Setting the stage for embodied activity: Scientific discussion around a multitouch tabletop display

Anne Marie Piper, Whitney Friedman, and James D. Hollan

Distributed Cognition and Human Computer Interaction Lab
University of California, San Diego

Abstract: Multitouch tabletop displays are a promising technology for supporting small group discussion and learning activities. Based on a view of human activity as multimodal, distributed, and embodied, we examine the pedagogical affordances of interactive tabletop technology, how it supports small group scientific discussion, and compare it with use of traditional paper-based study materials. We analyze video data from a five-week study involving 20 students from a university neuroscience course. Our analysis illustrates subtle but important differences in how students exploit their hands, bodies, and environmental resources depending on the medium. Finally, we discuss several characteristics of multitouch tabletop displays that make them particularly well-suited for supporting embodied conceptualizations during science learning.

Keywords: Diagrams, Embodiment, Gesture, Small Group Study, Tabletop Display

1 Introduction

Shared workspaces such as tables or desks are often an organizing feature of collocated collaborative learning activities. Recent advances in computer display and touch-sensing technology are transforming interactions around traditional tables into dynamic digital experiences. The technology enabling this change is a computationally enhanced touch-sensitive tabletop, also called a tabletop display. Tabletop displays are a particularly interesting technology for supporting collaborative learning, as large multitouch surfaces allow multiple learners to interact with digital materials simultaneously in a face-to-face fashion. This technology is increasing in availability and growing in use as a platform for research. Commercial versions of multitouch tabletop displays are available (e.g., Microsoft Surface). SMART Technologies has developed a multitouch tabletop system specifically for educational use. Recent work explores various small group learning activities involving tabletop displays (Khandelwal and Mazalek, 2007; Sluis et al., 2004; Piper et al., 2006; Muto and Diefenbach, 2008), and some researchers have begun to examine the embodied nature of activity around tabletop displays (Marshall, 2007; Marshall et al., 2009; Fleck et al., 2009; Rick et al., 2009).

In this paper we present a descriptive analysis of how undergraduate students discuss neuroscience concepts using either (a) traditional paper handouts from class (8.5" x 11" color printouts) or (b) digital versions of the handouts projected onto a multiuser, multitouch tabletop display. Data collection occurred over the course of an academic term and involved 20 undergraduate students taking a neuroscience course at our university and the course professor. An early analysis of this data reported by Piper and Hollan (2009) indicates that students working with digital documents on the tabletop display more often attempted a solution on their own before viewing an answer key, twice as often went back and repeated activities, and consistently performed higher on four exams over the course of the term. Given these early suggestive findings, an important pedagogical question is to understand how the different media shape the nature of student interaction and discussion. How does the large, horizontal multitouch display support collaborative learning experiences, specifically small group discussion? What are the cognitive consequences of touch interaction in this context? How do students make differential use of paper and digital representations of neuroscience concepts?

We analyze human interaction as a cognitive system that is multimodal, distributed, and embodied (Hollan and Hutchins, 2010). Through this theoretical framing, we describe how students use their bodies, speech, paper and digital diagrams, and the larger context of interaction to engage in scientific discussion. Based on this analysis, we suggest four key features of interaction with tabletop displays that may promote embodied learning experiences:

1. The large size of the tabletop display brings content to human scale, making the hands an appropriate tool for interacting with material representations.

2. The digital surface serves as a shared, co-owned workspace where students may collaboratively construct embodied representations.

3. Multitouch input necessitates use of hands for interaction, encouraging direct hands-on exploration of and facile coupling to digital representations.

4. Touch-interaction provides new flexible ways to interact with instructional content, thus supporting freedom and playfulness in interaction that contrasts with the well-established practices of paper and pen-based interaction.

2 Distributed cognition, embodiment, and gesture

Over the last decade there has been a shift from single-user computer systems that support isolated activity to multiuser technology workspaces that incorporate a range of digital and physical media. *Distributed cognition* provides an ideal theoretical framework for understanding human interaction in complex, multiuser technology workspaces (Hutchins, 1995; Hollan et al., 2000; Hollan and Hutchins, 2010; Rogers and Ellis, 1994; Halverson, 2002; Norman, 1993; Salomon, 1997;

Zhang and Norman, 1994). From the perspective of distributed cognition, the unit of analysis is always the functional system involved in a cognitive activity, including multiple people, their actions, artifacts in the environment, cultural practices, and the accumulation of representations and processes over time. Distributed cognition encourages one to look differently at data collected in laboratory experiments, such as the one reported in this article, by treating experiments as "settings in which people make use of a variety of material and social resources in order to produce socially acceptable behavior" (Hollan et al., 2000). Moreover, distributed cognition is a particularly productive framework for understanding interaction with multitouch systems because it considers the human body and action to be integral to cognition. Cognition is viewed as an emergent property of interaction, and as such the human body plays a critical role in a cognitive system (Hutchins, 1995).

Theories of *embodiment* (Clark, 2008, 1997; Johnson, 1987; Núñez, 1999; Varela et al., 1991) provide additional theoretical support for understanding how our physical bodies both aid and constrain how we interact with and reason about phenomena in the world. Fundamental to embodied cognition is that our ideas, thoughts, and understandings are shaped by our prior and ongoing physical experiences in the world. Researchers over the past decade have become interested in the role of the body as it relates to technology interaction (Dourish, 2001; Heath and Luff, 2000; Marshall et al., 2009). In this article we present data that illustrates how adopting an embodied perspective aids understanding multiuser, touch-based display systems.

One way to understand how the body participates in a larger cognitive system is to examine in detail the gestures and spontaneous body movements of people during discourse. Recently there has been a growing interest in examining the role of gesture in face-to-face communication (McNeill, 1992; Kendon and Muller, 2001), cooperative work (Zemel et al., 2008; Goodwin and Goodwin, 1996; Hindmarsh and Heath, 2000), and learning contexts (Crowder, 1996; Roth, 2000, 2001; Koschmann and LeBaron, 2002; Klerfelt, 2007). This is largely driven by a theoretical shift from considering gesture as peripheral to human interaction to viewing gesture as central to communication and thought. Kendon (1980) was one of the first to articulate the perspective that speech and gesture are inextricably linked. McNeill (1985, 1992) suggests that speech and gestures are built from a single conceptual source and part of the same psychological structure, therefore gesture studies may reveal mental processes of the gesture producer. However, from our perspective, gesture is not only a window into what is going on "in the head." Instead, we consider gesture to be a key aspect of socially and culturally organized cognitive systems (Hutchins, 1995; Hutchins and Palen, 1997).

Gesture is thought to play an important role in teaching and learning (Roth, 2001, provides a review). Evidence of learning or a readiness to learn can be observed in a person's gesture even though this readiness may not yet be evident in speech alone (Alibali and Goldin-Meadow, 1993; Goldin-Meadow, 2003). Work by Goldin-Meadow also suggests that gestures serve as a mechanism for cognitive offloading or task restructuring, allowing a learner to focus cognitive resources on other aspects of a task:

> Gesture and speech externalize ideas differently and therefore each may draw on different resources. Conveying an idea across modalities may, in the end,

> require less effort than conveying the idea with speech alone. In other words, gesture may serve as a "cognitive prop", freeing up cognitive effort that can be used on other tasks (Goldin-Meadow, 2003, p. 70).

Recent research also suggests that the body plays an important role in how learners formulate and negotiate scientific discussion. It has been shown that requiring students to gesture while explaining math problem solutions advances their mathematical understanding (Broaders et al., 2007; Goldin-Meadow, 2003). Gesture and body movement are also integral aspects of discussing and understanding physics concepts (Roth, 2001). Koschmann and LeBaron (2002) examine the way medical school students use gesture in scientific discourse to articulate medical concepts, yielding evidence of understanding. Furthermore, certain gestural forms used within a scientific community of practice (e.g., a chemistry laboratory) may act as cognitive artifacts for discussion of abstract ideas (Becvar et al., 2005) and play an important role in the discursive practices that nurture skilled performance and help scaffold embodied actions in professional education (Becvar and Hollan, 2010).

Beyond understanding the relationship between body movement and talk, we also examine the orchestration of these elements with respect to environmental resources. Goodwin (2007) describes this interaction as *environmentally coupled gestures*. Similarly, Goodwin (2003) details the highly situated nature of pointing gestures, indicating that meaning is constructed through the juxtaposition of multiple semiotic fields. Hutchins and Palen (1997) examine the critically interconnected nature of speech, gesture, and artifacts in space that together create multilayered representations. Importantly, these modalities are not merely additive; they build upon one another through complex relationships among a range of resources, central to which is the environment where the activity takes place (Hutchins and Palen, 1997; Goodwin, 2003; LeBaron and Streeck, 2000). Related analyses of cognitive activity involving environmental resources has been conducted under the framework of external cognition (Scaife and Rogers, 1996; Rogers, 2004).

With respect to diagrams, Ochs et al. (1996) characterize the use of linguistic resources and graphical representations in the activity of physicists. They state, "Graphic displays provide physicists with a cognitive and spatial domain to inhabit and wander in" (Ochs et al., 1996, p. 350). Similar to the study reported in this article, Roth (2001) compares interaction when students discuss static graphical models, dynamic computer-based graphical models, and a three-dimensional model of architectural structures. They suggest that gesturing around objects that are part of the content of students' expressions reduces cognitive load. They also assert that gestures provide a medium for developing scientific discourse and integrate layers of abstract thinking (Roth, 2001). In fact, students may develop scientific modes of discourse much more rapidly when the classroom supports the use of gestures compared to a context that does not support gesture in discussion (Roth, 1994, 2001). This raises a provocative question: How might collaborative learning technologies encourage gesture in discourse and subsequent embodied representations of complex phenomena? Our data suggest that a large multiuser, multitouch tabletop display is a promising technology for supporting and encouraging this type of embodied interaction.

3 Interactive tabletop displays

Unlike traditional computer workstations with a single keyboard and mouse, tabletop displays allow multiple learners to have equal access to and shared ownership over the activity. The broader category of display technology that accommodates multiple users is called single display groupware (SDG) (Stewart et al., 1999). SDG has been shown to lead to greater task engagement and activity participation (Stewart et al., 1999). Compared to vertical displays, the horizontal form factor of a table provides a more neutral and equitable surface for collaboration (Rogers and Lindley, 2004). The physical size of the tabletop provides ample area for multiple people to interact with content. Related work explores various multi-finger and whole-hand gestures on multitouch surfaces (Wu and Balakrishnan, 2003). Finally, multitouch capabilities allow a group of learners to simultaneously discuss, annotate, and manipulate shared digital artifacts.

Several tabletop applications focus on supporting learning in younger populations (children age four to 13). These include, for example, learning numbers, sorting, and patterns (Khandelwal and Mazalek, 2007), learning to read (Sluis et al., 2004), and social skill development (Piper et al., 2006). Findings from these studies emphasize the motivating nature of tabletop displays and report higher task engagement compared to other mediums. Research also examines tabletop displays for museum learning (Geller, 2006) and concept mapping (Do-Lenh et al., 2009; Roberto M Maldonado and Yacef, 2010). While tabletop technology appears to be a promising tool for supporting collaborative learning scenarios, the pedagogical benefits of presenting educational content on a tabletop display require deeper exploration. Kharrufa and Olivier (2010) work towards understanding tabletop interfaces for education by examining pen and paper interaction around traditional tables. They apply the framework of distributed cognition to understand collaboration around a table. In agreement with this prior work, we suggest that theories of distributed cognition but also embodied cognition are productive frameworks for understanding the implications of this technology for small group learning.

Marshall et al. (2009) contribute to this investigation by describing children's embodied interactions with physical and digital media around a tabletop interface, detailing how children use their bodies to negotiate access to physical and digital resources. Marshall (2007) discusses how tangible interfaces may enhance learning given the embodied nature of this interaction. Hornecker (2005) presents the idea of embodied facilitation, where we interpret systems as structures or spaces to move in, therefore determining use patterns, social configurations, and shaping how we collaborate. Fleck et al. (2009) examined the coupling of verbal and physical actions around a tabletop display. Other related work has examined how children configure themselves around a shared tabletop display (Rick et al., 2009). Our broader research agenda aims to understand the cognitive consequences of interaction involving large, multitouch tabletop displays. In this article, we examine the embodied nature of interaction among pairs of students using a prototype tabletop display system and a custom educational application we created.

4 Technology design

We implemented a basic tabletop application using a MERL DiamondTouch table (Dietz and Leigh, 2001) and the DiamondSpin toolkit (Shen et al., 2004). The interface allows students to view one activity at a time, much like the professor of this course does with an overhead projector and diagrams in class (see section 5.3). Also similar to the professor's instructional techniques, our tabletop application lets students add additional layers of information by stepping through phases of a process or turning on an answer layer to check their work. The activity content is a static diagram; that is, students are unable to rotate, resize, or move images. Chairs next to the tabletop are positioned so that students sit side-by-side instead of across from each other. This allows for ease of sharing text-based material. Each student has their own "draw" and "erase" buttons that allow them to mark on the diagrams with their finger. Students can also erase each other's annotations. This mirrors paper interactions where students are able to erase each other's drawings with a pencil eraser. Students have access to a shared menu that allows them to navigate between activities (including previous weeks' activities), view activity answers, and clear all annotations on the current document. When students display the answer layer, the answers appear in green on top of their annotations so they can check their work. We designed the tabletop application so that annotations and notes would persist over multiple sessions in a way similar to how pencil markings persist on paper. Our system exports each group's annotations and reloads them when the pair returns for a subsequent session.

5 Method

We conducted a five-week laboratory study with ten pairs (N=20, mean age=20.15, 15 females) of undergraduate students from an introductory neuroscience course. Successful students in this course need to memorize brain anatomy, understand and describe complex processes (e.g., firing of a neuron), and be able to generate graph and circuit drawings of brain systems and activity. Each student selected a partner at the beginning of the quarter and worked with this person throughout the study. None of the participants had worked with their partner nor used tabletop technology prior to the study. All pairs of students attended four one-hour study sessions over a five-week condensed summer term. Each of the four study sessions included three activities that were selected by the course professor: an anatomical labeling activity, discussion of a dynamic system, and a drawing activity involving a graph or circuit. The goal was to keep the students' experience as authentic and relevant to the course as possible. Students were informed that their professor selected all study activities specifically to prepare them for an upcoming exam. Students were told that they could use the study time however they choose and could use personal notes or books. We provided color copies of diagrams for students to take home (with or without their notes, as requested). All study sessions were conducted in our laboratory around the tabletop display to keep the environment and workspace consistent across conditions.

Pairs of students were randomly assigned to the paper and digital conditions. In the paper condition, students received one set of paper diagrams to share and erasable colored pencils. Students in the digital condition worked with digital images on a DiamondTouch table (79 cm diagonal, 4:3 aspect ratio) where they annotated images by touching with their finger. In both conditions students had access to their materials from previous study sessions as well as their personal notes and textbooks. The activity content was identical in both paper and digital conditions; however, the size of diagrams varied. In the paper condition, diagrams were printed in color on 8.5" x 11" sheets of paper. We considered giving students in the paper condition diagrams equal in size to the digital diagrams but chose to provide handouts of standard size to reflect classroom practices. Students in the paper condition received folders with activities and answers while students in the digital condition had access to a menu on the interface that opens activities and answers.

5.1 Video analysis

The following results are based on a detailed iterative review of 40 video recorded study sessions involving students working with paper and digital materials. Analysis focuses on segments of activity where one student explains a concept to their partner and there is a highly involved use of the hands and body in this explanation. We pay particular attention to interaction among the students, their talk, gestures, body movements, digital and physical materials, and how they organize their activity in the context of studying. We consider gestures to be spontaneous body movements that are in some way involved in communication, group coordination, or the unfolding cognitive activity. Annotations on the diagrams are not included as gestures, but rather, these are traces of interaction that have unique properties of their own. The segments of activity detailed in this article were selected because of their highly involved nature, where students exploit speech, gesture, and the diagram representation during discussion. Transcript notation includes bold speech to show a gesture stroke, underlined speech to show a gesture hold, and italicized text to describe the action.

5.2 Firing of a neuron

To facilitate comparative analysis, we extract examples from a single activity: discussion of the process through which a neuron fires. This process, and the associated diagram, involves energy traveling from one end of the axon to the other caused by chemical reactions across the neuron's cell wall. To understand how neurons fire, students must first understand a process of reaching equilibrium. That is, molecules in an area of greater concentration will diffuse to an area of lesser concentration. This force is the concentration gradient. The process begins in a resting state, called resting potential, when the neuron is ready to fire. There is a large electrochemical difference between the inside and outside of the neuron and the cell begins the firing process at the Axon Hillock (left side of diagram in Figure 1) and proceeds to the synaptic cleft (right side of diagram). Sodium gates open and allow sodium to rush into the cell, creating a greater positive charge inside the cell compared to outside the cell. The sodium gates then close. Now, to reach a balance, the potassium gates open and allow potassium to leave the cell, creating a more positive charge outside the cell. The potassium gates then close. This iterative exchange of sodium and potassium actively restores the initial resting potential state, resulting in a neuron that is again ready to fire.

We focus on this example for two key reasons. First, the process of a neuron firing is a fundamental concept in this neuroscience course and related curricula. Students must master this concept as a foundation for subsequent discussion of neuroscience systems. Second, students demonstrate a wide range of embodied displays when discussing this particular diagram. A detailed analysis of this activity portrays the range of communication possibilities that students use during discussions throughout the five-week study.

5.3 Material presentation in the classroom

From a distributed cognition perspective, it is important to understand the context of learning beyond our laboratory setting. This includes the larger ecology of materials and practices for this particular course. The course is taught in a traditional lecture hall. Interestingly at a time when projected laptop displays are typically used, the instructor uses an overhead projector and hand-drawn transparencies in class. She adds and rearranges cut out pieces of overhead transparencies to illustrate movement and various processes (e.g., an ion moving across the cell wall). We note the similarity between the presentation of information in class via the overhead projector and the diagrams presented to students in the laboratory on the top-projected tabletop display. One hypothesis is

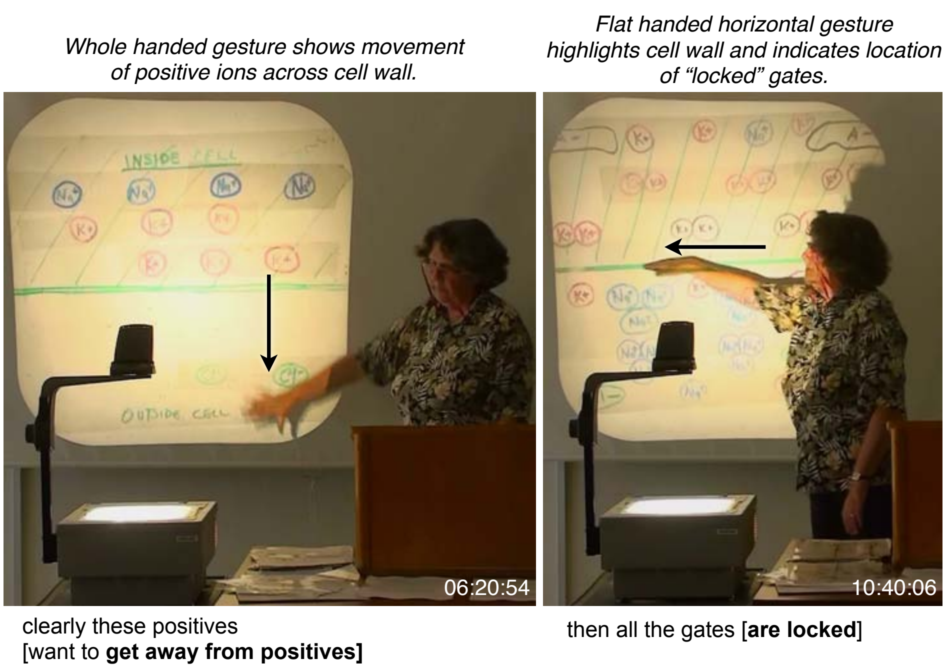


Figure 1 Course instructor uses overhead transparencies to describe the process of a neuron firing. Circles represent ions and green line represents the cell wall.

that the top-projected tabletop display is an analog for the overhead projector used in class. That is, the tabletop display may provide a bridge between how content is presented in class and in the laboratory study sessions. Figure 1 presents two excerpts from the lecture on how a neuron fires. Just as students do with diagrams in our laboratory, the course instructor creates embodied displays coupled to the diagram while she explains how a neuron fires.

6 Results and analysis

Complex, highly involved body movements across the shared workspace with respect to one's partner and class materials are pervasive throughout each study session. The use of the body and material resources is evident in student interaction. In our observations and data analysis, we note subtle but important variations in how students recruit their bodies and material representations during discussion depending on the medium. In the following sections we explore the ways in which students communicate, explicate, and demonstrate their developing understandings of this scientific process. Through this analysis we identify characteristics of a tabletop display that support embodied and distributed conceptualizations of scientific processes, such as how a neuron fires.

One salient difference between interaction with traditional paper documents and the projected digital images involves how students bring these material representations into their discussion through environmentally coupled gestures (Goodwin, 2007). The large, shared nature of the tabletop display enables students to interact with their hands directly on top of the diagrams. That is, the tabletop display brings content to human scale, making the hands and fingertips appropriate tools for interacting with the material representations directly.

Consider segment 1 below where a student working with the tabletop display explains the transfer of energy (or ions) across the cell wall of the neuron. Student 1B produces two curved handed gestures close to his body (lines 1-2). We see later on (starting in line 4) that this hand shape indicates that he is holding or grasping ions in each hand. He then places his curved hands directly on top of the display as he says, "picture these" (line 4). The juxtaposition of his hands, still in this grasping form, over these hand-sized groups of ions effectively transforms his empty hands into now holding these two groups of ions. He continues, "they have potential right." Now he explains that the cell membrane is a "wall" between the groups of ions (line 6). While still maintaining this bimanual curved-hand holding gesture, he uses the little finger of his right hand to trace along the cell wall as he says, "but there's this thing in the way, this wall." He returns his hands to the initial state of holding the groups of ions as he continues. "Here you have this potential energy that's being prevented." As he says "potential energy" he moves his curved hands up and down slightly to emphasize the connection between his hand position and the state of potential energy (line 7). Finally, he explains, "well, when you open the gates, you know that energy is being released." As he says this, he takes his two hands, still wrapped around the groups of ions, and moves each group to the opposite side of the cell wall. This movement along with the position of his hands illustrates the ions moving across the wall, or the process of reaching equilibrium.

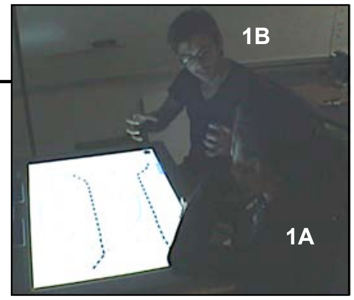
Segment 1

1 1B: they **go** (.7)

2 they have potential to **go** (.5)

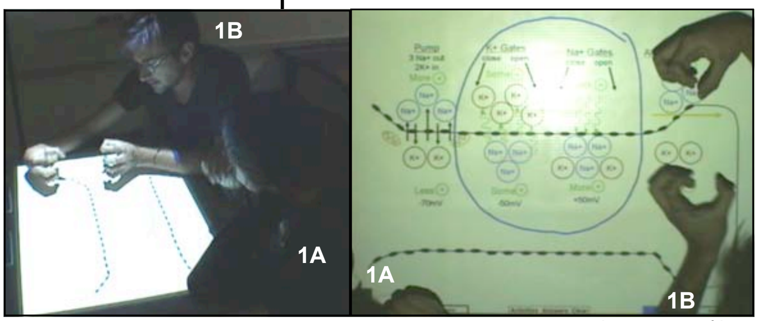
3 but something is preventing it

…



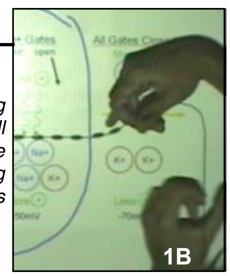
4 1B: **picture these** (1.1)

5 and they have potential right (.5)



grasping groups of ions

6 but theres this **thing in the way** (.) **this** (.) **this** (.5) **wall** (.8)



highlighting cell wall while holding ions

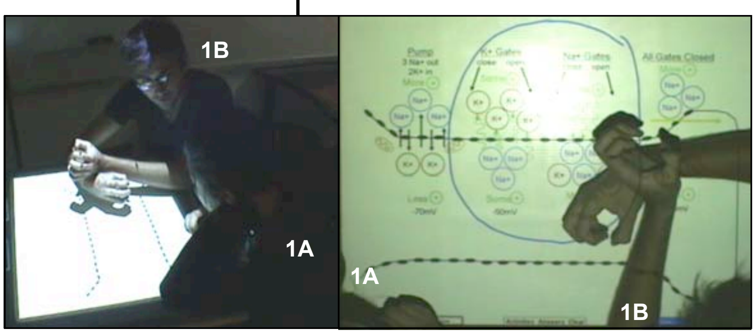
7 so (.) here you have this **potential energy** (.9)

8 thats being prevented (.2)

9 well (.) when you open the gates (.8)

10 **you know** (.)

11 that energys being released



energy exchange across cell wall

In segment 1, student 1B's explanation relies on his listener to understand the location and movement of his hands with respect to the meaning represented in the diagram. His hands are placed directly over two distinct groups of ions, and by this placement he implicates these ion groups in the process he later describes. Importantly, his hands take on multiple roles within this brief segment of activity. He illustrates force and tension between these groups of ions through the movement and visible exertion of muscle tension in his hands and arms (lines 2, 4, and 7). While this is going on, he then uses his little finger to highlight the cell wall for his listener. This action links what the hands are holding (groups of ions) to another section of the diagram (the cell membrane), showing the flexibility of the hands and the importance of diagrams that are at human scale.

Students working with paper documents also create bimanual gestures with a similar level of conceptual and physical involvement. These students, however, often create bimanual gestures in their personal space or even construct a conceptual space on the tabletop surface away from the diagram, as the next segment illustrates.

In Segment 2, a student (2A) working with traditional paper diagrams explains the same aspect of this process to her partner. In contrast to Segment 1, the student in Segment 2 goes to great effort to establish a physical and conceptual space for her embodied display of this process. Note that the paper document with the diagram is rotated and moved closer to student 2B. Instead of creating whole-handed gestures directly on top of the diagram as student 1B did in the previous example, student 2A creates a series of bimanual whole-handed gestures in front of her on the table.

Similar to the previous example, student 2A establishes that each of her hands are acting as a distinct and separate group of ions. She does this by spreading her hands apart on the workspace. Then she says, "let's say there's three balls here ((wiggles fingers of her left hand)) and one ball here ((wiggles fingers of right hand))" (line 1). She uses the deictic term "here" and the finger movements of her left and right hands to establish the presence of "balls" in the physical spaces her left and right hands occupy. The word "balls" is a metaphor she uses for ions. She then places her pencil in front of her but between the two hands. She does this while saying "and the line's right here," to establish that the pencil is a boundary (or the cell wall) between the two groups of balls (or ions). As such, she uses the pencil as a material anchor for this conceptual discussion (Hutchins, 2005). She continues her explanation and directs her listener's attention back to her left hand by fluttering her left fingers as she says "since there's three" (line 6). Importantly, there are three ions represented on the diagram, but she states that her hand has three ions without explicitly referencing the diagram. The student in segment 1, in contrast, did not need to explicitly reference how many ions were in each group because he recruited them into his explanation by placing his hands directly over these groups of three ions in the diagram.

She then prepares her listener to attend to the shift of ions from one hand to the other by fluttering her left fingers and then her right fingers while simultaneously saying "here" with each hand flutter (line 10). Then she demonstrates the transfer of energy by moving an ion (middle finger from left hand) across the cell wall (the pencil boundary) and holds this position for a second (line 13).

Student 2B uses her pencil tip to point to the organization of student 2A's fingers crossing over the pencil on the table to ask whether that display is the concentration gradient (line 17). Student 2B is able to do this because the material anchors her partner established are grounded in conversation and now a shared representation between the dyad that they both may access and build upon in future interactions (Hutchins, 2005). The concentration gradient is the force and

Segment 2

1 2A: if theres (.9) theres (.4) like lets say **three balls here** and **one ball here**

2 2B: mmhumm

3 2A: right

4 and **the lines right here**

5 2B: ok

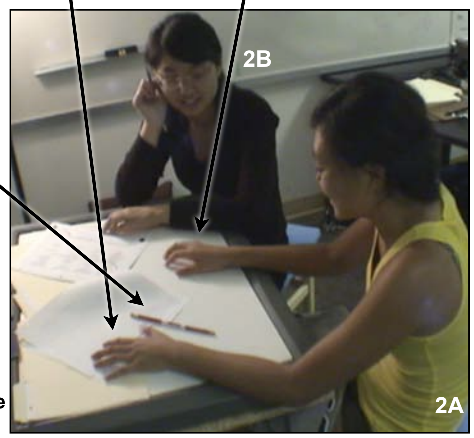
6 2A: so um **since theres three** (.)
flutters left hand fingers

7 it wants to (.)

8 it wants to achieve equilibrium

9 2B: mmhumm

10 2A: so (.3) **one ball here** would go **here**
flutters left hand then right hand



sets up space to describe energy crossing cell wall

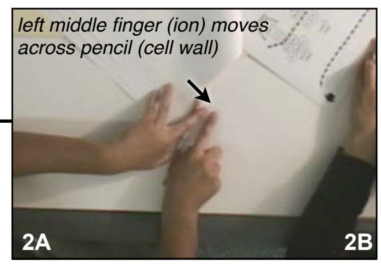
hands are groups of ions

moves pencil to represent the cell wall

11 2B: mmhumm

12 2A: okay (.) if **three** (.5) **one ball from the three here** (.)

13 goes over **like this**



14 2B: mmhumm

15 2A: so its going to **even it out** (.)

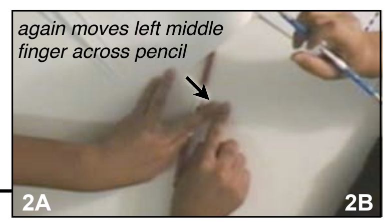
16 so **its going down** the concentration gradient (.4)

17 2B: so **this is called the concentration gradient^**
circles around S1's fingers with pencil tip

18 2A: it wants

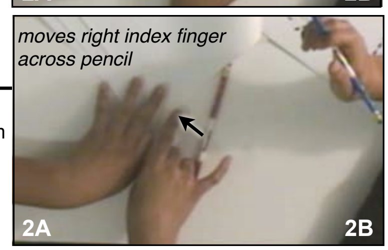
...

19 2A: **doing this** would be easier than making one ba (.)



20 forcibly **moving one ball** over here (.)

21 2B: yeah



22 2A: which would like (.3) disrupt the ca (.6) um equilibrium

pathway in which ions flow from an area of high density to low density, and it is represented through the motion of student 2A's fingers over the pencil boundary.

Building on the grounded interaction up to this point, student 2A is able to repeat an action such as moving her left middle finger across the pencil while saying "doing this" (line 19) to reference the complex exchange of energy from a region of high concentration to low concentration. The critical point she makes next is that "doing this" (line 19) is "easier than forcibly moving one ball over here" (line 20). As she says "moving one ball," she moves a finger from her right hand across the pencil boundary. Instead of using her hands to show force as the student in Segment 1 did, she evokes this explicitly through speech.

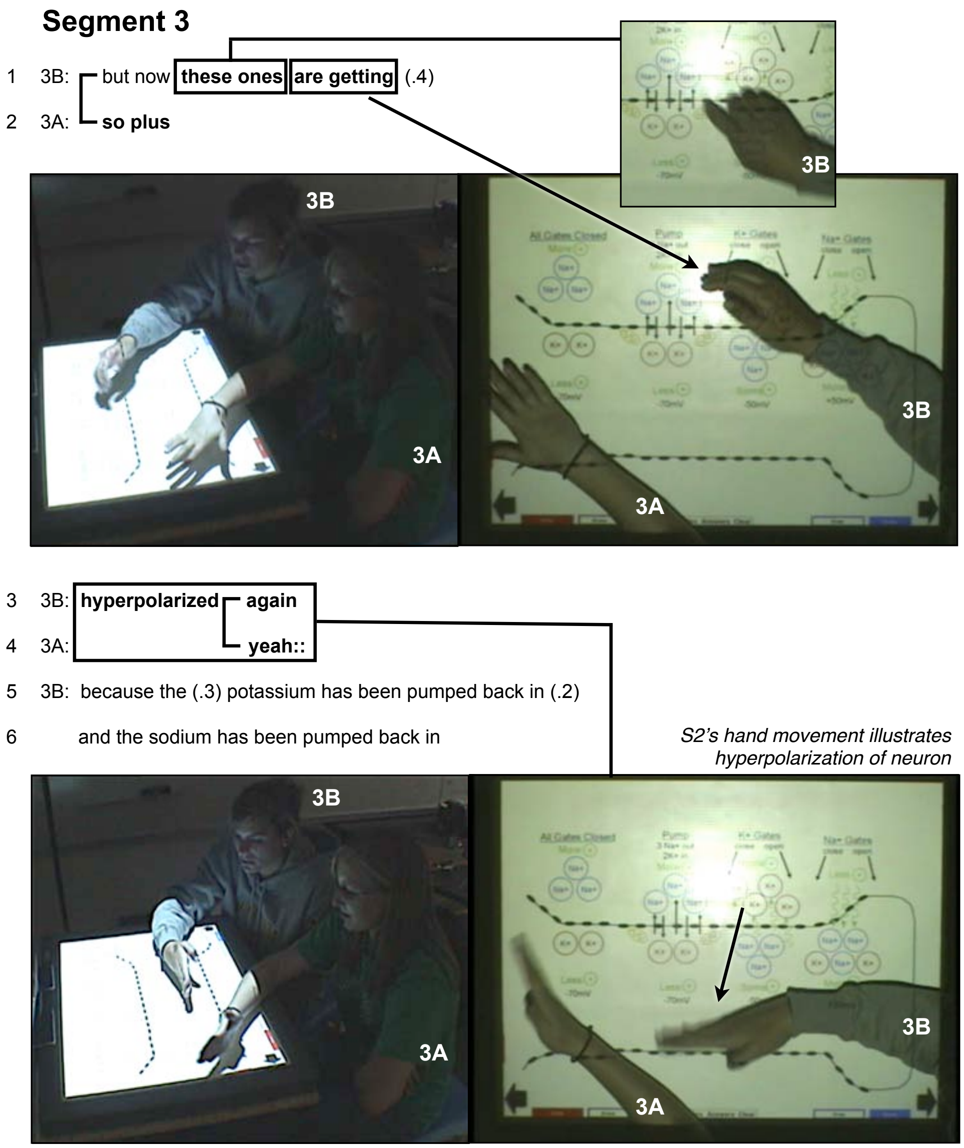
In Segments 1 and 2, students construct multimodal explanations of the same process (transfer of ions across the cell membrane), but they do so by exploiting the material resources in different ways. Segment 2 presents an example of the highly involved process of setting up a new conceptual space for illustrating an abstract concept. Importantly, students working with digital documents are able to effortlessly recruit material representations within the projected diagrams by creating whole-handed gestures directly over these resources. The diagrams projected onto the tabletop display enable students to draw on existing and explicit representations that are already grounded in interaction (Clark and Brennan, 1991). That is, the large projected diagrams are integrated into embodied displays without the cognitive burden of setting up a new conceptual space for interaction (Roth, 2001).

The size of the diagram has implications for interaction and makes certain embodied activities more or less feasible. We conjecture also that projection from above might encourage the diagrams and hands to be thought of as members of the same space. As we saw in the previous section, whole hands are able to grasp ions with the larger digital documents and fingertips become ions in a newly constructed conceptual space with the smaller paper documents. The tabletop display not only brings content to human scale, making whole-handed interaction with diagrams appropriate, but the large format of images on the tabletop also allows both students to reach in and construct embodied representations over the diagram at the same time. Through this, they collaboratively construct representations of the phenomena of interest.

We observed students creating collaborative or synchronized gestures when working with digital and paper documents. However, we only observed whole handed collaborative gestures when students interacted with the tabletop display. Students working with paper documents often pointed with the tips of their pencils in a coordinated way to show agreement and understanding. The following segments of activity illustrate this difference in interaction.

In Segment 3, two students use digital documents to discuss how the process of hyperpolarization moves down the axon from left to right. They both place their hands over the diagram and begin speaking at the same time, each referring to a different part of the diagram. Student 3A stops speaking and lets student 3B finish her statement (line 2). Student 3B then moves her hand down to show the hyperpolarization taking place at the center of the axon and says "hyperpolarized" as she performs this flattened hand, vertically oriented gesture. Student 3A immediately creates a similar vertically oriented flat-handed gesture and says "yeah" before student 3B is finished saying the word "hyperpolarized."

This coordination shows student 3A's attention to her partner's talk and gesture as they collaboratively construct these whole-handed gestures over various parts of the axon. Here, student 3A follows student 3B's explanation and mimics her flat-handed gesture, thereby demonstrating agreement about the hyperpolarization process. Importantly, the concept of hyperpolarization involves a downward dip in a graph (often discussed in class), and their flat-handed movement downward possibly corresponds to this graphical representation. We



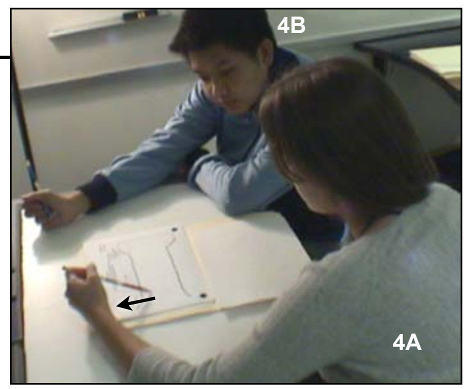
Overlapping speech and coordinated use of flat hand gesture shows agreement.

contrast this example with an example of students performing collaborative pointing in the paper condition.

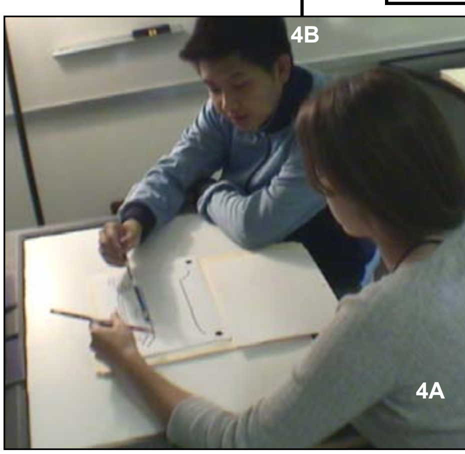
In Segment 4, two students working with paper documents use their pencil tips to point in coordination with each other while reaching agreement about the propagation of action potentials in a neuron. Student 4A initiates the conversation by asking student 4B when and where, after the first ion channel has opened, does the sodium-potassium pump begin. Student 4A begins by making a pointing gesture with her pencil that goes back and forth across the cell wall as she says "once these start" (lines 1 and 3), demonstrating the movement of ions across the cell wall on the left side of the diagram at the axon hillock. Next she asks when the sodium-potassium pumps begin. Moving her pencil quickly around the site of her previous gesture and down the channel, she asks, “do the pumps start once the process has reached here?” She simultaneously taps the right side of the diagram as she says “here” (lines 3-4). Lifting her pencil and bringing it again to the left side of the diagram, she proposes an alternative: now slowly moving the pencil from left to right across the axon, she asks, “or do they follow automatically?”(line 5). Student 4B responds in turn, shifting his body over the diagram and pointing with the eraser end of his pencil at the site of student 4A’s first gesture, first issuing coordination of topic by saying “the sodium-potassium pump” (line 6). He offers his answer, “I think it just...there,” now slowly moving his eraser a short distance left to right across the cell wall (line 8). Simultaneously, student 4A agrees, “it just follows behind it”, repeating her previous gesture by moving her pencil slowly

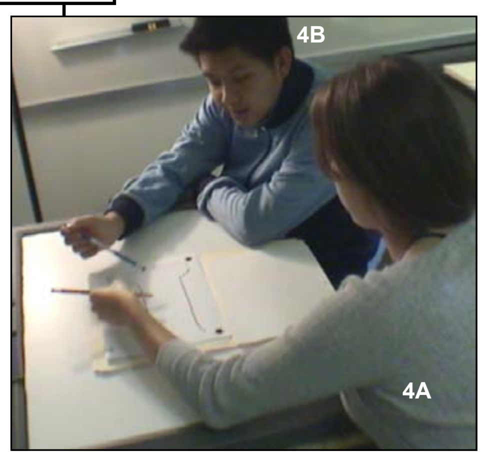
Segment 4

1 4A: once (1.2) these **start** (.)
2 4B: mmm humm (.9)
3 4A: do thee (.) the pumps **start** once (.3)
4 the process has reached **here** (.)
5 or do they follow **automatically** (.8)
6 4B: the patas (.) sodium potassium pump=
7 4A: =mmm umm (.)
8 4B: I think it just (.7) [**there**
9 4A: [**it just follows**=
10 4B: =**yeah** (.)
11 4A: **behind it** (.9) mmm kay



moves her pencil tip across cell wall





coordinated pointing with pencil tips and movement down axon shows agreement about process from left to right across the axon at the same time as student 4B completes his gesture (lines 9 and 11). Student 4B overlaps his response ("yeah") as they both agree. The students pause, then decide to check their analysis against an answer sheet located at the bottom of their stack of paper materials.

This type of pointing with a pencil tip—both independently and in coordination with one's partner—is pervasive throughout our video data of students in the paper condition. Segment 4 illustrates one example of how students use the material workspace, specifically pencils as an extension of their body for pointing, to construct a shared understanding of this scientific process. One difference between the two conditions is that while a pencil may provide more precision than larger finger tips during pointing, our hands are uniquely suited to communicate dimensions such as form and tension within a single pointing act.

7 Discussion

We present a descriptive analysis of how undergraduate neuroscience students use their hands, bodies, and material workspace during scientific discussion. We now describe four key characteristics of tabletop displays that appear to support embodied activity in discussion compared to traditional paper documents.

The large display size brings content to human scale, making the hands an appropriate tool for interacting with visual representations. Tabletop displays dynamically enlarge content, presenting visual representations at a size that makes whole-handed gestures appropriate. For example, in Segment 1 the ions in the diagram are large enough for an adult to grab them with his hands (lines 2-4). In contrast, when interacting with smaller paper diagrams, pointing with a tip of a pencil (Segment 4) is much more appropriate. The larger diagram size affords the use of whole hands and arms (Segment 1, 3) in rich gestures that not only direct attention but also elaborate and qualify speech in ways that pointing with a pencil or index finger alone does not allow. As the size of the table affords the use of the hands, it simultaneously and necessarily involves the engagement of the body (Segment 3).

An important follow-up study should compare interaction around the tabletop display to interaction around a large horizontal whiteboard (with easy-to-erase markers) and interaction involving large paper documents. However, it is worth observing that larger paper documents are readily available now, and yet they are not often used in classroom settings for this type of activity. We chose to study traditional (8.5" x 11") paper documents that are used in this course to maintain ecological validity. Another comparison that future work should make involves the tradeoffs with a smaller touch-screen (e.g., multitouch tablet computer). We propose that the large size and shared nature of a fixed tabletop display provides benefits for collaboration that may not be present with smaller portable multitouch devices.

The digital surface serves as a shared workspace where students may collaboratively construct embodied representations during discourse. The physical size and horizontal nature of the tabletop display provides and reifies a shared space for interaction. Compared to smaller paper documents that are easily rotated or moved and designed for a single person (Segment 2), content presented on a tabletop display is directly accessible to both students at the same time. This allows for students to use collaborative whole-handed gestures over the diagrams (Segment 3). The large, shared area of the digital tabletop provides a physical space for the conceptual construction of ideas. We regularly use the personal space in front of us to construct conceptual ideas with gesture (McNeill, 1992), and the physical tabletop now provides a shared and equally accessible space for this interaction.

Multitouch input necessitates the use of the hands for interaction, encouraging direct hands-on exploration of representations. Interacting with paper most often involves a pen or pencil; interacting with the tabletop display, however, necessitates the use of hands and fingers. The interaction language of each medium (Hutchins et al., 1985) determines how people should interact with the content, and thus may encourage additional gestural activity above the tabletop. The gesture-based interaction inherent in the tabletop display necessitates direct hands-on interaction with materials and may also prompt the use of gesture to augment discussion. Multitouch input to the tabletop display also frees the learner's hands, making the hands an available and unconstrained resource for communication. Students working with paper materials almost always held the pencil in their hand (e.g. Segment 4). The multitouch surface enables discussion without the constraints of holding a writing utensil, perhaps encouraging gestures that convey qualities that are challenging to express in words alone (e.g., tension and force in Segment 1). A related characteristic is that, with the tabletop display, students are able to leave a trace or marking on a diagram with any part of their body without holding a writing instrument.

Touch-interaction is a new flexible mechanism for interacting with instructional content, thus enabling freedom and playfulness in interaction. Paper is a common media for most educational content, and there are well-established practices involving paper and pen interaction in learning contexts. This stands in contrast to the multitouch tabletop display. While participants in our study had no previous experience with collaborative tabletop learning environments, they certainly had little difficulty adapting to the system we provided. In fact, the newness of the digital tabletop medium may encourage a certain freedom in the use of space, bodies, and resources during collaborative engagements. In Segments 1 and 3, in addition to seeing more whole handed gestures, we also saw more proximal interactions and whole body engagements. In contrast, students in Segments 2 and 4 maintained a more distal or 'polite' interlocutor orientation. This difference may have been encouraged not only by the size and novelty of the representation, but also in the necessary re-consideration of space when hands, instead of pencils, were the primary interactive medium.

Piper and Hollan (2009) note the playful nature in which students annotated with digital ink that was not apparent with pencil and paper interactions. Similarly, the low cost and low risk of digital annotations likely encourages students to spontaneously create drawings to support discussion. These impromptu sketches can support the learning process in cognitively important ways; the sketches provide an external representation of what students are discussing and may be important scaffolding for their developing understandings. Furthermore, the form and mode of interaction with the digital tabletop is a close analogue to the instructor's practices with her overhead projector in class, providing a bridge between learning environments for students working with the interactive tabletop.

8 Conclusion

Theories of embodiment suggest that conceptual understanding is manifest in the multimodal resources of the human body in coordination with the surrounding environment. This is well exemplified in our observations of students learning about the firing of a neuron. Part of the process for becoming competent in understanding an abstract concept such as neuronal firing may very well be the ability to express abstract concepts through multimodal embodied representations. In spoken language, we facilitate the communication of abstract concepts by use of metaphor. We also often use our hands, bodies, and gesture to construct embodied representations of abstract concepts. This devotion of multiple attentional resources may facilitate deep multimodal conceptual integration, and may be facilitated by technology, such as multitouch tabletop display systems, that enable and encourage use of embodied resources. In this study, we explore learning activities around two types of media in an effort to understand how the role of the body differs based on variations between paper and digital instructional workspaces. Our findings suggest that an interactive tabletop display affords greater involvement of participants' bodies and allows facile coupling of gesture to physical representations. By encouraging the use of the body and providing a shared space for embodied representations coupled to dynamic digital representations, we suggest that the digital tabletop display has distinctive potential to ease communication of and encourage deeper understandings of new concepts.

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