Enabling the Blind to See Gestures

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Human discourse is an embodied activity emerging from the embodied imagery and construction of our talk. Gesture and speech are coexpressive, conveying this imagery and meaning simultaneously. Mathematics instruction and discourse typically involve two modes of communication: speech and graphical presentation. Our goal is to assist Individuals who are Blind or Severely Visually Impaired (IBSVI) to access such instruction/communication. We employ a haptic glove interface to furnish the IBSVI with awareness of the deictic gestures performed by the instructor over the graphic in conjunction with speech. We present a series of studies spanning two years where we show how our Haptic Deictic System (HDS) can support learning in inclusive classrooms where IBSVI receive instruction alongside sighted students. We discuss how the introduction of the HDS was advantageous to all parties: IBSVI, instructor, and sighted students. The HDS created more learning opportunities, increasing mutual understanding and promoting greater engagement.

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1. INTRODUCTION

This article is based on the proposition that human discourse is an embodied activity. Our multimodal (gesture, gaze deployment, prosody, and speech) language emerges from the embodied imagery and speech construction. We explore the implication of this proposition within the context of mathematics instructional discourse for individuals who are not able, normally, to see gesture. By providing these individuals access to gesture as it conveys meaning with speech, we have an avenue to understand how gestural systems may function in interaction.

We advance our discussion by considering the role of embodiment in mathematics instruction. Mathematics instruction and discourse typically involve two modes of communication: speech and graphical presentation. For effective communication, dynamic synchrony must be maintained between the speech and focus on the graphics. In sighted individuals, vision is used for two purposes: access to graphical material, and

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awareness of physical pointing and other embodied behavior by the instructor. This awareness keeps communication situated by linking graphical material and speech. We present research to assist Individuals who are Blind or Severely Visually Impaired (IBSVI) to access such instruction/communication. We employ the typical approach of sensory replacement for the missing visual sense. Haptic fingertip reading can replace visual material. We present studies using a Haptic Deictic System (HDS) that pairs a haptic glove with computer-vision-based tracking to help the IBSVI maintain reading focus on a raised-line representation of a graphical presentation to which the instructor points while speaking.

As our title suggests, this article explores the nature of gestures as they participate in constructing joint meaning between a sighted instructor and the IBSVI. While the focus is on pointing gestures per se, we emphasize that pointing is more than the static form of the extended finger. We will show that for deixis to function properly, its uptake has to become so automatic that the conversants are able to participate in the process of multimodal discourse without inordinate attention to the mechanics of pointing. It must be so tightly packaged with the coexpressed speech that the information expressed becomes singular; both gesture and speech combining to express and comprehend the same thought. In a sense, our work with IBSVI provides us the opportunity to explore these fundamentals of embodied gesture and speech multimodal interaction. By aiding those who do not normally have access to gesture, we hope to contribute to our understanding of how gestural interaction may be designed as part of a multimodal system.

At pragmatic level, our work illustrates a practical application of our understanding of embodied discourse. We present an interactive approach to support learning in inclusive instruction scenarios. Our results show benefits for all three sets of participants in this setting: instructors, IBSVI, and sighted students. For instructors, the technology allowed them to: (1) adjust the pace of the lecture to ensure that all students were following them; (2) better understand the students' signs of confusion and act upon them to ensure their understanding; (3) act more naturally, as they did not have to think of how to verbalize the information displayed on the graphs. Overall, instructors agree that the use of the technology improved the quality of instruction. The IBSVI were able to comprehend the instruction more quickly and effectively when they were using the system. For the sighted students, the system: (1) improved lecture fluidity; (2) enabled the IBSVI to participate more in classroom discussions; and (3) did not make the instructors pay less attention to them.

We will present the theoretical foundations of our approach, followed by a detailed description of our system. We then discuss the challenges and motivations of taking our system to inclusive classrooms, framing the research questions that we address in our study. We overview our psycholinguistically-based analysis instruments to determine the effect of the HDS on instructional discourse, and present our findings. Finally we present our conclusions.

2. EMBODIED DISCOURSE, MATHEMATICS INSTRUCTION, AND THE BLIND

2.1. Gesture and Deixis

Gesture studies are uncovering the fundamental cognitive science that undergirds the necessity of embodiment in language [McNeill 1992, 2000; Quek et al. 2002; Goldin-Meadow 2003; Beattie 2003; Kendon 2004; Poizner et al. 2000]. When we speak, our heads, eyes, bodies, arms, hands, and faces are brought into the service of communication. But this is not their sole purpose. In fact, gestures are performed as much for the speaker as for the hearer [Goldin-Meadow 2003] (we gesture while on the phone). Gesture reveals how we use the resources of the body space to organize our thoughts,

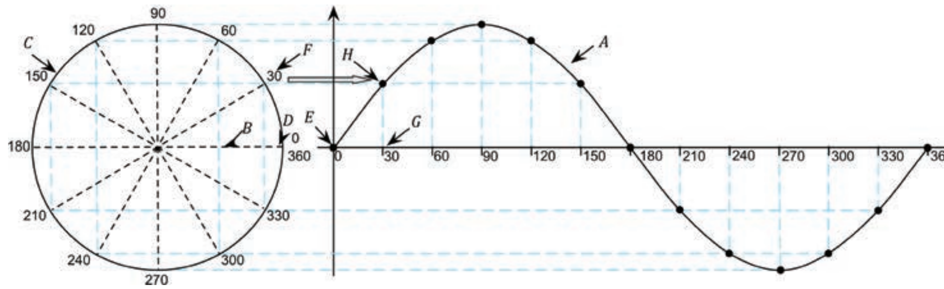


Fig. 1. A mathematical sine function illustration.

keep context, index our ideas, and situate/shape our mental imagery out of which our talk flows. Our capacity for spatial memory, situated attention, and motor activity fuel these embodied resources.

Specifically to the research reported here, embodied discourse enables us to convey meaning not available [McNeill 1992, page 128], or even not possible [Goldin-Meadow 2003, page 5 para 4] in speech alone. Mathematics discourse is particularly laden with imagistic content, and the use of gestures and embodied behavior in mathematics discourse has been well documented [McNeill 1992, pages 164–168; Alibali and Nathan 2007; Alibali 2005]. The essential role of visual-spatial reasoning in mathematics is expressed by Roger Penrose, mathematician and physicist, in *The Emperor's New Mind*:

> "... [A]lmost all my mathematical thinking is done visually and in terms of nonverbal concepts, although the thoughts are quite often accompanied by inane and almost useless verbal commentary, such as 'that thing goes with that thing and that thing goes with that thing'. " [Penrose 1989, page 424].

In mathematics instructional discourse, spatial imagistic content is often communicated in graphic diagrams. In such discourse, deixis plays a very important role in that it allows us to situate discourse within the interlocutor's physical environment [Clark and Marshall 2002; Clark 1996, pages 43–46]. It brings the entire imagery of the referent of the deictic field into view, situating it temporally with speech, providing information to resolve speech references that are available only in the interlocutors' environment [Hinrichs and Polanyi 1986].

We employ the constructed example in Figure 1 to illustrate this. To explain the sinusoidal function, the teacher may reference the figure and say: "The [**sine function**]^A {*points at the sinusoid*} traces the height of the end of a [**rotating arm**]^B {*points at B in the figure*} as it swings around [**a circle**]^C {*deictic gesture tracing the circumference of the circle in the counterclockwise direction*}. When the arm is [**at zero degrees**]^D {*points at the zero on the circle*}, the [**value of the sine function is zero**]^E {*points at E*}. When the arm is [at thirty degrees]^F points at F, the value of the sine function [**at thirty degrees**]^G {*points at G*} [**is this**]^H {*deictic gesture traces the path shown as a grey arrow*} ...". The teacher continues in her discussion showing that the arm traces the waveform shown. In this description, boldfaced words in the square brackets accompany the gesture labeled with the superscript. The location gesture is marked in Figure 1 with the same label (note that the italicized deictic markers do not appear on the illustration used by the teacher). The gesture is described in italics within the curly braces.

This illustration elucidates three key ideas that our research seeks to support in instruction for IBSVI: (1) Time synchrony is critical for both production and uptake of deixis with respect to speech, in essence bringing the graphic content of the diagram into the meaning of the utterance; much in the same way an iconic gesture [McNeill 1992] might imbue speech with imagistic content; (2) the teacher produces the gestures while speaking. Gesture and speech are coproduced as the teacher endeavors to explain the sinusoid. She does not think of the words to speak and then consciously think of what to point at to illustrate specific words; and (3) the student receives both gesture and speech during instruction. Uptake of deixis cannot be a laborious conscious process like Alice following the rabbit through the garden. If the focus is on the rabbit, she will not be able to appreciate the garden. Likewise if the effortful perception of the gesture is the focus, the focus is not on the language, and the discourse fails. Of course, this kind of exchange is lost to IBSVI, possibly accounting in a significant way to the difficulty of such individuals to advance in mathematics education (IBSVI are typically one to three years behind their seeing counterparts [Williams 2002]).

2.2. IBSVI, Gesture, and Mathematics

While IBSVI cannot see gesture, they have the capacity to use gestures. Goldin-Meadow [1999] found that speakers who are blind gesture routinely even though they themselves have never seen gestures. Iverson and Goldin-Meadow [1998] showed that congenitally blind speakers gesture at the same rate as the sighted. McNeill points out "[t]hat the congenitally blind gesture at all as they speak is itself evidence of a speech-gesture bond. Lack of vision evidently does not impede thinking in gestural forms." [McNeill 2005, page 26]. Furthermore, IBSVI have been shown capable of learning spatial reasoning and more broadly, mathematics [Landau et al. 1984; Millar 1985]. Hence, we posit that an impediment to IBSVI is the barrier to participation in mathematics and science imposed by their lack of access to the salient content in multimodal instructional discourse.

2.3. Inclusive Classrooms

An overarching goal of our solution is to enable inclusive classrooms, where IBSVI attend mainstream classes. It has been argued that inclusive classrooms are beneficial for both disabled [Dick and Evelyn 1997] and nondisabled students [Staub and Peck 1994]. Furthermore, such inclusive instruction is required by law in the U.S. [USC Disabilities Education Act Amendments (IDEA) 1997], and the *No Child Left Behind Act* [USC NCLB 2001]. A court ruling [Oberti v. Clementon 1993] also reinforces the nonsegregational approach. Therefore, the discussion is not if inclusive classrooms are good, it is how to make them work. The reduction of the gap between special and regular students requires both inclusion of those with special needs and effective educational methods for *all* students [Baker et al. 1994]. One of the most promising practices for helping students with disabilities to succeed in the classroom is the use of technology [Baear et al. 2005].

Several other systems have been proposed to help the IBSVI to access graphical mathematical content [Manshad and Manshad 2008; Wall and Brewster 2006; Wells and Landau 2003]. Differently from these, our solution promotes the collaboration between instructor and IBSVI, giving the parties simultaneous access to the same illustration content to which both parties can make deictic references. The importance of such shared representation in a collaborative task involving blind and sighted was identified earlier [Winberg and Bowers 2004; Sallnäs et al. 2006; McGookin and Brewster 2007]. This is corroborated by Lohse [1997] who found that different graph representations can have an impact on time and effort to extract information, even if they represent the same information. Mynatt and Wber [1994] point out that cooperation is assured when coherent visual and nonvisual interfaces are available.

Taking our system to inclusive classrooms also brings another set of challenges. The instructor must be able to adapt discourse to address both the IBSVI and nonimpaired

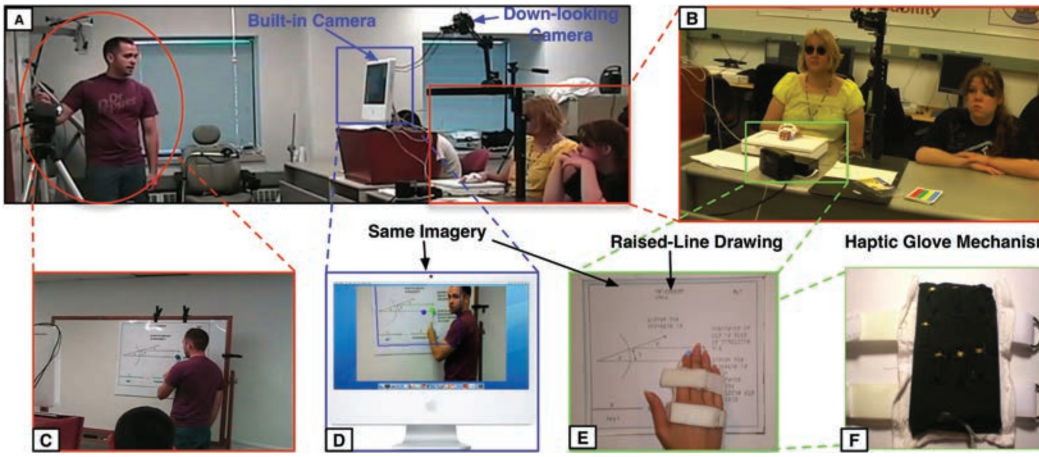


Fig. 2. The haptic deictic system – HDS.

students simultaneously. The goal is for the technology we develop to support natural discourse so well that the same instructional discourse can be effectively addressed to both groups, and so that uptake by both IBSVI and nonimpaired students would be nondisruptive to the flow of instruction to either.

3. SOLUTION OVERVIEW

Our illustration in Figure 1 is an enactment of *multimodal instructional discourse* where the student has to fuse three information streams: the spoken speech stream, graphic content of the diagram that accompanies the instruction, and the deictic gestures of the instructor that situates the speech with the graphic both temporally and spatially (i.e., pointing that synchronizes with the vocal utterance). For IBSVI, the latter two streams require some form of augmentation. We employ the sensory-substitution approach [Bach-y Rita et al. 1969; Sherrick 1985] by which the visual information is replaced by the tactile sense. For the graphic content, we employ embossed paper raised-line drawings that are relatively inexpensive to produce [Universal Low Vision Aids Inc. 2009b, 2009a], readily available, can be quickly and easily explored by those who are blind [Wall and Brewster 2006], and can be used during instruction. The problem is that a student who is blind cannot resolve the teacher's deictic references towards the instructional material as she speaks [Dick and Evelyn 1997]. Our solution is to furnish a third situating stream that unifies image/graphic with speech into a cotemporal package of thought and communication.

In our approach, the IBSVI has a tactile version of the graphic which the instructor points at while speaking. We define two foci that must be tracked and represented. The first is the *Point of Instructional Focus*, *PIF*. This is the reference point of the instructor's discourse and is detected by visually tracking the teacher's pointing hand, or some pointing tool like a wand. The second is the reading point of the student's "reading hand" on the raised-line graphic that we denote the *Tactile Point of Access*, *TPA*. We employ computer vision to track both the PIF and TPA, from which a *Focal Disparity vector*, *FD* is computed. The FD is computed as: $FD = T^{IS}(PIF) - TPA$, where T^{IS} is the transformation that locates the instructor's PIF in the student's raised-line graphic. We employ computer vision to track both the PIF and TPA and to update the FD in real time [Fang et al. 2010].

Figure 2 presents an overview of our Haptic Deictic System (HDS) in operation. Figure 2(a) shows a classroom scene with the instructor pointing into a graphic on a poster, and a pair of seated students (one IBSVI, and one sighted) receiving instruction. The instructor's pointing gestures (with a wand in the figure, but the system is capable of tracking an unadorned hand) are tracked via the camera in the iMac placed in front of him (Figure 2(c)). Figure 2(b) shows a close-up picture of the two students from Figure 2(a), with the IBSVI on the left reading an embossed raised-line version of the graphic on the poster. The down-looking camera visible in Figure 2(a) tracks the IBSVI's reading hand (a frame of this tracking video is shown in Figure 2(e)). In the instructor's display on the iMac monitor (see Figure 2(d)), the instructor can see the video stream from the tracking camera that is augmented by the location of his pointing focus (blue dot), and the reading location of the IBSVI (green dot). The IBSVI wears a haptic glove that is embedded with eight mechanical actuators (vibration motors sewn into a glove pad). The glove conveys the FD to the IBSVI so that she is able to locate the instructor's deictic focus. All motors come to a complete stop to indicate when the IBSVI has reached the PIF. Technical details of the HDS design may be found in Oliveira and Quek [2008] and Oliveira et al. [2011].

In essence, the HDS supports mutual embodiment and attention awareness between the IBSVI and her sighted instructor in deictically supported instruction. The haptic glove informs the IBSVI of the action needed, as a motion trajectory, to bring her to the instructor's deictic focus. The heads-up display on the iMac screen lets the instructor track the reading focus of the student in relation to where the instructor is pointing. This furnishes the instructor with awareness of the IBSVI's point of attention just as general gaze awareness and assessment allows her to gauge the attention of sighted students in a class.

Our choice of using a glove on the user's palm is driven by two considerations: spatial sensitivity and practicality. Research investigating tactile stimuli on various body parts includes Lee et al. [2004], McGehee et al. [2001], Gilliland and Schlegel [1994], Ho et al. [2005], Jones et al. [2006], Godthelp and Schumann [1993], Janssen and Nilsson [1993], and Vitense et al. [2003]. A typical measure of spatial tactile sensitivity is the Two-Point Discrimination Threshold (TPDT) [Christman 1979, pages 384–386], usually defined as the minimal distance at which two simultaneous stimuli are distinguishable from a single stimulus [Kaczmarek and Webster 1991]. The most sensitive areas of the body with the lowest TDPT are: the middle finger (2.5mm), index finger (3.0mm), thumb (3.5mm), upper lip (5.5mm), nose (8.0mm), and palm (11.5 mm) [Christman 1979, page 386]. Of this list, the palm is the most practical body location that has a balance of sensitivity and sufficient surface area to convey gestural information.

We tested a range of haptic/tactile signaling options on the palm including a variety of haptic vibrating gloves and reverse joysticks. The joysticks were quickly rejected as IBSVI need both hands on the reading material, with one providing spatial reference. Our pilot studies with low-power piezo-electric devices showed that they were difficult to perceive and that it was difficult to maintain solid contact between the actuators and the palm. We found that a set of vibration motors embedded in copper tubes provided the most perceptible signal. We tested a set of glove configurations. Our final design is the simple N-NE-E-SE-S-SW-W-NW 8-actuator configuration shown in Figure 3. The HDS is driven by a single-board controller driving the motors at repeated pulses of 33 msec. The FD is quantized into either one of four (E-N-W-S) or eight directions. The actuators were pulsed at two intensity intervals: strong and weak. When the TPA is far from the PIF the user experiences stronger pulses, and as the TPA approaches the PIF, weaker pulses are sent to the glove. Details of these design choices may be found in Oliveira and Quek [2008], Oliveira et al. [2011], and Oliveira [2010].

We conducted a set of perception studies to determine if the glove would be able to support embodiment awareness while listening and reading. To avoid overuse of our pool of IBSVI, we conducted the studies with blindfolded participants to answer three

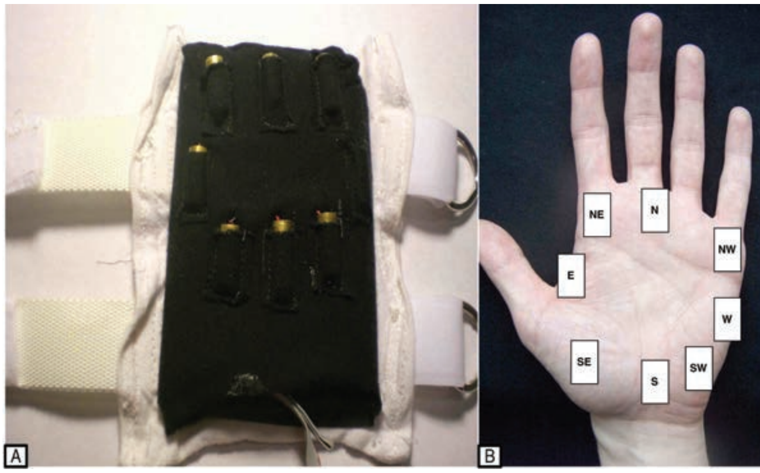


Fig. 3. The HDS glove configuration.

questions: (1) Can the glove convey sense of direction in a timely fashion; (2) does the vibrating glove interfere with fingertip reading; and (3) can a person navigate to read information with the glove while listening to a story in which some information is conveyed as raised-dot? Our studies [Oliveira and Quek 2008] determined that the fit of the glove to the participant was critical to its performance. With a properly fitted glove, the participants could quickly determine the sense of direction, could read with their fingertips while being guided by the glove, and were able to simultaneously receive aural information while navigating and reading.

The questions we address with the HDS relate to the two research levels set forth in our Introduction. First and foremost, we address the conceptual questions of how gesture and speech participate in a unified system of communication and how support for this nexus of speech and gesture is critical to enabling instructional interaction. What supports are needed for IBSVI to access visual embodied gestural behavior? How may our haptic glove system support uptake of deictic gesture in conjunction with speech? How transparent does this gestural awareness have to be to support instructional conversation? Second, we address the pragmatic questions concerning the use of the HDS in inclusive instruction. How does the HDS affect the fluency of instruction? What is the impact of the system on the classroom dynamics between the instructor, IBSVI, and sighted students? Does the HDS increase the IBSVI's "opportunity to learn"? What conditions must be met to furnish such opportunity? What new challenges in instruction arise from use of the technology?

4. EFFORTFUL GESTURE TRACKING IS NOT THE SAME AS UNDERSTANDING MULTIMODAL DISCOURSE (IT'S NOT LIE FOLLOWING THE RABBIT)

Our studies reported in the previous section establish the capacity of the HDS to support a participant's ability to follow directions and read while listening to a verbal narrative. This would be analogous to one's ability to follow a target while listening to a story. This, however, is not the same as engaging in embodied discourse involving both gesture and speech that requires transparent facility in perceiving each discourse mode. In our problem domain, especially, the student would have to comprehend the speech-gesture compound while engaging in mathematics instruction uptake. A challenge of our project is in recruiting a group of participants with similar visual impairment and matched-level mathematics ability. At this point, we judged that we were not ready to

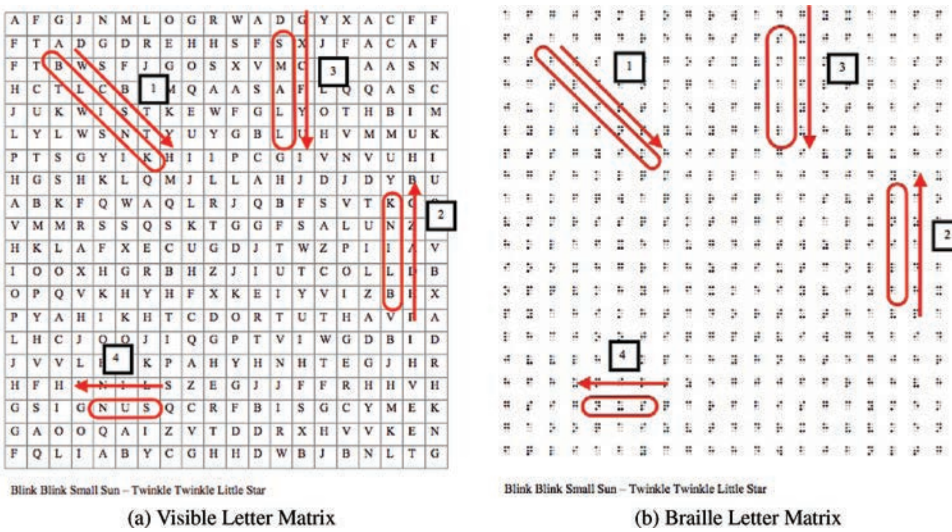


Fig. 4. Phrase charade game setup: (a) visible letter matrix (b) braille letter matrix.

engage the participants in our designed mathematics study (see Section 5). Hence, we designed a study to ascertain the capacity of the HDS to support instructional discourse uptake in advance of our eventual mathematics instruction studies.

We devised a *phrase charade* game to determine if a student can engage fluidly in the dynamics of a continuous multimodal discourse stream while simultaneously entertaining cognitive problem-solving and learning activities [Oliveira et al. 2010]. These studies show that being able to follow directional instructions, and even to navigate and read embossed information while listening, is not the same as participating in multimodal discourse. We shall also show how such multimodal discourse may be ultimately enabled.

4.1. Charade Game and Study Design

The perception-related experiments outlined at the end of Section 3 focused on the participant's ability to follow directions and read while listening in a passive way. Multimodal discourse and instruction, however, involves more than such passive ability. We designed a phrase charade game to test the HDS. This allowed us to: (1) exercise the entire system in the target dyadic discourse (or two-way reciprocal discourse) configuration; (2) explore what communicational affordances the system brings; (3) ascertain if this new interaction enables more fluent and effective communication; and (4) determine potential problems that arise in communication using the HDS.

The phrase charade involves a sighted *guide* helping an unsighted *follower* to solve a letter-grid puzzle such as the ones shown in Figure 4. The physical configuration is identical to that shown in Figure 2 with the guide in the instructor's role. The visible letter matrix illustrated in Figure 4(a) is presented as a poster into which the guide points while speaking. The Braille matrix (Figure 4(b)) is presented in embossed format to the IBSVI follower in the same way as shown in Figures 2(a), (b), and (e). The goal of the game is for the follower to guess a catch phrase given a clue phrase presented on the letter matrix. Without giving the catch phrase away directly, the guide helps the follower to locate and read a clue phrase ("blink blink small sun" in the example) using both speech and gesture. The unsighted follower reads the Braille version of the puzzle guided by both the speech and the signals conveyed by the glove, and then has

Table I. IBSVI Participant and the Studies

Participant	Gender	Blindness onset (age in years)	Studies
B1	F	16	1^{st} charade, game, 2^{nd} charade, instruction
B2	M	13	1^{st} charade, game, 2^{nd} charade, instruction
B3	M	from birth	1^{st} charade, game, 2^{nd} charade, instruction
B4	F	2	Game, 2^{nd} charade, instruction
B5	F	12	Game, 2^{nd} charade, instruction
B6	F	10	1^{st} charade

to guess the concomitant catch phrase ("twinkle twinkle little star" for the example). We ran a set of prestudies with a matched culture group to identify a set of 12 catch phrases that would be known to the target participant population, and to ensure that the clue phrases provided the necessary information to solve the puzzle [Oliveira et al. 2010]. The phrase charade is, therefore, designed to present a facsimile of a typical instruction scenario where an instructor communicates a set of information and where the recipient has to engage in a further cognitive task of thinking about the material presented.

4.2. The Participants

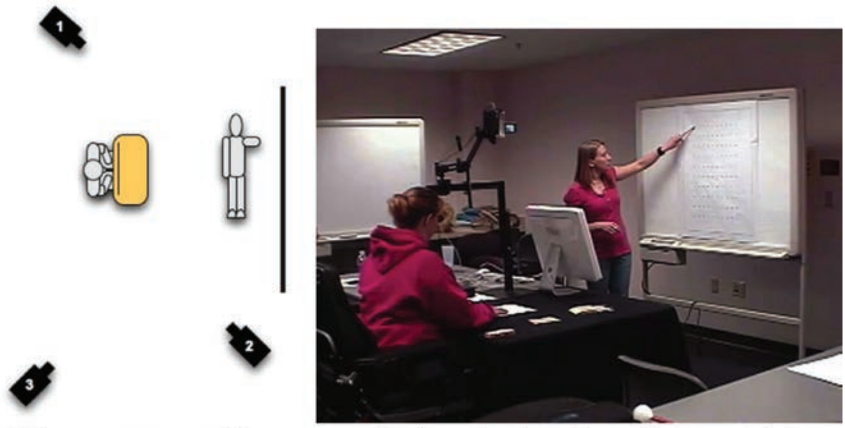
A typical challenge in working with individuals with disability is to identify a population of participants with closely matched prior knowledge and kind of disability. Our undergraduate participants were recruited at a campus that is specially designed to accommodate access by individuals with disabilities and that has an atypically large number of diversely-abled students who are integrated into the general student population. This environment is somewhat unique because of the low percentage of students with disabilities who attend college. Only a very small number of high school graduates who are blind, for example, go to college [Splindler 2005].

We recruited students with matched levels of mathematics ability (students not majoring in mathematics-related studies with a minimum of prealgebra capability) and visual impairment with central visual acuity of 0.05 or less that cannot be overcome with corrective lenses [International Council of Ophthalmology 2002; Department of Health 2007; WHO 2007, 2010] through the institution's Office of Disability Services.

Table I shows the participants, designated B1 to B6, their gender, the age of the blindness onset, and the studies in which they participated. Age of blindness onset is important because previous visual experience affects learning positively [Dick and Evelyn 1997]. In the following sections, we report four consecutive studies: the first charade study (Section 4.3), games and skill training (Section 4.5), the second charade study (Section 4.6), and the mathematics instruction study (Section 5). Because of the longitudinal nature of our research, not all participants were present in all studies. As one can see on the last column of Table I, B4 and B5 joined our research effort only after the first charade study, while B6 dropped out after that study. It is important to notice that all IBSVI participants are considered legally blind in the United States. A person who cannot achieve a visual acuity of 20/200 (6/60) or above in the better eye, even with the best possible optical correction, is considered legally blind in the United States.

4.3. First Charade Study

Four IBSVI participants (see Table I) played the role of follower. Two sighted graduate students with teaching experience were recruited to serve as guides. Each guide worked with a male and a female follower.



(a) 3 cameras to capture different aspects of the conversation (b) picture taken from Camera 3 in an actual trial

Fig. 5. Cameras recorded the trials from different vantage points.

The HDS system and the game rules were explained to each guide-follower pair. They were then permitted to familiarize themselves with the system and to play a practice phrase charade game. Each pair then played three more phrase charades. Video data were collected for the study.

4.3.1. Data Coding and Analysis. All trials were videotaped from three different cameras capturing different aspects of the interaction. We wanted to investigate how the pairs employed embodied discourse to work as teams, and what strategies they developed to accomplish their common goal. Camera 1 presents a close-up of the guide. This camera also captures the instructor's display and it is possible to observe when the guide looked at the monitor. Camera 2 provides a close-up of the follower along with the document (rendered in Braille) on top of her desk. This view allows us to observe signs of difficulty in reading the Braille-embossed document and to identify what kinds of problems arise from the HDS-aided navigation. Camera 3 provides a view of the whole scene and allows us to observe the temporal coordination and interaction between the participants. Figure 5(a) shows how the cameras were arranged and Figure 5(b) shows an image from the Camera 3 video stream.

The interactions between guide and follower in the multichannel video/audio were coded for both gesture and speech using the MacVisSTA [Rose et al. 2004] system, which supports time-aligned analysis. The discourse was further coded in terms of "coreference chains" at three levels: *object*, *meta*, and *para* levels [McNeill 2006]. Object-level references relate to the substance of discussion; in this case, the "joint project" [Monk 2003] of solving the charade. Meta-level utterances reference the talk or the solution process, and serves regulatory function to the object-level discussion. Turns relating to discourse repair and directional shifts in the solution process were coded as meta level. Para-level references relate to direct personal experience and people and objects that are present in the speaker's environment. Words of encouragement like: "there you go", "take your time", etc., and personal decisions like "I think this is right" were coded as para-level utterances. This coding and a set of postperformance questionnaires allowed us to understand the process of joint problem solving using the HDS system.

In all, we transcribed and coded 58.39 minutes of speech. Table II shows how we coded the 1,228 conversational turns recorded.

Table II. Charade Study Discourse Reference-Level Breakdown

Discourse Reference Level	Number of Conversational Turns
Object level	886
Meta level	310
Para level	32

We also coded the exchange using an adaption of Clark's presentation/acceptance model [Clark 2003, pages 107–143]. In our coding scheme, when the guide is pointing at a letter, she is *presenting* it. If the follower shows evidence that she has *accepted* that presentation, the guide would move on to present the next letter. If the guide sees signs of confusion from the follower, she engages in *expansion* trying to give more information for the follower to resolve the referent, that is, read the letter to where she is pointing. Sighted followers would almost immediately resolve the referent as it takes only a quarter of a second for the first human eye saccade at a peripheral target [Prablanc et al. 1979]. Therefore, the occurrence and length of expansion turns can be seen as troubling signs.

4.3.2. Study Results. All our IBSVI participants were able to complete the study and solve all the puzzles. We judged the interaction, however, to have failed to reach the fluidity needed for operation within an inclusive classroom. The discourse appeared labored and cumbersome. A significant chunk of their conversational turns (around 30%) were devoted to the mechanics of the interactive navigation task and the technology, addressing how to reach the letter to which to the guide was pointing. A third of the discourse was spent on conversational turns coded as either belonging to meta or para-level reference chains.

The exchanges were analogous to one attempting to conduct instructional discourse with an audience of language learners where the focus is on the process of talk and not on the substance of instruction. Our phrase charade study showed clear evidence of discourse breakdown. Research shows that when conversants feel that the technology is "getting in the way" of their interaction, they are likely to stop using it [Clark and Wilkes-Gibbs 1990; Clark and Brennan 1991; Tatar et al. 1991].

This brings us back to our analogy at the end of Section 2.1 that such mechanistic activity is far from participation in an embodied discourse, becoming more akin to consciously tracking a rabbit through a garden, where such effortful action hinders Alice from appreciating the garden itself. The interaction in the phrase charade was more like a process of mechanistic "follow-the-leader" than one of discourse with deixis. The effort of following the pointing hinders the embodied discourse uptake. In an inclusive classroom, this will either interrupt the flow of instruction if the instructor engages the IBSVI more intensively, or leave the IBSVI behind if the instructor proceeds with instructional discourse focused on the sighted students.

The presentation/acceptance analysis corroborates the preceding conclusion. Of the 3,077 seconds the pairs spent to present/accept the clue phrases, 1,338 (43.50%) were spent in expansion turns. Hence, it is fair to assume that it took 1.435 times longer for a blind follower to accept the clue phrase than for a sighted counterpart. As discussed Previously, sighted followers would almost immediately resolve the referent. Dick and Evelyn [1997] showed that it takes 1.5 times longer for a student who is blind to cover the same instructional material than that of a sighted counterpart. The numbers are close and suggest the dyads worked as if there was no technology available to them.

4.4. Development of Embodied Skill

We hypothesize that this inordinate focus on the operational aspects of our assistive technology at the expense of the functional task of solving the cognitive problem is due to a lack of fluency and familiarity with the device. We had assumed that the blind students would be able to employ the haptic device with minimal training, basing this on research on haptic devices that suggest a quick learning process (see Gallace et al. [2007]). This was partially true with our device, for example, as subjects were able to correctly ascertain the direction indicated by the glove and to navigate to specific targets after a short period of familiarization in the perception-action studies reported in Oliveira and Quek [2008]. Our first phrase charade study shows that this does not extend to blind students using our haptic device and engaging in the complex activity of multimodal discourse comprehension and production.

We posit that this is because deciphering the directional signals is a secondary task performed in the service of discourse maintenance, and as such must become far more automatic. This is especially the case since the glove is used to support the understanding of multimodal discourse. Clark [1992, page 140] suggests that the cognitive burden is heavier for the listener (the follower in our phrase charade) than for the speaker. Our device has to disappear in the sense of Dourish's concept of "embodied skill" that depends on "a tight coupling between perception and action" [Dourish 2001, page 120]. The blind follower's attention to the signals from the glove must recede into the background, so that her conscious attentional and cognitive resources can be dedicated to the far more complex task of multimodal comprehension and discourse maintenance. Evidence suggests that when a haptic stimulus is presented in a dual-task scenario, where other concurrent information is being conveyed in a different mode, the result is a dramatic decrease in task performance [Lloyd et al. 2003; Spence et al. 2001a, 2001b]. The haptically aided navigation task should turn from controlled to automatic. The difference, according to Wickens and Hollands [2001, pages 276–277], is that the controlled task demands attentional resources whereas the automatic does not. Wickens states that "extensive perceptual experience" and consistency of responses are necessary ingredients for a task to become automatic. Furthermore, extensive training helps to eliminate decrease in sensitivity [Fisk and Schneider 1981] and improves task performance by improving tactile discrimination and increasing activation of the somato-sensory cortical areas representing the stimulated body part [Hodzic et al. 2004].

4.5. Games and Skill Training

Our approach to supporting the development of embodied skill is through a game experience [Oliveira et al. 2010, 2011]. Csikszentmihalyi, for example, suggests using games to allow individuals to "experiment with [a] repertoire of behaviors in a nonthreatening setting and, hence, to learn by trial-and-error without paying too high a price for errors" [Csikszentmihalyi 1975]. A properly designed game can bring about a state where activity is fully absorbing, and produce a sense of "deep enjoyment" [Archambault et al. 2007; Johnson and Wiles 2003]. This nonthreatening and enjoyable experience has been used to help individuals with special needs to develop skills [Lecuyer et al. 2003; Inman et al. 1994, 2000]. Games have been used, for example, in conjunction with virtual reality to help people with special needs to develop new skills [Lecuyer et al. 2003] like going to the mall [Inman et al. 1994], simulating street crossing [Inman et al. 2000], and learning how to browse the Internet [Roth et al. 1999], and in rehabilitation (e.g., wheelchair use) [Inman et al. 1994]. More specifically to our research, games have been designed to help individuals with visual impairment to use Braille displays [Sepchat et al. 2006], use tactile transducers [Wang and Hayward 2006], derive visualization from a tactile and force-feedback systems [Raisamo et al. 2007; Johansson and Linde 1999], investigate better haptic/tactile assistive designs [Sjostrom 2001], and access three-dimensional graphics using an audio-haptic device [Iglesias et al. 2004]. Details of our game design, implementation, studies, and results can be found in Oliveira et al. [2010, 2011]. We summarize our game-training intervention and study here for context because the skill development presented in this section contributes directly to our following mathematics instruction studies.

We modeled our game loosely on the television and movie series *Mission Impossible*. The story is that “Dr. Evil” has hijacked the U.S. nuclear arsenal and will destroy a set of major cities one-at-a-time unless the player can find the detonators and destroy them within a specified time window. Following the guidelines of game flow theory [Chen 2007; Johnson and Wiles 2003; Sweetser and Wyeth 2005], the game was designed to maximize “challenge” while graduating difficulty to avoid either boredom or anxiety [Chen 2007]. The game has three levels, each harder than the previous. The levels of difficulty correspond to how close the player’s hand has to arrive at the specific grid location on a surface of the same size as the HDS reading area, and the dispersion of the targets across the area. Music pacing and sound effects were used to enhance the level of excitement corresponding to game state.

We introduced the game over the period of a semester at the institution the five (three females and two males; see Table I) IBSVI participants attended. One female and the two males had also participated in the first phrase charade study. The students could play the game at their leisure (a reservation process was used to allow experimenters to monitor the game play). To encourage play and to increase fun, we posted the game scores to introduce a sense of competition among our participants. We collected data on the tracked movement traces of the participants’ “reading hand” to explore the navigation strategies employed, and time to target for each target (normalized by distance to target). A postinterview was administered to assess each participant’s experience.

All of our participants got through the second level (requiring navigation to within 5 pixels of a target), and three reached level 3 (requiring navigation within 1 pixel of a target) of the *Mission Impossible* game, and improved their performance through the game between 45% to 62% in navigation speed. The increase in speed between level 1 and 2 was significant ($t(4)=1.80$, $p<0.001$) even though the target proximity requirement increased. There was a statistically significant decline in the number of navigation overshoots between the two levels ($t(4)=1.81$, $p=0.001$). The participants exhibited the typical interest of college undergraduates in playing the game. One participant asked if he could purchase the game from us. All said they enjoyed playing the game, and all but one could go on playing for another 45 minutes after having completed their level-2 game, typically playing 30 to 45 minutes (the only exception was a participant who said she could play 30 minutes more after playing uninterrupted for 54 minutes, which suggests that the device could be used in 45-minute-long lecture). Two participants tried to maintain the status of being the highest scorer, returning to play whenever their score was exceeded. All participants had significant increases in navigation efficiency (measured as the ratio between actual distance traveled against the Euclidean distance to target).

4.6. Second Phrase Charade Study

We revisited our phrase charade study after the game-based-training to see if the gains in game performance transferred to discourse performance. To put this in context, our first charade study took place in Spring 2007. It took us a year to develop and validate the *Mission Impossible* game which was run in Fall 2008. The second charade study was conducted in Spring 2009. Hence, this has been a rather longitudinal process for three participants who were in all three studies.

We did the same coding and analysis for the second phrase charade as we did for the first (see Section 4.3.1), and we summarize our results from Oliveira et al. [2010, 2011] here. The repeat participants (see Table I) completed the charades significantly faster

Table III. Blind Followers Experience - A Comparison between 1st and 2nd Charade Studies

Grp	Statement	Charade	
		1st	2nd
C	I felt comfortable using the glove	4.25	4.40
C	I'd rather use this glove than have someone physically move my hand to the letter	3.75	4.60
Cd	If I had someone physically holding my hand and putting it over the document, I would have performed better	3.75	2.80
Cd	I would perform better with practice	5.00	4.60
Cd	I would like to participate in future experiments because I believe this technology will help students who are blind	5.00	4.80
MT	I could perfectly listen to the *guide* while using the glove	4.50	5.00
I	Using the system did not interfere on my thinking of the solution	3.20	3.80
I	The conversation between the *guide* and myself flowed naturally	4.25	4.80
I	I was able to point at my chart and ask questions	4.25	4.60
I	I used pointing to reduce misunderstanding in what I said	3.25	4.00
I	Because of the system, I perceived that my communication was better understood	4.00	4.40

in the second study (an average of 239 seconds versus 444 seconds, an 86% difference). The time per charade rises to just 251.92 seconds when we consider all five participants in the second study. Also, virtually all discourse turns in the second charade study were focused on solving the charade (97.14% versus 77.7% for the first study). There was no evidence of overt attention being paid to the technology or the process of pointing.

Postquestionnaires were conducted verbally after both charade studies. These took the form of a set of statements to which the participants responded on an agreement Likert scale (1-strongly disagree to 5-strongly agree, 3 being no opinion). Statements were kept the same to facilitate the comparison between both studies. Table III shows a selected subset of these questions and the means of the answers for both first and second charade studies. The questions were grouped into five different categories: Comfort (C), Confidence (Cd), MultiTask (MT), and Interaction (I). We shall discuss the data on this table by groups.

By *comfort*, we mean one being comfortable with both wearing the haptic glove and interacting with the guide through the system. One can see that our participants are more inclined to wear the glove than to have someone physically holding their hand, as normally happens in traditional instruction. For *confidence*, we mean the confidence participants have that the system will bring gains in interactions similar to the charade. In this group, one can observe that after playing the game, participants are more inclined to believe that they would perform better using the system than with human help. We have argued earlier in Section 4.4 concerning the multimodal, multitask demands of a instructor/student-like interaction. In this group, numbers have also improved. When it comes to interaction, one can observe that our blind participants believed that: (1) the interaction with the guide flowed more naturally, (2) that they could also benefit from pointing, and (3) that the system helps the conversants.

Together these results show that our training to develop embodied skill produced measurable interactional gains. These gains gave us confidence to move on to the next phase of our research where we target mathematics discourse directly.

5. MATHEMATICS INSTRUCTION STUDIES

After the second charade, we had a population of participants who were trained in the use of the technology, and who were able to use the system in discourse. We note that the charade game differs from mathematics instructional discourse in one

Table IV. Instruction Experiment

Experimental Condition	Curr A(T1)	Curr B(T2)
Blind w/ System	G1(*B1*, S1, S2, S3) ÊG2(*B2*, S4, S5, S6)	G3(*B3*, S7, S8, S9) G4(*B4*, S10, S11, S12) G5(*B5* ,S13, S14, S15)
Blind w/o System	G3(*B3*, S7, S8, S9) G4(*B4*, S10, S11, S12) G5(*B5*, S13, S14, S15)	G1(*B1*, S1, S2, S3) G2(*B2*, S4, S5, S6)

Legend: Cur A – Curriculum A, Cur B – Curriculum B
T1 and T2 – Teacher 1 and teacher 2.
G1. . . G5: 5 groups.
S1. . . S23: 15 sighted students.
B1. . . *B5*: 5 IBSVI

important respect. Contextual information in the latter helps one to link the speech with the semantics of the graphic content while for the word puzzle the participant has to rely only on the glove for navigation. The participants in both the *Mission Impossible* game and the second phrase charade then participated in the final study that directly addressed mathematics instruction in an inclusive learning configuration. In the following sections we will present: (1) our experiment design; (2) our analysis instruments followed by data analysis; (3) discussion; and (4) conclusion.

5.1. The Participants

As outlined in Table I, the five IBSVI participants in our inclusive mathematics instruction studies have gone through our game training and the second charade study described in Sections 4.6, and have therefore received considerable training on the HDS in nonmathematics instruction contexts.

Like our five IBSVI participants (see Table I), the sighted participants were all college undergraduates in nonmathematics majors.

We designed two mathematics curricula (A and B; see next section) for the study and recruited an instructor to teach each. Curriculum A instructor T1 is a male mathematics graduate student in his mid-twenties who wants to become a high school mathematics teacher but had no real-world teaching experience. Curriculum B instructor T2, is a female professional high school mathematics teacher in her late forties. Though she has almost 30 years teaching experience, she has never taught an IBSVI.

5.2. Experiment Design

For our studies, we constructed inclusive teaching/learning scenarios in which one IBSVI was grouped with three students with normal sight. We developed two mathematics three-class mini-courses (curricula A and B) that are suitable for our population. Curriculum A was on planar geometry, and Curriculum B covered trigonometric concepts. We employed two instructors T1 and T2. T1 taught Curriculum A, and T2 was assigned to Curriculum B. All student participants were required to take oral exams both before and after attending the classes.

Table IV details how the participants were grouped. Our five IBSVI were assigned to groups G1 to G5 and to our study conditions such that they are counterbalanced across with-HDS and without-HDS conditions and curriculum-instructor pairs.

6. DATA COLLECTION METHODOLOGY AND ANALYSIS

6.1. Challenges

Although we were careful in our participant recruitment efforts, and had reasonable success in locating five subjects matched for disability and mathematics background, we were still vulnerable to variance of prior knowledge and mathematics ability. Despite five matched disability participants being a good number for the kind of long-term study we were doing, this number is too small for us to be able to do any statistically significant subject-matter learning outcome analysis. Also, we made no restriction to what year the students were in their undergraduate program. One can argue that freshmen would have an advantage since related mathematics material covered in high school would be fresher in their minds than it will be for seniors. Finally, we had only two instructors teaching different curricula and with very different backgrounds. We acknowledge the fact that having only one instructor and one curriculum would make our quantitative analysis easier. But it would also make our qualitative analysis much poorer. These analyses are designed to provide indications as to whether the students had opportunity to learn the material by investigating the dynamics of interaction between instructor and class.

We performed three kinds of analyses on our data. First, we developed a pair of psycholinguistically informed analysis approaches to gain insight into discourse process changes brought on by the system, and to ascertain if the HDS presented the IBSVI with the opportunity to learn by having access to the mathematical concepts being conveyed. Second, we employed a battery of analyses to determine if the HDS impacted instructional discourse fluency. Third, we analyzed the experience of all the participants in the inclusive learning scenarios (the instructor, IBSVI, and the sighted students) using postinstruction questionnaires.

6.2. The Data

The data collected comprised pre- and poststudy oral exams, classroom interaction, and poststudy questionnaires. Forty-four oral exams (22 pre-, 22 poststudies) were videotaped, anonymized, had their audio extracted, and were given to an independent teacher for grading. These oral exams established that the students came into the class at approximately the same level of mathematics sophistication. The postclass exams were inconclusive because of our sample size and student variance, as we have discussed. All classroom interaction was videotaped with a camera arrangement similar to the one used in the charade studies (see Figure 5(a)). This resulted in 36 datasets (3 lessons per class per curriculum $\times$ 6 classes per curriculum $\times$ 2 curricula), totaling 753 minutes recorded on 108 video tapes. All that interaction was transcribed and coded (9,424 conversational turns totaling 96,961 words). We also identified the speaker and the duration (in seconds) of each turn. For each lesson, we created a MacVisSTA [Rose et al. 2004] project comprising of its videos and their transcription all properly time-aligned. Figure 6 shows a screenshot of one of these projects. In the same figure, one can observe panes where the transcribed discourse of each participant is displayed in synchrony with the videos. The tool also allows the creation of new panes that can be used to mark particular segments of interaction that relate to activity such as concept conveyance.

6.3. Situated Language Analysis

6.3.1. Psycholinguistically Grounded Analysis Instruments. To determine the effect of the HDS on inclusive instruction, we developed a situated analysis approach [Harrison et al. 2007] that analyzes the situated activity of multimodal discourse to gain insight into the instruction-uptake process.

To understand how the HDS affects the relationship between image and discourse, we employed two sets of psycholinguistically grounded analyses. In the first, we used McNeill and Quek's concepts of growth point [McNeill 2005, pages 81–82] and hyperphrase [Quek 2004] to understand how the system affects gesture and speech synchrony and how it impacts the creation of learning opportunities for the IBSVI.

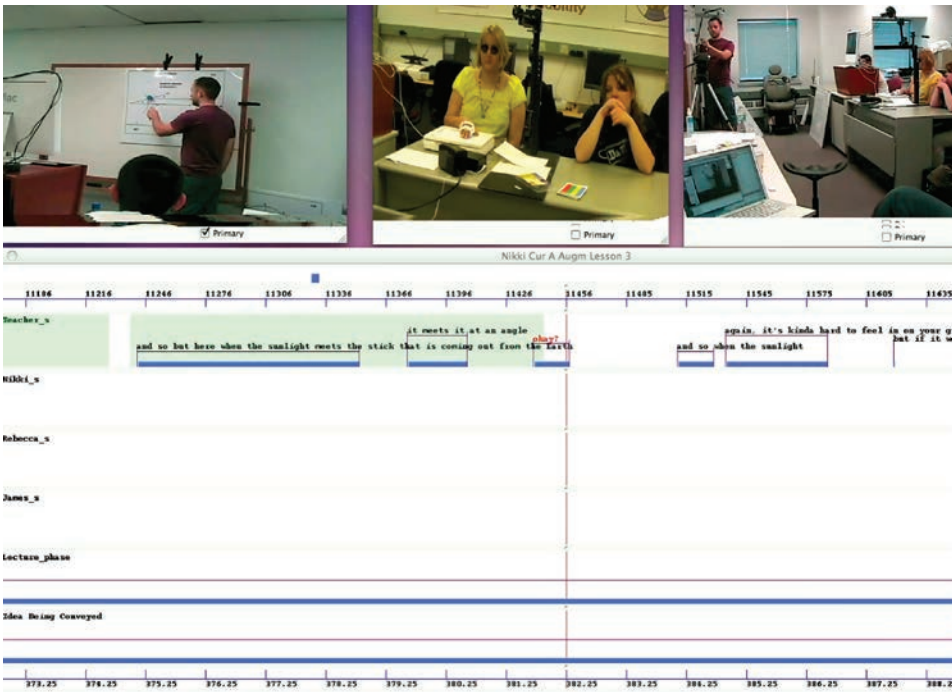
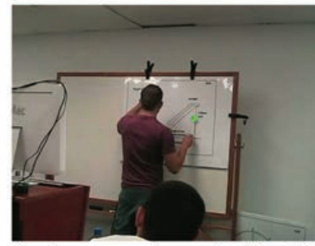


Fig. 6. All data synched – situated analysis.

In the second analysis, we used Clark's Common Ground theory [Clark 1992, page 4] to understand how instructors and students used *evidence* [Clark 1992, page 37] and *assumption* [Clark 1992, page 39] to generate mutual understanding with and without the system. To facilitate analysis, we selected a set of "focus mathematical concepts" that are discussed in the mini-courses. We chose concepts that had clear extents (i.e., are clearly delineated in the discussions), and that occur in every instructor-class-HDS use condition. For example, one concept was 'Transversals' that describe the geometric properties of a line intersecting a parallel line-pair. We coded for 10 concepts, and narrowed our analysis to three concepts (transversals, vertical angles, and diameters). This yielded over 40 minutes of video to be further coded and analyzed.

A. Situated Analysis (Growth Point and Hyperphrase). For McNeill [2005, pages 81–82], Growth Points (GPs) are idea units and come from the dynamic combination of linguistic categorical and imagistic components which "live" a period of instability. The resolution of this instability "crystallizes" an idea unit. GP is normally inferred from the speech-gesture synchrony and coexpressivity. If instructor and student share the same GP, we can say that they inhabit the same "state of cognitive being", where they are mentally focused on the same concept. A hyperphrase is a multimodal communicative package comprised of verbal, gestural, and gaze components simultaneously organized thematically around an idea unit [Quek 2004]. We can, then, analyze deixis-laden discourse to produce three conditions leading to different learning opportunities: (1) *shared GP*, where the instructor produces a vocal utterance and points. The IBSVI arrives at the focal point during the utterance, therefore participating in the GP. (2) *Reduced hyperphrase synchrony* is where the topic of the GP has ended, and the instructor has moved to a "transitional" phase in preparation for the next topical unit

Table V. How HDS Affects Speech and Gesture Synchrony

Shared GP	**Reduced hyperphrase synchrony**	**GP/hyperphrase disconnect**
"Right here – when the sunlight meets the stick as its coming out from the ***Earth****"*	*"And then this* ***parallel*** *line is also the sunlight hitting the Earth"*	*"My stick is 5ft"*
		
The instructor points at the intersection of Lines A and C. His focal idea or GP is the angle of sunlight (pointing at the graph) with respect to the surface of the Earth (in speech). These form a thematic unit. The student receives signals from the glove and starts moving her hand along her graphic line toward the intersection.	Instructor's wand moves up the line on his graph. His GP or core idea here highlights the parallelism of the line (rather than any other property). The student, again, is not at this line but begins to move up to the line on her graphic. As she reaches it, the instructor is saying:	The instructor points at the side of the rectangle corresponding to the stick. The student starts moving toward the teacher's pointing. Before she gets to the side of the rectangle that corresponds to the stick, the instructor moves to another side of the triangle and says:
"It meets at an ***angle****"*	***"And so"***	***"and my shadow is 10"***
		
Student's reading (blue dot – the student's tactile point of access (TPA)) reaches the Line A-C intersection just as the instructor says "*angle*". She can then form an idea unit or GP with her deixis with this word, which is the same idea unit the instructor had focused on. So here is a case where the student, thanks to timing, and despite inevitable delay, can directly apprehend the core idea.	The IBSVI's deixis and the instructor's speech do not form the same GP. The IBSVI's GP comprised of deixis and the speech transition. Although not the instructor's GP, it also links back to the instructor's utterance. This hyperphrase bundles the student's deixis and the instructor's speech, including the entire stretch that included his original focal idea.	The instructor introduced a new idea (the shadow), before the student had the opportunity to apprehend the previous idea (the stick). This confounded the student because she is unable to form either an appropriate GP or hyperphase.

with its own GP. The IBSVI's reading hand arrives during this part of the hyperphrase before the next GP begins. We can infer that the IBSVI may be able to grasp the idea of the first GP without the second GP being a distractor. (3) *GP/hyperphrase disconnect* is where the instructor has moved to a new GP before the IBSVI has an opportunity to access the graphical context of the former GP. We mark this as providing the lowest opportunity for understanding.

Table V provides a sample analysis showing our three conditions (across the table columns). In the coded segment, the discussion is of Erastothenes' method of estimating the circumference of the Earth from antiquity as a means to illustrate the concept of parallel lines (sunbeams) intersecting with parallel lines (transversals). Each column shows the transition between two consecutive segments (speech above the illustrative image for each segment, and activity description with comments beneath).

B. Situated Analysis (Common Ground). For Clark, "[a]ll language use rests on a foundation of information that is shared by the participants, what is technically called their common ground" Clark 1992, page 4]. Speakers try to convey information that they think listeners already have or can understand. Key to the present analysis is Clark's observation that "people's mental representations of mutual knowledge are inferences based on certain evidence and assumptions", [Clark 1992, page 5]. Clark defines the Immediate Physical Copresence (IPC) as the strongest evidence possible. The following exchange illustrates how instructor and students can engage in IPC.

Instructor: says "This line" and points at the line.

Students: look at the line.

Instructor: sees that the students are looking at the line.

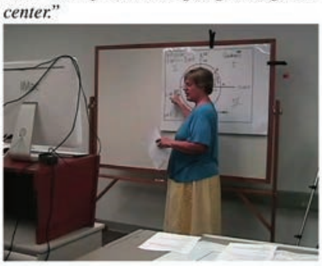
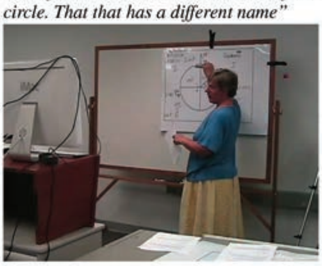
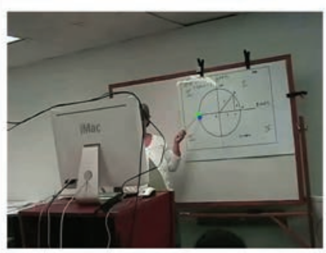
The pointing gesture helps the parties to establish IPC because it simultaneously provides physical evidence to both instructor and students about the object under discussion (the line). If there were a IBSVI in the audience, she would not have engaged in IPC with the instructor. She would not have physical (or perceptual) evidence of the instructor's pointing. In this case, the instructor would have two options. She could change her behavior to engage in IPC with the IBSVI (maybe holding the IBSVI's hand and directing it to the line), or she may assume that she has enough previous information to identify the line.

The latter illustrates what Clark calls the Locatability Assumption (LA) [Clark 1992, page 39]. The speaker *assumes* that the listener can discover the referent ("this line") and bring it to "view" simultaneously to her. According to Clark's presentation/acceptance model [Clark 1992, pages 151–173], utterance presentations can either be accepted (understood) or not. Such utterances need to be repaired before they snowball [Clark 1992, page 164], or in our case, harm concept conveyance.

We analyzed concept conveyance across experimental conditions in terms of the number of episodes of direct evidence and assumptions and their impact on utterance acceptance. The analysis was confined to utterances referencing our focus mathematics concepts that all involve presentation or references to graphical elements in the instruction material. We used MacVisSTA [Rose et al. 2004] to identify and code for occurrences of IPC and LA. Each occurrence of IPC or LA was assigned an estimation of the listener's ability to resolve the referent, and consequently, accept the utterance. This estimate is assigned after watching the videos and judging if the listener had a real chance to understand the speaker. Possible final state values are: R (Resolved), U (Unresolved), P (Probably resolved). P status is assigned when a speaker does not do the "final check" on the listener's understanding and the coder is not sure if the listener really understood.

Table VI shows transcriptions of three different instances where the same instructor discusses the concept of a *diameter* across our three treatments (left column: *all sighted class*, middle column: *inclusive class with HDS*, and right column: *inclusive class without HDS*). The two cells in each column depict two consecutive parts of the same instruction segment. The instructor's speech is presented above the image, and the behavior description is presented beneath. The utterances for the all sighted class were all assumed to be IPC(R) (Immediate Physical Copresence - Resolved). In the inclusive class with HDS, the instructor held her deixis until she saw the IBSVI arrive at the equivalent point on her raised-line graphic (using the feedback screen on the iMac; see Figure 2(d). This was judged as ICP(R) as well. In other instances, when the instructor did not hold the deixis, we judged these as one of IPC(U), LA(R), or LA(U), depending on the coders' estimation of whether the IBSVI had sufficient information to resolve the meaning without access to the deixis. The coding was done independently by each author and only those in which they agreed were taken into consideration. In the episode of inclusive class without HDS shown in the right column, the instructor began by pointing at the graphic (top cell). The IBSVI had no way to resolve this, so the instance was labeled IPC(U). The instructor realized this,

Table VI. Concept of Diameter Being Conveyed across Experimental Conditions

All Sighted	**With the System**	**Without the System**
"Okay, diameter measures, how about if I said this: from one side of the circle to the other side of the circle going through the center."  Instructor points twice, once at each end of a diameter – 2 IPC(R).	*"From the right edge of the circle to the left edge of the circle, right through the middle, that's the diameter."*  Instructor drifts her wand over the line representing the diameter, checks if the student was able to follow her – 1 IPC(R).	*"Is this a diameter?"*  The instructor traverses the circle with her hand in a straight trajectory that does not pass through the middle - 1 IPC(U).
"So don't think it's like up here from one side of the circle to the other side of the circle. That that has a different name"  Instructor points twice, once at each end of a *chord* but never saying the word (*chord*) – 2 IPC(R).	*"and thats the key by the way, right through the center of the circle"*  Instructor holds her pointing while conveying the concept. She waits and checks if the IBSVI was able to move along the line corresponding to the diameter.	*"Okay, and what I did G [laughs] what I did, if I'm not gonna scare you to death, is like just went across like this"*  Instructor holds the student's hand and traces the area on his graph that corresponds the area she traced on the board – 1 IPC(R). The instructor conveys the same concept twice: One for the sighted, another for the IBSVI.

and proceeded (with apology) to physically place the IBSVI's hand. This was coded as IPC(R).

6.3.2. Situated Analysis Conclusions. With respect to growth point and hyperphrase, three distinct situations of system use were identified: (1) Instructor utterance-student deixis synchrony creates conditions for immediate GP; (2) instructor utterance-student deixis synchrony creates hyperphrase that includes but does not precisely localize the GP; and (3) instructor's utterance stops prematurely and student is unable to form neither an appropriate GP nor hyperphrase.

This suggests that the HDS can create more effective learning opportunities by supporting inter-psychic image and discourse fusion through pointing to support GP/hyperphrase sharing. This is, however, contingent upon the instructor adopting cross-modal strategies that enable the IBSVI to engage in immediate GPs and shared hyperphrases. We note that such sharing is commonplace in normal communication situations among sighted individuals, but that this, too, is contingent upon effective communication strategies that have been developed over a lifetime of interacting in society. Teachers, in particular, are trained to provide sufficient "wait time" and gain experience through practice to graduate instruction rate to signs of student comprehension. The HDS does not obviate the need for communication skill, and may require additional skills to instruct effectively using the system. This suggests follow-on research on how to encourage the development of such skill in using the HDS, and how more effective feedback may help.

With respect to common ground analysis, the use of the system created the conditions for higher number of IPCs because: (1) the instructor's display provided timely evidence to the instructor of the student's ability to resolve the referent; and (2) the haptic glove not only helped the student to navigate to the referent (greatly increasing the chance of its resolution), but also indicated when it had been reached.

These two components (instructor's display and haptic glove) correspond to what Clark calls *manifest coordination devices* [Clark 1996]. They create perceptual cues that instructor and IBSVI use to coordinate their actions.

The losses in the without HDS condition can be compensated if the instructor verbally checks the student's understanding. Alternatively, instructors can engage in IPC with the blind student by taking her hand and helping her to explore the figure. Furthermore, instructors made verbal references to labels on the figures to help the IBSVI finding the relevant portions of the images. This label-aided referent resolution strategy was also observed by Supalo [2005].

These "compensating" strategies, however, do not come for free. Such utterances demand more time and effort to be produced and understood [Clark and Brennan 1991; Kraut et al. 2002]. Several times in our study, the strategies were abandoned as instructors ramped up the pace to cover the lessons objectives. When that happened, the IBSVI were inevitably left behind. This is what typically happens 'in the wild' – as instructors are pressured to cover a certain amount of material in limited time they are presented with a Faustian choice either to leave the IBSVI behind or to reduce the material covered at the expense of the rest of the class.

6.4. Instruction Fluency Analyses

6.4.1. Fluency Analysis Measures. Since the HDS is designed to support instructional discourse, one would expect an impact on the instruction fluency. To better understand such impact on classroom dynamics, we devised four fluency measures: (1) number of Words Per conversational Turns (instructor) or WPT; (2) mean number of Hand Positioning Events, or HPE; (3) percentage of conversational Turns aimed at the Lesson's Objectives, or TLO; and (4) percentage of Deictic Expressions, or DE.

Number of words per conversational turn (Instructor) – WPT. Pointing adds precision to an utterance and makes it shorter. We compared the mean number of words per utterance in the instructor's speech with and without the system. The sum of words uttered by the instructor in one lesson was divided by the number of her conversational turns in that lesson in one experimental condition and compared to the same lesson from the same curriculum in the other experimental conditions. We found that T1 had consistently lower WPTs when he used the system. No conclusion could be reached for T2.

Mean number of hand positioning events – HPE. When teaching IBSVI, instructors normally have to hold the student's hand and help her to explore the images. In inclusive classrooms, this disrupts the class, brings unwanted attention to the IBSVI, and elevates the risk of stigmatization. We investigated the HDS' impact on the number of hand-positioning events. We counted the times the instructor stopped the lesson, walked up to the IBSVI, and physically repositioned her hand to maintain her situated in the instruction. The events were averaged by lesson and then averaged by curriculum and experimental condition. Again, our intervention led to lower HPEs only for T1. Differences in style and the fact that two of T2's IBSVI were not having a "good" day during their with-HDS trials (detailed in the following section) might have influenced this measure.

Percentage of turns aimed at lesson objectives – TLO. When a new human-to-human mediating technology is introduced there is the risk of "attentional shift". We wondered if the system made instructors and students less focused on the lesson objectives. For this, we employed the speech coding we described in Section 4.3.1: classifying utterances as belonging to the object, meta, and para levels [McNeill 2006]. We counted Object-level utterances dedicated to task for this measure. T1 and his class were consistently more focused on the lessons' objectives when the system was used, with an overall mean of 97% of the turns aimed at the lessons' objectives. For classes where the system was not employed, an overall mean of 81% was found. Such change was not observed for T2 and her classes. Our explanation for the HPE results can also be applied here. Due to her energetic and encouraging nature, T2 used more para-level conversational turns (e.g., encouragements) when the system was employed.

Percentage of deictic expressions – DE. With this measure we can assess the impact of the system on the creation of deictic opportunities in the instructor's discourse. Each conversational turn was automatically parsed for deictic words like "here", "there", and "that". A second manual parse was then performed to determine if the expressÊions containing these words are indeed deictic. We compute DE as the percentage of turns containing deictic expressions (number of turns having deictic expressions/total turns). HDS lead to higher DEs for both T1 and T2. T1 used deictic expressions in 14% of his conversational turns when the system was used against a mean of 4% when it was not. As for T2, she used deictic expressions in 12% of her conversational turns when HDS was in use and 3% when it was not.

It is important to note that instructors used DE effectively in the non-HDS condition only when holding the student's hand. This shows that the introduction of the system had an impact on the instructorÕs utterance formation.

6.4.2. Conclusions from the Lecture Fluency Analysis. Instructor T1 benefited more from HDS. He had more economical conversational turns, fewer class interruptions, and used more deictic expressions during the lessons where the system was employed. T2 seemed not to have altered her teaching style when using the HDS as much as T1. Differences in personal style, age, and IBSVI behavior might help explaining these differences.

6.5. Instructor and Student Experience

Upon the completion of both curricula, instructors and students who attended inclusive classrooms responded Likert-scale questionnaires (1-strongly disagree to 5-strongly agree, 3 being no opinion). All participants (instructors and students) were urged to comment on their answers. We group our questionnaire results under four headings: (1) how previous studies prepared the IBSVI for attending inclusive classrooms; (2) how HDS impacted discourse production; (3) how the HDS supports mutual understanding; and (4) how the HDS supports engagement and learning.

Before proceeding, we must disclose relevant information about the trials. This study was performed during the two weeks before the final exams week. Due to class schedule at the institution, B5 (IBSVI) was available for only one day each week. Our study lasted two weeks, so she had to take all three lessons of each course in one day. B5 arrived one- and- a- half hours late for her study. B3 also had all lessons with the system in the same day. When greeted upon his arrival for the trial, he said: "I'm hungry, tired, and broke. For the preceding reasons we have two distinct groups of opinions. In group 1 (G1), we have: B1, B2, and B4. B3 and B5 form group 2 (G2).

6.5.1. How Previous Studies Prepared the IBSVI for Attending Inclusive Classrooms. Recall that our inclusive classroom study participants had participated in the arcade-style game to develop embodied skill, and in the second phrase charade game (simulating instructional discourse) to assess how the skill transfers to the speech-gesture nexus. We wanted to see how the these games prepared the IBSVI for attending an inclusive classroom.

All but B3 agreed that playing the arcade game and the charade helped them to get ready for class. B3 thought that the arcade-style game was too different from the classroom condition, but that the charade game was helpful. He thought more in-class practice would have been more effective ("[t]his is comparing apples to green beans. The game was important for us to get comfortable with the glove, but the task was completely different. The charade was closer. Attending more classes [with the HDS] would help"). This perception, however, has to be balanced by the fact that B3's navigation speed increased 45% between level 1 and level 2 in the arcade-style game even as the game became more difficult (smaller targets, and greater distance to target), and the participant's discourse fluency increased markedly (three times the speed, no talk about technology) in the second phrase charade study from the first.

6.5.2. How HDS Impacted Discourse Production. In the previous section, we saw how HDS Êimpacted discourse fluency and production. Here we discuss how the participants perceived the change.

Both instructors agreed that they were able to express themselves more effectively with the HDS. "Because I could continue being the instructor instead of going to a particular student and help him find something. They could be finding while I was talking and keeping up with the instruction," said T2. Did the HDS slow down or speed up the lecture?, we asked. "It sped up because I didn't have to go over the student," said T1. "It somewhat slowed it. It is probably advantageous that it slowed it down. When teaching the only feedback you have is eye contact. The system made me acutely aware that the student was not paying attention," added T2.

6.5.3. Does the HDS Support Mutual Understanding?. Speakers, especially teachers, are always looking for signs that they are being understood. From our situated analyses, we learned that the system created more perceptual evidence that can be used to enhance mutual understanding. We now present some opinions regarding that matter. T1 and T2 strongly agreed that the instructor's display helped them to understand the student behavior, although T1 expressed some reservation ("It might be distracting in a larger class").

When asked if they thought that the IBSVI understood the lectures better when they were using the HDS, T1 strongly agreed, while T2 agreed with qualification: "It really depends on the blind students themselves". T2, however, expressed enthusiasm for the value of the system in the real world: "I'm excited to see where it goes." For T1, the IBSVI showed less confusion when the system was used, whereas T2 had no formed opinion. "They would get more frustrated [without the HDS]", said T1, while T2 claimed "they seem to adapt."

Both instructors strongly agreed that the system helped instructor/student interaction. "I didn't have to think of what I was going to say (verbalize) as much as I did without the system. It helped the conversation flow more like a normal every day conversation". This was according to T1.

G1 members reported that they were comfortable using the system in class, while those from G2 had no opinion. Only B5 perceived the system as an impediment to keeping up with the instruction ("Mathematics is so demanding. You have to listen and follow along and using the system can be overwhelming").

All IBSVI participants felt that instructors paid more attention to them in classes when the system was used. "In which circumstances did you lose track of the instructor?" we asked. B1, B4, and B5 reported that with the HDS, they lost track of the instructor fewer times. "There were times I had no idea of what she was talking about," B1 commented on her without-HDS trials. B2 complained that she could get lost even with the HDS when the instructor adopted poor strategies: "I got lost when he moved his wand around very fast ... The instructor drew new figures and pointed at them with the wand and I lost that," said B2.

6.5.4. Does the HDS Support Engagement and Learning?. It is known that academic performance correlates positively with a student's engagement [Brophy and Good 1986; Cancelli 1993; Fredrick 1977]. We wondered if the HDS raises IBSVI engagement. We asked the instructors: How did the system impact the IBSVI engagement in class discussion? "It promoted it," said T1. "All blind students were very engaged. No matter what. More than the sighted, said" T2. Twelve of the fifteen sighted participants perceived greater IBSVI engagement when the HDS was employed. "I thought it helped her. She was able to participate and see what was going on. She was able to visualize what we were talking about (the graphs)," said a sighted participant.

Both T1 and T2 agreed that those who attended classes where the system was used would have a better chance on the exams. "Because there was less confusion, said" T1. "I think you may see some positive results, said" T2.

As for the IBSVI, G1 members found it easier to understand mathematics concepts using the HDS, while B3 preferred the classes where the system was not used. B5 had no preference. "Will the use of the system improve your chances of getting a better grade? we asked the IBSVI. B1 and B4 said "yes". B3 said "no," while B5 formed no opinion. B2 indicated that she thought teaching style was more important.

6.5.5. Opportunities for Learning. As presented in the last section, instructors thought that the system improved the quality of the lectures mainly because it raised their awareness of the IBSVI behavior, enabling them to act upon any signs of confusion to ensure understanding. The sighted students also believed that IBSVI were more engaged in classroom discussions and showed more signs of understanding when the system was used. Our situated analysis also suggests that when the system was used, the instructor and IBSVI were more likely to share growth points and hyperphrases than when it was not. It also demonstrated that the use of the system created more evidences of mutual understanding when compared to the without-the-system condition.

These are all good indicators. However, opinions were divided among the IBSVI. Most of the students who attended classes with the system agree that it supported their learning. Others like B2 did not like the fact that the instructor used the wand to make gestures other than pointing. It is also important to acknowledge that because of the novelty of the system and lack of proper instructor training, the system also created new situations of confusion. It is also important to note that they all agreed that the system was not a source of stress during lectures, and they perceived that instructors paid more attention to them during the with-the-system trials.

The preceding discussion leads us to believe that those IBSVI who attended with-HDS classes would get better grades on the exams. However, as indicated before, other factors, maybe even more important than the system, have impact on exam performance. As B2 properly observed, "teaching style is more important." Previous knowledge and which curriculum was covered in which experimental conditions are equally important factors. Our study provides suggestive indications that the system will indeed improve learning.

6.5.6. Future Projections. Finally, we asked our participants to estimate the promise of our system in actual day-to-day classrooms. Both instructors agreed that the system will be useful in real-world teaching, and would rather teach inclusive classrooms using the HDS. All five participants agreed that the system will be useful in real classrooms. “The performance of both instructor and student will improve as they use the system,” remarked B3. “But not for math. Math is too demanding,” cautioned B5.

7. DISCUSSION

We discuss the results of our study and system along the two themes that we set forth at the beginning of this article how the HDS enables IBSVI to participate in embodied discourse in general, and how the HDS may support inclusive mathematics and science instruction at a pragmatic level.

7.1. The HDS and Embodied Discourse

Our intervention approach and the design of the HDS are informed by the science of human embodied language. A key question arising from this is whether the HDS enables the IBSVI to participate in embodied discourse. Our results show that the HDS does indeed enhance instruction in inclusive classrooms with IBSVI. We believe that these enhancements follow from the way in which the HDS supports the performance and uptake of gestural deixis in conjunction with speech.

However, our mathematics instruction study would almost definitely have been unsuccessful without the prior training with the arcade-style game. The marked difference in discourse characteristics in our phrase charade studies before and after the arcade-style game intervention shows that the ability to follow pointing must become nearly automatic before the HDS can support deictic discourse. This is in tune with the intuition that uptake of embodied behavior is a well-learned phenomenon in sighted individuals. Our second charade study suggests that, with training, the HDS signal can become part of the gesture-speech system of the IBSVI hearer.

It was, however, not entirely given that the facility acquired in game-based training would transfer to the far more automatic requirement of gesture uptake necessary for discourse comprehension. There is evidence, for example, that the mirror neuron system [Montgomery et al. 2007; Rizzolatti et al. 1996] is implicated in the recognition of motor behavior in general, and of gesture in particular. Since we have no evidence (and it is unlikely) that the HDS activates the mirror neuron system, gesture uptake using the system was not a foregone result. Furthermore, there is a difference between the ability to “recognize” physical behavior and the ability to interpret purposive communicative deictic gestures towards instructional material. The latter is a cultural phenomenon that requires experience to resolve the referent in conjunction with speech. Our results show that the game-based skill training does enable the IBSVI to engage in this discourse, which requires almost automated gesture tracking before the reference resolution can proceed.

That the HDS enables IBSVI to participate in multimodal embodied discourse is supported primarily by our situated psycholinguistics analysis and our fluency analysis, and also by our experience questionnaire results.

Our growth-point-based analysis shows that the HDS creates opportunity for IBSVI to participate in the moment-by-moment unfolding of concepts presented by the instructor. The IBSVI were typically able to arrive at the point of instructional focus either during the deictic utterance or in the transition period before the next utterance. This is similar to embodied discourse between sighted individuals. The common-ground-based analysis similarly shows how IBSVI may comprehend deictic discourse only as common ground is maintained, and where localizing assumptions do not accumulate (the IBSVI is able to resolve all deictic references). Our observation is that the maintenance of common ground and shared growth points depends as much on the communicative skills of the speaker as in the ability of the recipient to comprehend the speech and resolve the gestures. This is the same for instructional discourse between sighted individuals. An instructor can easily leave the student behind with unskillful use of graphical materials in conjunction with speech.

Our discourse fluency analysis, as well, suggests that the introduction of the HDS alters discourse in the same way that the opportunity to use gestures in face-to-face meetings does for sighted interlocutors. With another channel to carry the communicative load, the number of words per turn shortens. With the opportunity for one's interlocutor to resolve anaphorics and deictic terms, the frequency of deictic expressions increases. Again, this supports our claim that the HDS does indeed support deixis as a component of multimodal discourse (as opposed to the conscious deliberate task of target following).

Finally, our participant experience questionnaires show general agreement that the skill training, which encourages automatic behavior, helped in the use of the HDS in the instructional discourse. The impression by all participants (IBSVI, instructors, and sighted students) was that HDS improved instruction fluency and language production. One instructor reported that the HDS' support for awareness of the IBSVI's attention allowed her to regulate her presentation in the same way awareness of sighted students' gaze does. The perceptions of increased mutual understanding and engagement provide further circumstantial evidence of the HDS supporting the use of pointing gestures with speech.

7.2. Support for Inclusive Instruction

The key conclusion of our study is that the HDS is able to support mathematics/science instruction in inclusive classrooms by supporting situated instructional discourse. The HDS is, of course, not an instructional magic bullet. The caveat is that the efficacy of the system depends to a large degree on the instructional and communicative skill of the instructor. The instructor has to be aware of the state of attention of the IBSVI as well as of the sighted students, and pace the instruction accordingly. There needs to be adequate "wait time" for the IBSVI to access and comprehend the ongoing discourse, including the interpretation of the graphic referent of deixis. We note that these requirements apply for instructors teaching sighted students as well. With appropriate instructor training and communicative skill, our results show that the HDS can furnish the IBSVI with opportunity to learn.

Our results further suggest that the HDS has a positive effect on inclusive classrooms with IBSVI. Inclusive classrooms have to navigate between the Scylla of paying too much attention to the IBSVI's need and pace of information uptake at the detriment to the rest of the class, and the Charybdis of focusing on material coverage and the teaching of the rest of the class and leaving the IBSVI behind. The HDS can help to ameliorate this difficulty by increasing the fluency of instructional discourse. Our second phrase charade study showed a decrease of 86% in solution times of the puzzle over the first phrase charade study. What this says is that our participants took nearly three times as long to finish the puzzle in the first phrase charade before they acquired sufficient skill to participate more fluidly with the embodied discourse.

Our mathematics instruction studies bear out the claim of communicative efficiency and efficacy improvements in instructional discourse with the HDS as opposed to without the system. The number of words per turn decreased, and the number of deictic expressions increased. This suggests that with the HDS, the instructor was using deixis and the instructional graphics to carry part of the communicative load as they would with an all-sighted class. The percentage of turns aimed at lesson objectives, as well, increased with HDS. All these are important as they allow the pace and method of communication to be more homogeneous, and we hope, to lead to better learning by both sighted students and IBSVI. The number of "hand-positioning events" indicate that speech and deixes provides the necessary information, obviating the need to physically position the IBSVI's hands to the appropriate points of focus throughout the instruction.

These results are consistent with the comments by all stakeholders in our inclusive instruction scenarios. The instructors reported that they found the communication easier as they did not have to reformulate all graphics into words for the sake of the IBSVI. They could use their awareness (owing to the HDS' feedback mechanism) of the students' reading focus to help pace their instruction in the same way they employ gaze awareness for sighted students. The instructors, IBSVI, and sighted students all felt that the HDS improved the pace of instruction and mutual comprehension when proper communicative strategies are employed. The IBSVI, especially, did not feel that it inordinately impacted the pace of instruction as would happen when the instructor has to stop the instruction, walk up to the student, and position his hands. This also made the IBSVI feel less self-conscious that he was disrupting the rest of the class.

7.3. Ongoing Challenges

Our studies show that the HDS presents significant promise in facilitating mathematics/science instruction in inclusive classrooms. It does require skill training for the IBSVI and the instructor. However, our studies were performed with college-level students with a focus in pure visual impairment. As we noted earlier, given the challenges faced by IBSVI, few make it to college. Hence, those who do may be considered extraordinary students.

We do not know how the system may scale to middle and high-school classes where illustration-assisted mathematics and science instruction takes place. For the HDS to have a greater impact, we need to know how the system would function across a broader spectrum of students with need, across a greater range of instructors across the grades, and across educational content and instruction styles through the grade range.

This will require more extensive studies with the system. This scaling involves both the technology (how to make the devices adaptable and robust enough for the broader population?), the students (how to adapt the game-based training, how a broader range of teachers may adopt the technology?), and the instructors (how to support instructors in use of the technology, and adapting their instructional styles). Also, the HDS requires prior preparation of all material in raised-line form, and that there is a direct spatial mapping between this material and the visible illustrations presented to the class. The HDS also does not support the instructor augmenting this presentation with additional writing. All this can impact adoption of the technology in real-world inclusive classrooms. We note, however, that these requirements may actually increase the sensitivity of instructors to the needs of IBSVI in their classes.

8. CONCLUSION

It is well-understood that individuals deprived of sight do not have instrumental use of vision to read and access fundamentally visual information. The challenges these individuals face in comprehending embodied discourse is less well-appreciated. Our research has explored an interactive technology that students with blindness or severe visual impairment to access pointing gestures performed in conjunction with speech in inclusive instructional settings. Our Haptic-Deictic System enables employs a haptic glove paired with computer vision and HCI to enable a new kind of interactive augmentation to facilitate IBSVI participation in such inclusive instruction. The HDS also allows the sighted instructor to be aware of the attention of the IBSVI.

Employing usability engineering techniques, we designed a haptic signaling system that: (1) is able to convey sense of direction; (2) does not interfere in fingertip reading; (3) enables a user to navigate a document while listening to a story, fusing the information received from tactile reading, the haptic glove, and speech.

We designed and conducted a series of phrase charade studies that simulates communication in an instructional setting where an instructor points into a graphic illustration while speaking. These studies show how being able to follow directional instructions, and even to fuse information while following such instructions, is not the same as participating in multimodal discourse. We showed, furthermore, that with appropriate skill training that automatizes the use of the glove, the IBSVI is eventually able to participate in such discourse. We presented training through an arcade-type game designed specifically to encourage the development of such embodied skill.

Finally, we conducted a set of new mathematics instruction studies to determine the efficacy of the HDS in supporting mathematics instructional discourse. We developed two three-session mathematics curricula that were administered in inclusive instructional settings to five IBSVI who had undergone our skill-training and charade studies. These studies were analyzed in three ways: psycholinguistically-motivated situated language analysis, instruction fluency analysis, and survey analysis for instructor and student experience. Our results show that the HDS does indeed have the potential to support inclusive learning situations involving multimodal discourse and instructional illustrations. We ascertained that with appropriate instructional techniques, the HDS can help to furnish IBSVI with the opportunity to learn. We also showed that the HDS does increase the instructional fluency of the class, and presents all stakeholders in inclusive education (the instructors, the sighted students, and the IBSVI) with positive instructional and learning experiences.

For instructors, the technology allowed them to: (1) adjust the pace of the lecture to ensure that all students were following them; (2) better understand the students signs of confusion and act upon them to ensure their understanding; and (3) act more naturally as they did not have to think of how to verbalize the information displayed on the graphs. Overall, instructors agree that the use of the technology improved the quality of instruction. The IBSVI were able to comprehend, more quickly and effectively, the instruction when they were using the system. For the sighted students, the system: (1) improved fluidity; (2) made the IBSVI more participative in classroom discussions; and (3) did not make the instructors pay less attention to them.

In summary, the HDS demonstrates the importance of addressing gesture within the framework of embodied discourse and interaction. Indeed, the fact that speech, which is often thought of as the means of encoding purely symbolic information, is permeated by embodied conceptualization suggests that embodiment is not just about the body. Embodiment extends to mind and language. This insight allowed us to address the pragmatic question of how to improve mathematics instruction for individuals deprived of sight. Reciprocally, we believe that our research also extends our understanding of the importance of embodied behavior uptake for communication and comprehension.

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