations. These processes are both cognitive and social, and involve skills and habits included in national science education standards (National Research Council, 1996).
Specific Focus: Visual data on plate tectonics

We focused on the role of gesture in meaning construction by a group of three 6th-grade students during the course of a science inquiry unit that involved complex visual data available through the GIS data visualization tool MyWorld (http://www.worldwatcher.northwestern.edu/myworld/). We specifically examined the data patterns that supported the emergence and development of an understanding of crustal plate movements, particularly three types of plate motion relevant to their investigation: 1) subduction, in which one plate slides under another at a boundary, (2) rift, in which two plates diverge at a boundary, and (3) buckling, in which two plates converge and rise to form continental mountains. We selected this focus because these are central concepts in plate tectonics, and they were concepts that students had little or no familiarity with prior to the unit. This contrasts with other more familiar concepts discussed in the unit, such as islands, mountains and elevation.

Our choice to focus on small-group interactions was motivated by several considerations. The small-group context contributes to both individual and shared meaning making around complex data, and is a place where students can try out their emerging models of science concepts among peers. In this effort, they may be more likely to try to make their understanding visible than when they are in a whole class setting and gestures may therefore figure prominently. Gestures produced in the small group allow a student’s emerging conceptual models to be manipulated, copied, and inspected by the listener. The relative lack of direct mediation of students’ communications by the teacher makes the small group a convenient setting in which to study the emergence of these understandings.
Similar to several other studies that have begun to explore this relatively uncharted territory of knowledge construction in small groups and the role of gestures in this process, (e.g., Enyedy, 2005; Roth, 1999, 2003), the present study is a detailed case analysis of one group of students over an extended period of time working together. The goal of this exploratory case study (Yin, 2003) is not to make claims about the representativeness of particular patterns of gestural interaction. Rather, the goal is to further understand the kinds of mediational roles gesture can play in groups.

Method

Research Setting and Participants

This study was conducted in an urban public elementary school, an ethnically and economically diverse magnet school (i.e., drawing students from a range of neighborhoods) that is non-selective in admissions, resulting in academic diversity as well. The study took place in a 6th grade classroom during the enactment of the Earth Structures and Processes project (Radinsky, Loh, Mundt et al., 1999), a 9-week inquiry unit on plate tectonics using GIS. The unit was part of the regular science curriculum. We followed a group of three-6th graders, two girls and one boy: Eliana, Kerry, and Leo (pseudonyms). This group was selected for analysis in collaboration with the teacher, with the goal of having diversity both in academic performance and in gender. We followed this focus group over the course of the unit, tracking the emergence of the target concepts evidenced in their small group work with visual data.

The Corpus. There were 40 episodes of classroom activity across 19 instructional days. Each episode was videotaped by one researcher, with another present in the classroom taking field notes. Of the 40 episodes, 13 were small-group work (the others were whole-class discussions, teacher instructions, mini-lessons, or individual work). During the small-group
episodes the video camera followed the focus group of three students; in all other situations it followed the teacher and/or the flow of whole-class interaction. Of the 13 small-group episodes, we selected five. These five are the complete sample of small group episodes during which students were working with visual data. Another seven of the small-group episodes were prior to the introduction of data, and an eighth was not analyzed because of instructional time missed due to computer problems.

Students’ curricular task during these five small-group episodes was to apply concepts introduced in whole-class instruction to generating an explanation for crustal formations (i.e., elevation patterns) and earthquake and volcano data patterns found in a particular place on earth. Each group of students was assigned a different location to study. The group presented here was assigned the 25° square area surrounding Japan (see Figure 1), which includes the island, the sea of Japan to the west, a deep ocean-floor trench on the Pacific side, and a strong pattern of earthquakes and volcanoes passing from northeast to southwest through the region.

[INSERT FIGURE 1 ABOUT HERE]

Of the five episodes of small-group work studied, the first involved students analyzing patterns of elevation using a topographic model of the region created earlier; the second and third involved using elevation data in the GIS; and the fourth and fifth added earthquake and volcano data in the GIS. Students were assigned the tasks of finding the plate boundaries, determining the type of plate motion at the boundaries (e.g. subduction, rift, or buckling), hypothesizing the direction of plate motion, and preparing a presentation to the class explaining their findings.

These five focal episodes were transcribed in their entirety, including an accuracy check by a second researcher for each transcript. Each session transcript included all student talk for the continuous time allocated to small-group work (excluding visits to the group from the teacher).
In addition, an individual post-interview was conducted with each student in the group. The post-interview was used in the present study to provide a final point in time for tracking students’ mention of target concepts in speech and gesture, as discussed in the results. Due to pragmatic constraints we were not able to collect pre-interviews in the course of this study. The semi-structured interview consisted of 22 free-response questions designed to determine students’ understandings of key concepts in the domain, i.e. elevation, depth, earthquakes, volcanoes, and plates, as well as a prediction and observation exercise with a map showing volcano data. Interviews (approximately 15 minutes in length) were transcribed by a researcher, and transcripts were verified by a second researcher.

**Coding and Reliability**

We transcribed and coded speech and gesture from the videotaped data. We describe the coding and reliability processes we followed for both speech and gesture.

*Speech.* All student speech during each target episode was transcribed and time-coded by one researcher, and each transcript was verified by a second researcher. The verbal unit of analysis was the *turn* in group talk, i.e. an uninterrupted speech burst by an individual student with no pause greater than two seconds. Overlapping speech by two students was treated as two separate turns, with the overlap indicated in the transcript. To ensure reliability of the segmentation of turns, a sample of 10% of the total transcribed discourse was transcribed independently by a third researcher to test for agreement in turn segmentation. Agreement on turn segmentation was 81.4%, and all disagreements were resolved through discussion. Discourse that involved any participant other than the three members of the target group (i.e. the teacher, a researcher, or another student) was excluded from the analysis.
Each turn was coded for spoken references to the three target plate movement concepts: subduction, rift or buckling. An occurrence was coded if the word was used (e.g., “subduction”) or if there was a description of the meaning of the concept (e.g., “one plate slides under the other plate” was coded as subduction). If the word and a description occurred in the same turn it was counted as a single occurrence of that concept. If more than one of the target concepts was referenced in the same turn, it was counted as two occurrences, one for each concept.

To establish reliability of speech coding, two researchers independently coded three of the five target episodes for occurrences of spoken references to these three plate movement concepts. Both researchers agreed that 24 turns contained references to one or more of the target concepts. Two additional turns were identified by only one of the researchers, and discussion resolved these conflicts in favor of occurrence in each turn. In the 26 turns in this reliability sample that contained references to the target concepts, the two researchers agreed 100% of the time on which concept was referenced. Appendix A contains examples of speech and the target concept it was coded as.

Gesture. Coding for gesture was done from the videotape of the episode with a turn-segmented transcript of the verbal information at hand. Using an adaptation of McNeill’s (1992) gesture coding scheme, one researcher coded all five of the episodes for points, traces, and representational gestures. As discussed earlier, our focus on this paper is on the representational gestures, but in coding the episodes we did code for all three types. This enables us to determine the relative frequency of representational gestures compared to other gestures that were involved with co-construction processes.

Points were coded if the student used their fingers or hand to indicate some specific location (e.g., Japan) or object (e.g., volcano) on the GIS displays or on any of the other
materials they were looking at during the episode (e.g., clay model, handouts). Traces were coded if the students moved their fingers or hand along a part of the GIS displays (e.g., a line of earthquakes) or other materials.

Representational gestures were coded on two dimensions: hand-shape (e.g., two flat hands with palms faced down or one hand with a closed fist) and motion (e.g., hands moving horizontally toward each other, hands moving horizontally away from each other or hands moving vertically, up and down). Appendix A provides additional descriptions of examples of how we coded gestures. The meaning of the representational gesture was inferred based on the context of the accompanying speech. For example, a student making a spreading-apart motion, with both hands flat, faced down, while saying, “the plates spread apart,” was coded as a spoken and gestured reference to the concept rift.

To establish reliability on the gesture coding, another researcher (not the same one who did the speech coding reliability) coded two of the five small-group episodes for occurrences of gesture and their meaning in the case of gestures identified as representational. Gesture coding for the first episode was used to establish clear code definitions and clarify the gesture-coding process. Reliability on the second episode was calculated separately for occurrence and number of gestures in a turn, each type of gesture (points, traces, and representational gestures), and their meaning. There was 90% agreement on whether or not a turn contained any gesture, and on number of gestures per turn. Disagreements were resolved in discussion. Forty-five of the 407 turns in the episode contained gesture, and a total of 73 gestures were identified within these 45 turns. Coders agreed on over 85% of the gesture-type identifications, resolving disagreements in discussion. Specifically, agreement on points was 86%, on traces 90%, and on representational
gestures 87%. For identified representational gestures there was 100% agreement on the meaning.

RESULTS AND DISCUSSION

The coded data were used to determine the frequency of occurrence of each type of gesture and to construct a history of each student’s use of speech and representational gesture in reference to plate motions (i.e., subduction, rift, and buckling). As shown in Table 1, gesture occurred in 18% of the total turns identified across the five episodes (426/2,403), with notable differences in the percentages for each student (from Kerry’s 8% to Eliana’s 27%). These 426 turns contained a total of 518 gestures, with multiple gestures occurring in 49 of these turns. Table 2 presents the frequencies of each type of gesture for each student and for the group as a whole. Points were the most frequent across the group (62% of the total), and for each student. Traces were least frequent (17%), and representational gestures comprised 21% of all gestures.

The data in Table 2 also show that two students (Eliana and Leo) produced the vast majority of gestures in this group (475/518), although all three students produced some gestures of each type. The points and traces typically functioned as means of directing attention to specific data objects to establish a common visual referent. These gesture types are backgrounded in the present analysis, as described above. The remainder of this discussion focuses on representational gestures.

Students used representational gesture to communicate their understandings of plates and plate motion to each other: 43% of the 111 representational gestures conveyed plate movement concepts, i.e., rift, buckling, and subduction. The other 57% of representational gestures covered a wide range of concepts both in the domain (e.g., earth, elevation, lava) and out of the domain.
The present analyses focus only on references to these three plate motion concepts because we want to examine the role of gesture in meaning construction when students are learning new science concepts. As noted earlier, we did not have pre-interview data from these students. However, we did conduct the same interview on a second cohort of students in the same school. Based on the data from the second cohort, we were reasonably certain that the target concepts tracked in this study (rift, bucking, and subduction) were not already part of these students’ knowledge base. This inference is supported by the fact that none of the students used these terms at any point in group work or class discussions before they were introduced by the teacher, despite numerous opportunities for students to do so. Students’ prior knowledge of other more familiar domain-relevant concepts, such as elevation and lava, was more ambiguous. Hence the decision to restrict the analyses to the three plate motion concepts.

Our analyses suggest that representational gestures played two major roles in the sense-making activity of the group. First, representational gestures referring to each concept preceded verbal mention of each concept over the course of small-group work, suggesting that these gestures facilitated communication in the group about concepts which students had not yet begun to use in speech. Second, over the course of the unit, the gestural representations became a focal point of co-construction of understandings of rift, buckling, and subduction, both in negotiating the meaning of these unfamiliar concepts, and in deciding how to apply the concepts in explaining visual data. We now take up each of these findings in turn.

Representational gesture preceded speech for target concepts

Table 3 shows the day and minute of the first instance of each student’s reference in gesture or speech of each target concept. Table 3 shows that the students’ initial references to all three concepts were conveyed in gesture before they were communicated in speech. For
example, on Day 1, all three students conveyed the *rift* plate motion in gesture only, but none referenced it in speech. On Day 2, spoken references to rift appeared in describing plate motions: “…so this one must be splitting apart from this one making another type of earthquake, the rift zone, so that would make earthquakes here.”

[INSERT TABLE 3 ABOUT HERE]

The same is true for *buckling*, which was first gestured on Day 2, minute 13.35 by Eliana before being referenced by her for the first time in speech on Day 4, minute 11.49. Similarly, *subduction* was gestured first on Day 2, minute 3.0 by Leo, before being referenced for the first time in speech later the same day (at minute 6.74).

Not only did gesture precede speech for each concept for the group as a whole but the same was true for each student individually. Each concept for each student occurred in gesture before speech, sometimes earlier on the same day (e.g., *subduction* for Leo on Day 2), sometimes on a preceding day. Note that for Kerry none of the concepts was mentioned in speech until the post-interview, and *subduction* was never spoken at all; it was referenced only in gesture during the post-interview.

For some students there was movement of references for a particular concept across modalities (e.g. from gesture to speech) within a session. For example, at the beginning of Day 2, Leo conveyed *subduction* in gesture only, and by the middle of that same session he described *subduction* in speech. Students’ communication of these concepts changed and moved, both at a micro-time scale (within a small-group session), and also building over a longer period of time (over the course of the unit).

Gesture appeared to play a role both in helping the gesturer to communicate to the group, and also in enabling the listeners to engage with one another's newly developing understandings.
prior to being able to articulate them. It is also worth noting that speech did not replace gesture as a means of referring to the plate motion concepts in this small-group context. Rather, both co-existed and participated in the co-construction of understanding of the target concepts, to which we now turn.

_Gesture mediated co-construction of the meaning of concepts_

Figure 2 depicts all turns coded as references to the three target concepts (rift, subduction, and buckling), in speech and in gesture, during the five small-group sessions in which students worked with visual data. These turns are represented on a timeline for each day (plotted by minutes, derived from the time-coded transcripts) for each concept. The symbols on each timeline distinguish references in speech (white squares) from references in gesture (black diamonds).

[INSERT FIGURE 2 ABOUT HERE]

The representation of the coded data in Figure 2 reveals several brief time periods that are characterized by a rapid series of references to target concepts, appearing as clusters of squares (spoken references) and diamonds (gestured references) in the figure. These clusters reflect the combined turns of all three students. Five such clusters can be seen in Figure 2:

- Day 1, minutes 34-36,
- Day 2, minutes 1 – 4,
- Day 2, minutes 17 – 21,
- Day 4, minutes 7 – 14, and

Analysis of the video during each of these clusters revealed that they involved intensive interaction, in which concepts introduced by one group member were often picked up,
manipulated and discussed by others in the group. References to the concepts moved across modalities and from student to student.

For example, Figure 3 provides a more detailed view of the cluster of references that occurred on Day 4 min 7-14, showing the student and modality of each reference. During this episode all three students were inspecting the elevation data in the GIS, trying to figure out how the ocean-floor trench near Japan was formed by plate motion. Kerry said, "I think they go like this," while bringing both hands, flat palms faced down, meeting at tips, and then forming a peak – a normative gesture to represent buckling. Figure 4 provides still photographs of this gestured sequence. Within the next couple of turns both Eliana and Leo mentioned buckling in speech as a possible explanation for the trench (Figure 3, min. 11-12). Kerry responded by saying, “That’s what I said,” to which Leo agreed, saying, “We’ll call it Kerry’s theory.”

We interpret this episode as reflecting multimodal co-construction. Several aspects of the interactions among the group members provide evidence for this interpretation. First, both Eliana and Leo appropriated in their speech Kerry’s buckling explanation, although Kerry had communicated it only in gesture. In addition, Kerry’s claim in this exchange (“That’s what I said”) equated her gesture with having “said” buckling, even as her group-mates’ agreement acknowledged that her gesture had “spoken” to them and communicated a theory.

In this episode, information in gesture was picked up and discussed in the group, furthering their shared understanding of the concept of buckling. Gesture provided useful shorthand that helped students share understandings, standing in for concepts they did not yet articulate in speech (as Kerry did not throughout this episode). The result was an “interweaving”
of gesture and speech (Crowder, 1996) – alternating occurrences of spoken and gestured references to buckling.

The same interweaving pattern was found in other cases after the initial reference to a concept in speech, e.g. for rift (Day 2, min 1-4 and min. 17-21) and subduction (Day 2, min. 17-21; Day 4, min. 4-14; and Day 5, min. 16-20). These episodes involved pick up, discussion, and modification among the group members within the same session. Concepts did not move unidirectionally from gesture to speech, but were "knocked around" in the group back and forth across modalities. Gesture also provided a shared space in which students negotiated and debated both the meanings of the target concepts, and also their application to explaining specific patterns of visual data.

For example, the concept of rift was first referenced in the group toward the end of Day 1, in a cluster of references in gesture only (see Figure 5), as they were discussing the deep trench they observed in the ocean off the eastern coast of Japan. On the following day the group engaged in an extended discussion of what might happen at a rift zone, now using both gesture and speech to communicate (Figures 6 and 7). The graphs of these episodes indicate that rift was referenced in speech (Figure 6, min 1-2), and then in a flurry of spoken and gestured references (around min 3). Later the same day we see rift being referenced repeatedly in both modalities.

[INSERT FIGURES 5, 6 and 7 ABOUT HERE]

Figure 8 provides an excerpt of the speech and gesture of this discussion, showing the complexity of the concepts being discussed. Leo was of the opinion that either a rift zone or a subduction zone might cause a trench to form. The earlier part of the discussion (not included here) indicated that both Eliana and Leo understood that rift zones involve plates moving apart from each other, but they were not sure what might happen in the boundary area as the plates
diverge. Leo stated that when the plates split apart the magma might form “a tiny little ditch” (Figure 8, Turn 5). Eliana had earlier shown uncertainty about whether the magma would sink at such a boundary, as Leo suggested, or whether it would rise. Her comments in this exchange show that she was considering both possibilities: a rising hand accompanied the words “magma is coming out” (Turn 4), and then a falling finger showed the other possibility, accompanied only by the word “lava” (Turn 6).

This exchange about the nature of rift took place across gestured and spoken modalities (Figures 6 and 7). Furthermore, as Figure 8 shows, the gestured representation of the physical relationships in the proposed models of rift were distributed across Leo’s and Eliana’s hands. When Leo raised his hands to show adjacent plates in gesture, Eliana first moved Leo’s hands apart (the rift motion, Figure 8 turn 2), and then raised her own hand between Leo’s to represent magma, first moving it upward (turn 4) as one possibility, then moving it downward (turn 6) as another. In speech and in gesture, we see Eliana and Leo’s collaborative construction of two clear alternatives of what rift might involve.

This negotiation of meaning across gesture and speech is remarkably complex, both spatially and in terms of the underlying causal model. The motions being debated involve spatial processes in three dimensions (two directions of lateral plate movement as the plates diverge, and two possibilities of vertical motion as the magma either rises or falls). The two possible causal models are both plausible: that magma would fall between the diverging plates, or that magma would rise as the plates create space (the accepted scientific model). The data in Figure 8 suggest that the gestural representation provided a medium that was used in the group not only as a shorthand for concept words, but also to make these complex meanings understood to one
another. Students used gesture to help each other coordinate various components of plate motions (e.g., Eliana moving Leo’s hands apart and adding the magma to Leo’s rift explanation in Figure 8). The external nature of gesture meant that students could manipulate each other’s representations, copy another student’s gesture, add to, correct, and revise a concept through gesture.

A similar case of co-construction involving substantial interaction in the gestural plane occurred when Eliana and Leo had conflicting ideas about the direction of plate motion in subduction zones. During the cluster of references on Day 4, min 7-11 (see Figure 3) they were observing multiple data variables in GIS: elevation data and earthquake and volcanic activity. Eliana was trying to communicate to Leo her explanation of the deep trench near Japan, using only gesture to describe plate motions (see Figure 3, min 8-11). We now take a closer look at these interactions using transcript and still photographs (Figure 9).

The initial exchange between the two about subduction took place only in gesture. Eliana’s initial gestural representation of subduction (see Figure 9, Turns 1-3) featured only one element of the movement in space: the vertical rise of one plate and fall of the other. Leo interacted with Eliana’s representation by mocking her vertical gesture (Figure 9, Turn 6; also Figure 3, min 8.12). He later (min 8.27) produced a version of subduction with less vertical rise and adding a sliding-under motion of the lower plate. Eliana then adapted her subduction gesture later in this episode (min 10.6, min 10.82), mirroring Leo’s correction of her previous gesture.

This exchange illustrates co-construction of a shared understanding of subduction, this time through correction of one student by another, completely in gesture. No aspect of Leo’s correction of the motion was described in speech. Leo’s mocking of Eliana’s subduction gesture...
is more than just teasing: it accomplishes a refinement of a complex spatial relationship between plates that would have been difficult in speech, but takes less than a second in gesture. Eliana’s subsequent adaptation of her subduction gesture provides evidence of the effectiveness of this gestural communication. In turn, Leo also modified and added elements to his subduction gesture, exaggerating the lateral motion of one plate moving under, in order to show Eliana the corrected subduction gesture.

Our data suggest that these interactions in the gesture space appeared to impact changes in understanding. The interactive, multi-modal process of shared sense-making provided these learners with a space in which they revised their own models in speech and gesture, particularly their models of those motions that were co-constructed or picked up during small group work with data. This was evident in Eliana’s modified subduction gesture, as well as in Kerry’s description of buckling during the post-interview. Leo modified and added to his subduction gesture when he had to correct Eliana’s gesture. We interpret these transformations of representational gestures in this group over the course of the unit as indicating a development of their representations that was mediated by their interactions with one another, including some exclusively gestured interactions and several multi-modal exchanges.

CONCLUSION

In sum, gesture assisted students in communicating complex or novel concepts, and these concepts moved across modalities, both within and across episodes, and from student to student. As concepts developed across modalities they were often modified in both speech and gesture. This was true both in the unfolding of a concept within an episode, as well as in the development of concepts across the duration of the project. Furthermore, the gesture space was a modality in which students worked out the meanings of concepts together.
The findings presented in this paper contribute to the emerging knowledge base regarding the role that gesture plays in the sense-making process of scientific understanding. We have shown that as scientific understanding emerged, students used gesture before they used speech as a medium for conveying their ideas. This is similar to Roth (2000; 2003) and Crowder’s (1996) earlier work on student’s reasoning about static electricity and seasonal change. Building on Crowder’s (1993) observation of “interwoven” gestured and speech explanations of seasonal change within individuals, this work also demonstrates that the same phenomenon of interweaving gesture and speech can be found across individuals who are working collaboratively. In addition, our work adds to the literature on “embodied cognition” which suggests that the body, acting in the world, plays a role in shaping the mind (Wilson, 2002). Students’ use of gesture embodied their understandings of plate motions and trajectory – dimensions that students could not directly observe. These findings support Roth and Welzel’s claim that “gestures provide the material that 'glue' layers of perceptually accessible entities and abstract concepts” (Roth & Welzel, 2001, p. 1).

The finding that peers adapted their gestures in response to one another in small-group work broadens the understanding of how gesture can mediate instruction (Alibali & Nathan, in press; Church, et al., 2004; Singer & Goldin-Meadow, 2005), in this case in instructional interactions between peers. In the small-group context students are functioning as both teacher and learner, and are benefiting both from producing and observing gestures. Students could inspect both their own and one another's understandings by manipulating embodied representations of the domain concepts being explored.

Small-group work provided a productive context in which to observe the emergence of understandings in this way, as the high interactivity of the group provided many opportunities to
gesture and to interact with others' gestures. It was an interaction space in which students could try out their emerging models of science concepts that they might not have been able to express in the whole-class setting. The gestures produced in the small group allowed the students' representations to be inspected, imitated, or even manipulated by the listener. These interactions appeared to contribute to the group’s shared understanding of plate tectonics, and also may have the potential to mediate individual student learning. For these reasons, we see analysis of small-group interactions as a productive space to study further.

While the present work demonstrates that gesturing has the potential to contribute to student’s changing understandings of plate tectonics, there are a number of issues that bear further investigation. For one, the analyses presented here are based on the data from one group of three students. Additional data are needed in order to address any generalizations of these findings. We are currently analyzing six groups of students from the same school and instructional unit as one effort in this direction. In addition, the present work does not address the accuracy of the explanatory models students developed. We are in the process of analyzing data on the same instructional unit, including pre- and post-interviews, to be able to examine this issue. Future analyses will also address whether other kinds of gestures such as pointing and tracing contribute to particular aspects of a scientific reasoning with visual data (e.g., linking concepts and explanatory models with data patterns).

The finding that gesture preceded speech for every concept, for every student, suggests that gesture may provide a meaningful pathway for beginning to access unfamiliar and difficult concepts. It will be valuable to pursue further study of this finding with other types of unfamiliar science concepts, as well as with familiar ones, to better understand the role this sequence might play in the emergence of such understandings across modalities of speech and gesture. Finally, it
will also be important to examine ways that the design of learning environments, including explicit attention to gesture in instruction and assessment, may impact the development of domain understandings in science investigations.
REFERENCES


Appendix A: Examples of plate motions in speech and gesture

<table>
<thead>
<tr>
<th>Plate Motion</th>
<th>Speech</th>
<th>Gesture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subduction</td>
<td>“if this were one plate, and this were one plate, this one and this one were banging into each other and this plate is more powerful so pushed this one under…”</td>
<td>Both hands with palms faced down, hands moving toward each other, then left hand sweeps under the right hand</td>
</tr>
<tr>
<td>Rift</td>
<td>“the plates separated and then the magma came up and created this tiny little ditch”</td>
<td>Both hands together, side by side, with palms faced down, then pulling hands apart in opposite directions</td>
</tr>
<tr>
<td>Buckling</td>
<td>“the plates crash and make a mountain….buckling zone”</td>
<td>Both hands, palms faced down, meet with tips touching, hands then come together to form a peak or mountain shape</td>
</tr>
</tbody>
</table>
1. Scientists believe that trenches are formed by subduction, and that rift boundary zones are characterized by slightly raised elevations where new crust is formed.

2. The accepted scientific model of *subduction* involves two plates converging, with one plate sliding under the other, forcing a rise of the upper plate and fall of the subducting plate.
Table 1. Number of turns and turns containing gestures in the five focus episodes for each student.

<table>
<thead>
<tr>
<th>Student</th>
<th>Total turns</th>
<th>Turns with 1 or more gestures (as % of total turns)</th>
<th>Turns without gesture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliana</td>
<td>851</td>
<td>226 (27%)</td>
<td>625</td>
</tr>
<tr>
<td>Kerry</td>
<td>470</td>
<td>38 (8%)</td>
<td>432</td>
</tr>
<tr>
<td>Leo</td>
<td>1,082</td>
<td>162 (15%)</td>
<td>920</td>
</tr>
<tr>
<td>Total (all students)</td>
<td>2,403</td>
<td>426 (18%)</td>
<td>1,977</td>
</tr>
</tbody>
</table>
Table 2. Total number of gestures and types of gestures in the five focus episodes for each student.

<table>
<thead>
<tr>
<th>Student</th>
<th>Total number of gestures</th>
<th>Points Number (%)</th>
<th>Traces Number (%)</th>
<th>Representational Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliana</td>
<td>275</td>
<td>182 (66%)</td>
<td>44 (16%)</td>
<td>49 (18%)</td>
</tr>
<tr>
<td>Kerry</td>
<td>43</td>
<td>22 (51%)</td>
<td>11 (26%)</td>
<td>10 (23%)</td>
</tr>
<tr>
<td>Leo</td>
<td>200</td>
<td>115 (58%)</td>
<td>33 (17%)</td>
<td>52 (26%)</td>
</tr>
<tr>
<td>Total (all students)</td>
<td>518</td>
<td>319 (62%)</td>
<td>88 (17%)</td>
<td>111 (21%)</td>
</tr>
</tbody>
</table>
Table 3. Each student’s first reference to each target concept in gesture and in speech.

<table>
<thead>
<tr>
<th>Student</th>
<th>Concept</th>
<th>First reference in gesture</th>
<th>First reference in speech</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliana</td>
<td>Rift</td>
<td>Day 1, min 31.90</td>
<td>Day 2, min 1.85</td>
</tr>
<tr>
<td></td>
<td>Buckling</td>
<td>Day 2, min 13.35</td>
<td>Day 4, min 11.49</td>
</tr>
<tr>
<td></td>
<td>Subduction</td>
<td>Day 2, min 3.11</td>
<td>Post-interview</td>
</tr>
<tr>
<td>Kerry</td>
<td>Rift</td>
<td>Day 1, min 30.95</td>
<td>Post-Interview</td>
</tr>
<tr>
<td></td>
<td>Buckling</td>
<td>Day 4, min 10.48</td>
<td>Post-interview</td>
</tr>
<tr>
<td></td>
<td>Subduction</td>
<td>Post-Interview</td>
<td>N/A</td>
</tr>
<tr>
<td>Leo</td>
<td>Rift</td>
<td>Day 1, min 30.65</td>
<td>Day 2, min 0.89</td>
</tr>
<tr>
<td></td>
<td>Buckling</td>
<td>Day 3, min 34.78</td>
<td>Day 4, min 11.56</td>
</tr>
<tr>
<td></td>
<td>Subduction</td>
<td>Day 2, min 3.00</td>
<td>Day 2, min 6.74</td>
</tr>
</tbody>
</table>
**Figure Captions**

Figure 1. GIS maps of the area around Japan with color representations of elevation, and dot representations of earthquake and volcano locations.

Figure 2. All references to plate motions (*rift, subduction, or buckling*) in gesture and speech, during small-group work with data, plotted by minute of time in each group-work session.

Figure 3. Cluster of references to all three plate motions on Day 4, min. 7-14.

Figure 4. Kerry gestures buckling while saying “I think they go like this.”

Figure 5. Cluster of references to *rift*, in gesture only, on Day 1, min. 34 – 37.

Figure 6. Cluster of references on Day 2, min. 1-4.

Figure 7. Cluster of references on Day 2, min. 17-21.

Figure 8. Eliana manipulates Leo’s initial gesture to show two possible models of what might happen at a rift zone: magma rising or falling between separating plates. Kerry mimics Leo’s gesture in the foreground.

Figure 9. Eliana gestures a vertical version of subduction, and Leo mocks her gesture.
Figure 1.
Figure 2.
Figure 3.
Figure 4.

K shows plates … … coming together … … and buckling upward.
Figure 6.
Figure 7.

Kerry
Leo
Eliana

R = reference to RIFT
S = ref. to SUBDUCTION
B = ref. to BUCKLING
☐ = in speech
◆ = in gesture
L: OK, there’s one other possibility, OK, either it's subduction zone where the plates go like this, or it could be, see how this is a line this one line that's sooo deep, it may be that they were titonic plates (*L’s hands make long C shapes with tips touching*) they

E: Like that (*E pulls L’s hands apart; L holds*)

L: They separated and that's

E: and the magma is coming out (*E’s right hand sweeps up through L’s hands*)

L: But the magma cools and there's a tiny little ditch (*while holding left hand, L’s right index finger traces line between thumb and index on left hand*) where it's surprisingly low (*both hands making long C-shape with tips touching*), don't you think that could be an answer, too
and it went pulcechhh (L pulls right hand away from his left hand)

6 E: Lava (E pulls L’s left hand and then sweeps one finger down through his hands)

7 L: Lava and then it cooled and there's a trench (while holding left hand C-shape, right hand points in C-shape) And, that's how trenches are made.
E: Let me show you my theory. Look, see, look at me, see right there … now look, it’s going, *(both hands palms down with finger tips touching)* it seems like it’s really high.

L: YES

E: It seems like it’s really high like this *(both hands palms down, left hand moves up, right hand moves down)*, but then since I don’t know what the zone is called but some sort of zone that goes

L: Rift zone

E: That goes, that goes like that so it seems like the volcanoes are right here

L: There’s no zone, there’s no zone that goes like NAAHHH *(mocking E’s subduction gesture)*