

A Tactile-Proprioceptive Communication Aid for Users who are Deafblind

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Figure 1: Combinations of different hand orientations define manual signs that correspond to different letters of an alphabet. For input, hand orientations are measured using low-cost mobile devices with integrated accelerometers, for output, users scan through a set of available orientations where a particular target orientation is indicated using vibrotactile feedback

ABSTRACT

Users who are congenitally deafblind face major challenges in communicating with other people and often rely on an intervener with who they communicate with using a manual sign language. In recent years—to allow for deafblind individuals to communicate more independently—a number of haptic gloves have been developed that can recognize and/or convey manual sign languages. These gloves are expensive to construct and currently not commercially available. To address this issue we present a bimanual communication aid, called AUTOSEM that instead of using the hand as a display surface for manual signs, uses combinations of different orientations of both hands to define a set of semaphores that can represent an alphabet. A significant benefit of our technique is that it uses both hands and it can be implemented using low-cost motion sensing devices. User studies with fourteen able-bodied users evaluate both the output and input capabilities of our technique. A deafblind individual provided qualitative feedback on AUTOSEM using a case study.

Index Terms: K.6.1 [Management of Computing and Information Systems]: Project and People Management—Life Cycle; K.7.m [The Computing Profession]: Miscellaneous—Ethics

1 INTRODUCTION

There are approximately 45,000 individuals in the US – including 10,000 children– who are deafblind, e.g., individuals who experience some degree or a complete loss in both vision and hearing [4]. Approximately 50% of the deafblind population has *Usher syndrome*, a genetic condition in which a child is born with a hearing impairment and progressive vision loss occurs later on in life from retinitis pigmentosa [5]. Deafblindness may also be congenital where a child is born with both a hearing and visual impairment, for example, caused by a birth trauma [1]. With an increase in longevity in developed countries, the deafblind demographic is anticipated to significantly increase and change, as it will primarily be composed of elderly who acquire deafblindness through age-related loss of both vision and hearing. In the next decade, deafblindness is estimated to affect up to 3% of the population over 67 [18]. The current obesity epidemic may also increase the number of deafblind

individuals as diabetes is one of the major causes of vision loss due to macular degeneration [15].

Deafblindness puts severe constraints on being able to communicate with others [12]. There are various ways deafblind individuals communicate, which depends on the nature of their condition and the age of onset. A small group of deafblind individuals uses tactile lip-reading (Tadoma). Individuals with congenital deafblindness are more likely to use a manual sign language, whereas individuals who become deafblind at a later stage in their life use tactile languages, such as Braille [20]. A manual sign language is typically based on a deaf sign language but modified so signs are written in the deafblind individual's hand or hands. For deafblind individuals with little residual vision or hearing, acquiring independence in communication is extremely challenging, and they often completely rely upon on a caregiver or intervener for communicating with other people [10]. In recent years several glove-based devices have been developed (see next section) that can interpret and/or convey manual signs. These solutions can give greater independence to users who are deafblind as it allows them to communicate without an intervener and with people that do not know manual signs, as these gloves can translate text based messages into manual signs. Communication is constrained to using a single hand. Currently these gloves are not commercially available and are expensive to construct. As accessible technology is often criticized for its high cost [11], we present a bimanual communication aid, called AUTOSEM, which can be implemented using low-cost motion sensing hardware that is already present in game controllers and mobile devices. AUTOSEM is inspired by flag semaphores used in the navy to communicate information over a distance, but instead communicate and interpret manual signs to a deafblind user themselves using their own hands. AUTOSEM builds on prior work [21], that has explored using a single hand for conveying messages but extends it to using both hands and finds no decrease in performance.

2 BACKGROUND AND RELATED WORK

In the past decades, a number of communication aids have been specifically developed to accommodate the abilities of deafblind individuals. The TeleBraille [9] is a device that allows a deafblind individual to place telephone calls to a standard telephone. A 20 cell 6 dot refreshable Braille display is used for output and Braille keyboard is used for input. TeleBrailles were discontinued a decade ago and were very expensive. The DeafBlind Communicator [3] from HumanWare consists of a Braille communicator and a cellphone to provide real-time text-to-braille translation to allow deafblind people to communicate with able bodied people. Braille

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communicators such as the popular BrailleNote devices are generally very expensive costing close to \$5,000 each. V-braille [16] uses a standard mobile phone to represent Braille characters using its touch screen and internal vibrotactor. The touch screen is divided into six areas representing the dots of a standard Braille cell. When users move their fingers over the screen a vibrotactile cue indicates whether the dot is raised or not for each area to represent Braille characters. User studies with nine subjects found an average Braille character reading time that varied between 4.2 and 26.6 seconds. Braille based devices are difficult to use for deafblind individuals who are congenitally blind as they typically never learn Braille and a different set of technologies has therefore been developed that seeks to automate the use of manual sign languages. The talking glove [17] is a bi-directional aid developed for deaf, deafblind, or non-vocal individuals. This glove allows its user to interact verbally with other people. This glove can interpret American fingerspelling, e.g., different finger positions are used to generate letters which form words, which are then converted into synthesized speech. Using voice recognition a deafblind user would be able to read incoming speech on a portable refreshable braille display module. The software to recognize finger spelling cost \$3,500 and can be used with a commercially available gesture recognition glove (CyberGlove). A robotic fingerspelling hand was developed [24] that consists of a solenoid-actuated and cable-driven hand made from aluminium. This technique can only be used for output and is rather bulky and not mobile. The DB-HAND Glove [12] is a bi-directional communication glove that can interpret and convey the Italian Malossi manual sign language. This glove consists of couples of transducers (pressure sensors and tactile actuators), which are located on the 16 points of the hand defined by Malossi alphabet. This glove recognized presses and pinches made on a finger, which represent letters in the Malossi alphabet and convert these into text. For output, letters are converted into tactile impulses on a finger. The Lormer [6] is a haptic display that can render the German Lorm manual sign alphabet in the user's palm using a stylus like device within a metal sphere. The Lorm alphabet is different from the Malossi alphabet as it uses gestures that are written in the hand as opposed to presses and pinches on individual fingers. This device is attached to a regular computer where a deafblind user may use a keyboard to provide input. Mobile Lorm [14] is a glove that translates the Lorm manual sign language into text and vice versa. From a technical perspective the Lorm alphabet is more challenging to implement using a glove as it uses gestures that are more difficult to detect, for example, gestures that cross over multiple fingers. This glove is made out of a stretchy fabric and contains pressure sensors in the palm of the hand. Vibrotactors (200Hz output) are placed at corresponding positions of the pressure sensors on the back of the hand. Users wear the glove on the left hand where the right hand's finger is used to write letters using Lorm gestures. Whenever a pressure sensor is touched, the corresponding vibrotactor is activated to confirm the user's input. For output, Lorm gestures are simulated on the back of the user's hand by activating particular vibrotactors in sequence. All these approaches enable bidirectional communication but require users to take turns as to avoid input and output to interfere. Though these glove-based techniques have great potential to achieve independence in communication for users who are deafblind, none of these gloves are currently commercially available. Cost is an important factor in the large scale adoption of accessibility technology [8] and though for these existing approaches no cost information is provided, from experiences with a related project we know a haptic glove may cost up to \$1,500 to create [26], which includes issues, such as technical design and hardware.



Figure 2: TWuiST: The user scans through different orientations of their mobile device where a target orientation is indicated using a vibrotactile cue. Each orientation corresponds to a message, i.e., the phone pointing forward indicates new email.

2.1 Prior Work

In prior work we developed a novel display technique for mobile devices called TWuiST [21]. This technique uses a combination of device orientation and vibrotactile feedback to convey messages to the user using particular hand orientations; effectively turning the body into a display. Users scan through different possible orientations of their mobile device where a haptic cue indicates a particular target orientation (See Figure:3). For example, when the target orientation of the phone is pointing forward this could indicate a new voice-mail and when it is pointing down it could mean a new text message. This type of display is called a *tactile-proprioceptive* display as it uses the proprioceptive sense to sense the orientation of the device in an ear and eye free manner. A benefit of this approach is that it can be implemented using hardware (vibrotactor/accelerometer) that is already present in most mobile devices. A user study with 16 users explored the efficiency of two different information spaces. For six orientations defined in a space we found an average search time of 2,466 ms and for eight orientations defined in a plane an average search time of 2,612 ms was found, with no significant differences between search times when corrected for the size of the information space.

3 DESIGN OF AUTOSEM

The proposed work extends prior work on TWuiST [21], with the difference that TWuiST only explored using the orientation of a single device for communicating a message, where in this work we expand it to both hands to create a manual language for deafblind individuals. Where glove based devices only utilize one hand, AUTOSEM uses both, which may double communication bandwidth. Our approach is inspired by flag semaphores used in the navy to communicate information over a distance. Using this method a signal man holds two flags in different positions to signal letters of the alphabet and numbers. A flag can be held in one of eight possible directions and cannot overlap. Our approach is similar for communicating messages to another person but different for receiving messages as we use semaphores to communicate information to a deafblind user using their own hands. Combinations of hand orientations define unique manual signs that may represent letters. For example, one hand pointing up and one down could indicate the letter 'e' (see Figure 1). By using combinations of hand orientations, an information space is created that is large enough to contain an alphabet, effectively creating a new manual sign language that could be used by deafblind individuals. Our technique is called AUTOSEM, where AUTO stands for "self" and SEM for "semaphoring". AUTOSEM supports bi-directional communication as it can be used for: (1) input, to communicate information to another user electronically, by positioning two orientation aware devices in different orientations as to spell out words; and (2) output, where sets of orientations are indicated using vibrotactile feedback and letters are spelled out to a deafblind user using their own hands. Our proposed technique has several advantages:

- **Cost:** The proposed manual sign language can be implemented using commercially available sensing devices. For

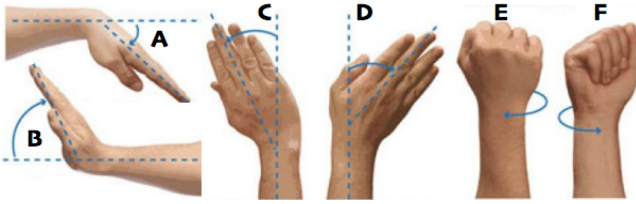


Figure 3: Available wrist rotations: 60° of flexion (A) 45° of extension (B) 25° of abduction (C) 65° of adduction (D) 80° of pronation (E) 88° of supination (F).

example, Nintendo Wii remote controllers are capable of providing vibrotactile feedback, communicate with a PC using Bluetooth, and can sense their own orientation using an internal accelerometer. With these controllers costing \$15 each, our solution is an order of magnitude cheaper than existing communication devices for deafblind users and could therefore also be used in developing countries.

- **Rigidity and Usability:** game controllers are designed to be sturdy, and hence the proposed solution is more robust than a glove with electrical wires and sensors sticking out that must be handled with care lest they break. Further, donning a glove and the associated computing hardware may be challenging for a deafblind individual, where a pair of controllers can be picked up and used independently.
- **Efficiency:** our solution uses both hands and because manual sign are defined by using combinations of two hand orientations there are fewer orientations per hand, which may be significantly faster to learn and to recognize than existing manual alphabets where all signs are conveyed to a single hand.

3.1 Information Space

We first designed an appropriate information space. This information space must at least include the 26 letters of the English alphabet and ten digits. Alternatively users could spell numbers and use 10 manual signs to represent special characters such as a space, comma, period or exclamation point. This defines 36 unique manual signs and requires six unique orientations per hand. Though we could use seven orientations per hand, orientations will then become harder to recognize, as they are closer defined to each other. Five orientations per hand would be easiest to recognize but is not sufficient to contain 36 signs. Six unique orientations creates an information space of $\log_2(6) = 2.58$ bits of information per hand, for a total of 5.16 bits of unique states that can be communicated using a combination of both hands. Given that we require six orientations per hand, we must determine how to define these orientations. The directions in which the hand can feasibly point is constrained by the allowable physical rotations of the wrist. A wrist has 60° of flexion, 45° of extension, 25° of abduction, 65° of adduction, 80° of pronation and 88° of supination (see figure 3). Based on previous experiences with TWuiST, orientations can be defined in a plane or a space, where each approach has benefits and disadvantages. Orientations should be defined at equidistant angles as to increase the users ability to distinguish them. For a given size information space, orientations defined in a space are more distinguishable than when defined in a plane, but orientations defined in a plane can be scanned through with a constant velocity than orientations that are defined in a space and can hence be found faster. For TWuiST, we compared the efficiency of orientations defined in a plane versus a space for a single hand but this comparison was unbalanced, as we used information spaces with different sizes (6 orientations for a space and 8 for a plane). In our first study, we compare the efficiency of orientations defined in a space versus a plane for the same

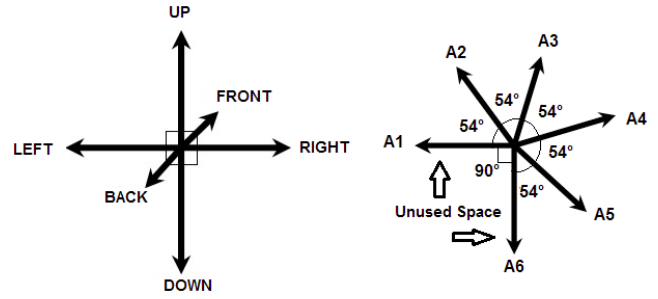


Figure 4: The information space for six equidistant orientations in space (left) and in a plane (right) for the left hand

size information space ($n=6$), where users scan simultaneously with both hands.

- For a space, the hand can point to almost any direction in a sphere through a combination of: (1) rotations of the wrist (flexion, extension, abduction and adduction); (2) rotations (pronation, supination) of the forearm at one of the proximal radioulnar (elbow) joints; and (3) rotations of the shoulder joint (abduction, adduction) [23].
- For a plane the largest range of motion of the hand in a plane ($\sim 270^\circ$) can be achieved through supination and pronation of the forearm supplemented with adduction and abduction of the shoulder [23]. This rotation starts in the pronated position of the forearm with the shoulder adducted to about 90° , followed by a combined supine rotation of the forearm and abduction of the shoulder joint.

Given these identified physical ranges in which the hand can be pointed, we define two sets of six equidistant orientations for a space and a plane. For a space, six orientations (UP, DOWN, LEFT, RIGHT, FORWARD, BACK) can be defined along the positive and negative axes of a Cartesian coordinate system (see Figure 4 left) where each orientation is at 90° or 180° of the other. These orientations can be visualized by imaging the hand to be inside a cube where each orientation points towards its inside face. For a plane, six orientations (A1, A2, A3, A4, A5, A6) spaced 54° degrees from each other within the available 270° range of motion. Figure 4 shows the orientations for the left hand and the set of orientations for the right hand is the mirror image across the vertical axis. The unused space in the figure indicates the range of rotations that may be stressful to achieve as it involves rotations of the shoulder joint. Our technique can be used for bi-directional communication; therefore user studies in the next section evaluate its input and output capabilities.

4 STUDY 1: INPUT

Our first user study evaluates the input capabilities for both sets of orientations. A significant barrier with evaluating our technique using the intended target demographic (deafblind individuals) is that learning a manual sign language may take a significant amount of time. It may take years for a deafblind individual to learn and master a manual sign language especially if these individuals are congenitally deafblind [18]. Because we deem it important to identify the feasibility and demonstrate proof of concept of AUTOSEM as an alternative to existing manual languages, user studies with able-bodied subjects are conducted. User studies will provide insight into design alternatives before user studies with the target demographic can be conducted. Existing glove-based approaches [12, 17, 6, 14] have not been evaluated at all with deafblind users nor with able-bodied subjects. For input, users spell words by recalling particular combinations of orientations from memory that

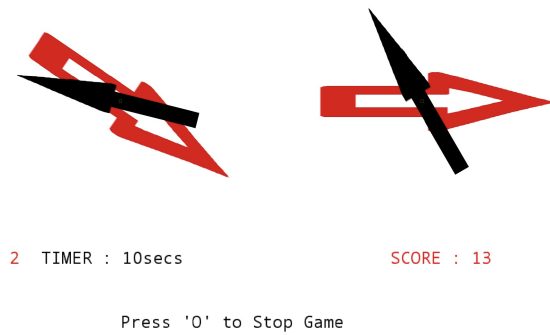


Figure 5: Screenshot of the Arrow Pattern Matching Game

represent letters. Learning a new manual language takes a considerable amount of time [20]. Performance may also be subject to a larger variation due to individual differences in ability to memorize manual signs. To overcome these constraints we simulate input provision using a visual pattern matching task, as this may yield performances that approximate recalling orientations from memory [25]. We implemented a game that requires users to match the direction in which their controllers points with visual arrows that are displayed on a screen. The faster each controller is pointed in the target direction the more points the user scores. The use of a game was motivated by the observation that games are considered powerful motivators and which may hence allow for measuring optimal performance when used in a user study.

4.1 Instrumentation

Our technique is implemented using commercially available motion sensing controllers called the Sony Playstation Move. The controllers' orientations can be tracked using inertial sensing (accelerometer and gyroscope). The controller further features an LED that serves as an active marker where the uniform spherical shape and known size of the LED allows for controller's position to be tracked in three dimensions with high precision (1 millimeter) using an external camera called the PlayStation Eye, which captures video at 640x480 (60Hz). For this study we use two controllers, where the LED's on each controller automatically use a different color from each other as to allow the PS3 to distinguish them (see Figure 1). Our game was developed in C# using XNA Game Studio 4.0 and runs on a laptop that communicates with a PlayStation 3 to retrieve the current position and orientation of each Move controller. The game implements both information spaces, e.g., orientations defined in a plane and a space. Figure 5 shows a screen-shot for the plane version. The game works as follows. Black solid arrows indicate the current orientation of each controller and red hollow arrows indicate the target orientation. Users have 15 seconds to find assume the set of target orientations. An orientation is considered correct if the current orientation is within 20° of the target orientation and remains within this range for one second until both target orientations are assumed. This value was determined experimentally. We experienced little noise in the data from the accelerometer and hence we did not need to filter it. When the correct orientations are detected, a cash register sound is played and the user's score is announced using synthetic speech. The screen goes blank for 5 seconds and then a new set of target orientations are generated. Target orientations are determined at random where the previous target orientation is excluded, such as not to skew the search times.

4.2 Participants

We recruited 8 computer science students (3 female, average age 28.4, $SD=3.8$). All subjects were right handed and none had any self-reported impairments in tactile perception or motor control.

4.3 Procedure

Participants were randomly divided into two groups A and B with 4 participants in each group. Group A played the plane version of the game first and then the space version, whereas group B performed it the other way around. Prior to playing their assigned version of the game, participants were demonstrated how the orientations were distributed. Participants were given a brief demo of how to play the game and they were given an opportunity to explore scanning through the different orientations for both versions. None of the participants experienced any difficulty or discomfort in trying out the different rotations. Users were instructed what the goal of the game was and how the scoring mechanisms worked. The game would be reset and users would play the game until 24 random pairs of targets were found. All target orientations; orientations of each controller, and time to find each target orientation for each controller were recorded in a log file. Users were not instructed to hold the controllers in any particular start orientation.

4.4 Results

Tables 1 and 2 and Figure 6 list the found average search times and standard error for both the information spaces for each hand. Combining the averages for each hand, on average it takes 1,843 ms ($SD=181$) to find an orientation in a plane and 2,318 ms ($SD=629$) to find an orientation in a space. Every pair of target orientations was found in the time for each trial. This difference in search times was found to be statistically significant ($T_{2,14} = 5.722$, $p < 0.05$). No significant difference in search times between hands, or between orientations was found for both information spaces.

5 STUDY 2: OUTPUT

Based on the results of the first user study, we explore the output capabilities of our proposed technique. In this case words are spelled to a deafblind user where a manual sign is indicated using a combination of hand orientations. In order to convey a manual sign representing a letter, the user must scan through the set of available orientations, where a haptic cue indicates the target orientation for each controller that defines the manual sign. The first study conveyed that a particular orientation could be assumed faster when orientations are defined in a plane. Orientations defined in a plane have the benefit over orientations defined in a space that they can be scanned through with constant velocity, if the user starts their search in one of the orientations at the beginning or the end of the search space, e.g., orientation A1 or A6 in Figure 5. For this study, we only explore output capabilities using orientations defined a space. This decision is further motivated by results with TWuIST [21] where for single hand use, a target orientation in a plane was found faster than a target orientation in a space. There is no reason to assume that for bimanual use these results would be different. For the second study, we use the same game as in the first study, but instead of users using visual feedback to find the target orientation a haptic cue is provided to the user when each controller is held in the target orientation. To find the correct target orientations, users scan through the set of predefined orientations in a space until the target orientation for each controller is indicated with the haptic cue. Users have to hold the correct combination of target orientations for one second before proceeding to the next combination of targets.

5.1 Instrumentation

We use the same Sony Move controllers as in the first study. This controller can provide vibrotactile feedback with a frequency range of 91 to 275Hz. When the orientation of the controller is within 20°

Table 1: Search times for each orientation defined in a plane (ms)

Hand	Measure	A1	A2	A3	A4	A5	A6	Avg
Left	Avg	1,717	1,603	1,702	1,675	2,158	2,338	1,866
	StdDev	244	326	744	304	668	843	522
Right	Avg	1,772	2,179	1,323	1,649	1,933	2,071	1,821
	StdDev	338	929	367	400	343	463	473

Table 2: Search times for each orientation defined in a space (ms)

Hand	Measure	Back	Down	Fward	Left	Right	Up	Avg
Left	Avg	2,702	2,477	2,442	2,554	1,944	1,774	2,316
	StdDev	799	792	1732	767	222	860	862
Right	Avg	3,236	2,538	1,641	2,449	2,495	1,565	2,320
	StdDev	1,769	685	324	609	1,698	395	913

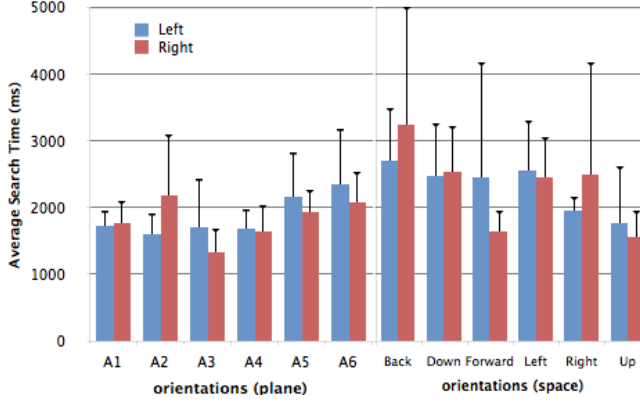


Figure 6: Avg Search Time for plane (left) and space (right).

of the target orientation, a haptic cue with a frequency of 275Hz is provided. User follows a fixed sequence in scanning for the target orientation, e.g., A1 → A2 → A3 → A4 → A5 → A6 until the target orientation is found for each controller. When the user has correctly assumed the start position (A1) for both hands we indicate this using a low frequency vibrotactile cue (91Hz), upon which a random target orientation is chosen. We do not exclude the start position (A1) from the set of possible target orientations, as this orientation could be part of the manual sign.

5.2 Participants

We recruited six computer science students (3 female, average age 26.5). All subjects were right handed and none had any self-reported impairments in tactile perception or motor control. Five of these participants had participated in our first study.

5.3 Procedure

We followed a similar procedure as with the first study. Users were instructed how to play the game and how to find the target orientation. A difference with the first study is that users were instructed to start their search for the target orientation in the A1 position for both hands, e.g., with the controllers pointing to the user's side (see Figure 8). After assuming the start position users were instructed to scan through the sequence until the target orientation was found. Once both targets are found, the participant was instructed to repeat the process by putting the controllers in the initial position. After trying out the game for a few targets, the game was reset and users would play the game until 24 pairs of targets were found. All target orientations, orientations of each controller and time to find each target orientation for each controller were recorded in a log file.

Table 3: Search times for orientations in plane (ms)

Hand	Measure	A1	A2	A3	A4	A5	A6	Avg
Left	Avg	32	3,007	2,626	3,229	4,890	5,500	3,214
	StdDev	26	658	618	887	1,984	1,308	913
Right	Avg	16	3,076	2,380	3,147	4,014	5,286	2,987
	StdDev	0	1,318	1,507	1,881	1,631	2,034	1,395

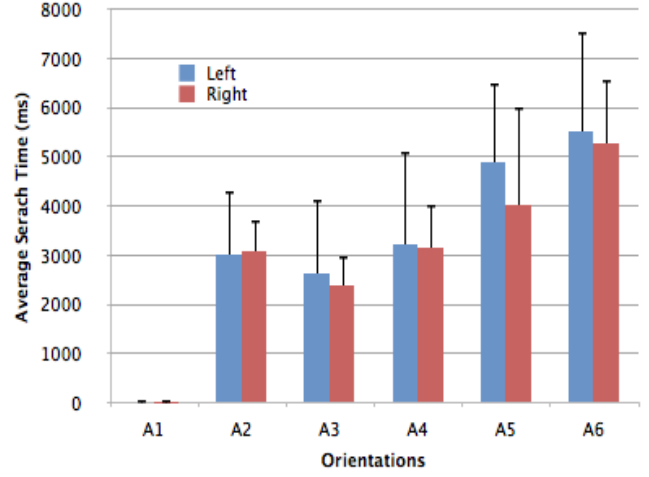


Figure 7: Average Search Time for User Study 2.

5.4 Results

Table 3 lists the average search times and standard error for each hand. Combining the results for both hands, on average it takes 3,100 ms (SD=1,839) to find both target orientations. This result does not include the 1 second holding time. A one-way MANOVA found no statistically significant difference in search times between the left and right hand ($F_{5,5} = 2.50$, $p > .05$, Wilk's $\lambda = .250$, partial $\epsilon^2 = .750$), which demonstrates subjects were equally proficient scanning with either hand. Figure 7 shows the average search time for each orientation. Overall it shows a linear increase in scan times for each orientation except that the search times to find A2 is slightly higher than A3. Though this difference was not found to be significant closer analysis shows that for a few cases users may have accidentally skipped over this orientation and scanned all the way to A6 before searching backwards. When user starts scanning, the controller is accelerated from 0 to the scanning velocity, which is approximated to be 50°/second. During this acceleration it becomes difficult for the accelerometer and gyroscope to determine the orientation and if the user accelerates too vigorously the user will skip over the A2 orientation, this could possibly be circumnavigated by increasing the distance between the initial orientation and the first orientation, at the cost of a smaller information space.

6 CASE STUDY

Due to the relative sparseness of the deafblind population and the challenges in teaching this population to use new technology, qualitative feedback on AUTOSEM was collected using an informal case study with a single deaf-blind user. Related glove-based approaches have not evaluated with deaf-blind users at all [14, 12] and other related approaches [10] have limited evaluation to a single deaf-blind



Figure 8: The start position, with both controllers pointing outwards.

user as well. Our subject was a 54-year-old woman, who was recruited using a local National Federation of the Blind chapter. She has had severe hearing loss since birth and relies on hearing aids and sign language. In the past years she started suffering from macular degeneration, with her visual acuity currently being 20/200 (legally blind). She has difficulty seeing colors and depth and is highly sensitive to sunlight and wears medical sunglasses. She relies on a cane for navigation. Her sight and hearing have significantly decreased in the past years and she is expected to go deaf-blind in the near future. She is currently learning a tactile sign language through vocational rehabilitation services. She does not use computers, but she does use a cellphone. We invited her to our lab and explained her what the purpose of AUTOSEM was and how it worked. We used a free-exploration approach, where she first explored spelling different letters using different orientations. She then explored using AUTOSEM for receiving messages by finding target orientations for each controller as indicated using haptic feedback, similar to user study 2. After a little bit of practice she was able to find the different target orientations with relative ease. We interviewed her using open-ended questions to collect qualitative experiences on the design of AUTOSEM.

Overall, she liked using AUTOSEM, she found the different orientations of each controller easy to distinguish and she understood how combinations of different orientations could be used to define letters. She found the controllers a bit heavy. For her left hand she said rotating the controller all the way down was a bit hard, but she explained that was because she has arthritis in that hand. After we initially mixed up the controllers, she suggested that we should allow for a way to allow deaf-blind users to distinguish each controller as there was no way to physically distinguish the left from the right controller. She thought finding the orientations using haptic feedback was easy to learn and she liked that different vibration frequencies were used to indicate the start and the target orientation. Overall she thought AUTOSEM could be a useful tool that could help deafblind users like her lead more independent lives.

7 DISCUSSION AND FUTURE WORK

The overarching goal of our study was to demonstrate the feasibility of our proposed technique with neither a goal to be complete nor exhaustive. Contrasting our results with results achieved with TWiST [21], we found an average search time for both hands (3,100 ms) that is only slightly higher than the search time for using a single hand (2,612 ms). We anticipated that the conjunctive use of two controllers would significantly increase the cognitive load of using our technique and lead to a decrease in performance but this effect turned out to be minimal; demonstrating the scalability of our approach. It also demonstrates that users were able to scan with both hands simultaneously rather than sequentially. Users with sensory impairments may even be more proficient in using our technique due to the plasticity effect [13], which may lead to a greater sensitivity to haptic feedback. Bimanual use may double input and output bandwidth, but there is an obvious tradeoff if AUTOSEM needs to be used in mobile contexts where it may be more desirable for a deafblind user to leave a hand free for sensing the immediate environment, for example, using a cane.

For a complete analysis of the efficacy of AUTOSEM, we should evaluate the user's ability to associate combinations of hand orientations with a particular manual sign. This requires users to accurately discriminate between different orientations, which our study did not evaluate. The results of such a study may significantly affect the design of our information space, for example, if users find it difficult to distinguish orientations in a plane because they are defined too close to each other, we may need to revert to using orientations defined in a space or reducing the number of orientations in a plane.

Comparison of AUTOSEM with other systems is challenging as no user studies have been performed with comparable manual glove

Table 4: Sample assignments of Letters to Orientations

Letter	Frequency	Left	Right
e	12.7%	A1	A1
t	9.06%	A1	A2
a	8.17%	A2	A1
x	0.15%	A5	A6
q	0.10%	A6	A5
z	0.07%	A6	A6

based systems [14, 12], though V-braille [16] is comparable in the sense that it can communicate characters (in Braille) using low-cost commercially available hardware (see related work). User studies with V-braille found an average character reading time that varied between 4.2 and 26.6 seconds, which makes our approach seem more efficient. A study with the tactile perception of manual signs shows that experienced users who are deafblind achieve rates of 1.5 signs per second with 75% accuracy [22]. In this study words were spelled instead of individual letters where a higher performance can be expected as users anticipate particular signs as the word is formed. Though evidently our technique is slower than tactile signs, it does not require an intervenor to achieve a high rate of communication.

Reflecting on what was the inspiration for AUTOSEM, e.g., flag semaphores, expert signal men in the navy can communicate at a rate of 20 five letter words per minute [7]. Our first study found users to be able to communicate at approximately a third of that rate using AUTOSEM. Performance could probably increase when orientations are recalled from memory. Rather than using a visual pattern-matching task, we believe a visual pattern-matching task is a good approximation for deaf-blind users recalling orientations from memory without having sighted subjects memorize signs.

Though our case study with a single deafblind person gave us some insights in the usability of AUTOSEM, for a complete analysis, user studies with our technique need to be conducted with a larger number of deafblind users, as to collect quantitative results and a larger amount of qualitative feedback. There are some significant challenges to evaluate our technique with users who are completely deafblind as it requires learning a new manual sign language, which may take some time to learn [20], but we believe feedback from subjects who are legally deafblind can be just as useful. A limitation of our user studies is that we did not evaluate how easy words can be formed from letters, as we only explored the efficiency of forming hand orientations. Cognitively, there is a significant difference between these two tasks, which can only be evaluated with the target demographic using a longitudinal study. With regards to using AUTOSEM as a valid communication device a number of issues still need to be addressed. An approach needs to be developed for segmentation of input, e.g., how to separate sequences of characters? A possible solution could be to let users press the triggers on the controller when a letter has been formed. We should also allow for correcting errors by erasing a letter. An accessible interface needs to be developed that allows users to read messages and compose or reply to messages.

For the design of our information space we focused on Latin based alphabets. The Chinese alphabet has thousands of symbols, which would render this approach unusable. Due to its low cost we anticipate our technique to be useful in developing countries, where deafblind individuals don't have an opportunity to learn a manual sign language at all and where our technique may be the only option to achieve independent communication at a low cost.

Using AUTOSEM as an output technique could be further optimized by taking into account that certain letters in the alphabet are more frequently used than others. By associating frequently used letters such as 'a' and 'e' with combinations of orientations that are closest to the start orientation, they can be faster found, which may improve overall scanning time. Based on an analysis of the fre-

quency of letters in the English language [19], table 4 shows how particular letters could be correspond to particular orientations of each hand. This optimization could however increase error as frequently used letters will become harder to distinguish as they are defined closer to each other.

Implementation: In our user studies we used a commercially available motion sensing controllers (Sony Move) that is tethered wirelessly to a Playstation 3 console. However, our solution can be easily implemented using a smartphone that typically feature accelerometers, and a single low cost motion sensing controller, for example the Nintendo Wii remote, which retails for less than \$20. The smartphone and the controller can be connected using Bluetooth, implementing the same display as we used in the studies. An application on the smartphone can implement the display and facilitate communication with the outside world, for example, by using text messages or speech synthesis and speech recognition as a bridge to our manual sign language. This setup allows users who are deafblind to communicate with others that do not know manual sign languages and it is mobile and rugged allowing for independent usage. For our technique to be deployed in developing countries it can be argued that that smartphones are not cheap. However, cell phone adoption in developing countries is booming [2] and large-scale availability of low costs smart phones in developing countries will only be a matter of time.

8 CONCLUSION

Existing communication devices for individuals who are deafblind are often expensive and not commercially available. We present a bimanual communication device for users that are deafblind that can be constructed out of low-cost commercially available motion sensing controllers at the fraction of the cost of comparable devices. Unlike most available solutions AUTOSEM can be used for input as well as output. A new manual alphabet is proposed that consists of combinations of hand orientations. A user study with eight and six users explore the input and output capabilities of this technique for two different types of information spaces, with orientations defined in a space and a plane. Using orientations in a plane is more efficient than using orientations in a space. Compared with a similar approach that uses a single hand, there is no significant decrease in performance when using both hands. Qualitative feedback was collected using a case study with a single deafblind individual.

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