Signing on the Tactile Line: A Multimodal System for Teaching Handwriting to Blind Children

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We present McSig, a multimodal system for teaching blind children cursive handwriting so that they can create a personal signature. For blind people handwriting is very difficult to learn as it is a near-zero feedback activity that is needed only occasionally, yet in important situations; for example, to make an attractive and repeatable signature for legal contracts. McSig aids the teaching of signatures by translating digital ink from the teacher's stylus gestures into three non-visual forms: (1) audio pan and pitch represents the x and y movement of the stylus; (2) kinaesthetic information is provided to the student through a force-feedback haptic pen that mimics the teacher's stylus movement; and (3) a physical tactile line on the writing sheet is created by the haptic pen.

McSig has been developed over two major iterations of design, usability testing and evaluation. The final step of the first iteration was a short evaluation with eight visually impaired children. The results suggested that McSig had the highest potential benefit for congenitally and totally blind children and also indicated some areas where McSig could be enhanced. The second prototype incorporated significant modifications to the system, improving the audio, tactile and force-feedback. We then ran a detailed, longitudinal evaluation over 14 weeks with three of the congenitally blind children to assess McSig's effectiveness in teaching the creation of signatures. Results demonstrated the effectiveness of McSig—they all made considerable progress in learning to create a recognizable signature. By the end of ten lessons, two of the children could form a complete, repeatable signature unaided, the third could do so with a little verbal prompting. Furthermore, during this project, we have learnt valuable lessons about providing consistent feedback between different communications channels (by manual interactions, haptic device, pen correction) that will be of interest to others developing multimodal systems.

Categories and Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Haptic I/O*

General Terms: Human Factors

Additional Key Words and Phrases: Multimodal interaction, visually impaired users, handwriting, audio and haptic feedback, children

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1. INTRODUCTION

There are many situations throughout life where a signature is required; on legal documents, cheques, bank loans or important letters, for example. In many cases, a signature is the final step needed to seal an agreement and without one no deal can be made. Moreover, people are also judged on the visual appearance of their signature. Some visually impaired people we have spoken with during this project believe that a *normal* looking signature may be the difference between getting a job interview and not. Most people learn to write as a child and take this ability for granted, so much so that signing a name takes little concentration. Proficiency in generating a consistent, repeatable, visually appealing and verifiable signature which is complex enough to be difficult to forge is something we rarely think about. However, for children with a visual impairment learning this skill is very difficult. Yet, blind people also need to generate consistent signatures in the same way as their sighted counterparts. This research was motivated by our interactions with blind students who were unable to form a signature for research consent forms for a previous project. Subsequently, we became aware that most blind people had significant problems with signatures and that many were embarrassed about the quality of their signatures.

Blind adults told us that learning to create an attractive and repeatable signature was a dull and difficult task for them as children. It is dull as they receive no easy feedback from the ink they lay down on the paper. It is difficult because they have little experience with writing and drawing as part of their normal education. Yet, as adults they had become cognisant of the importance of the visual appeal of their signature—one described her own signature as "resembling the meanderings of an inebriated fly" (see Figure 1). When asking for consent form signatures in another project, we observed that many younger blind people could not form any signature, nor could some create simple marks such as an X.

At the same time, we were sometimes surprised by the reactions of sighted people when explaining this research. The most common reaction was "what do you mean, blind people can't write?" Many sighted people had not considered that it is very difficult for blind people to learn to write because of the lack of feedback.

Until 20 years ago, visually impaired children in many developed countries went to specialist schools for the blind. However, integration is now common and children regularly attend their local school alongside sighted schoolmates. In specialist schools, learning to sign their name was a part of the curriculum, but this has not followed into the integrated model of education.

The McSig system has been developed to help blind and visually-impaired people to learn handwriting and the skills required to generate signatures. It exploits three non-visual modalities: hearing, touch (skin-based feedback) and kinaesthesis (force-feedback). The teacher and student work together, with the teacher demonstrating writing on a Tablet PC. The teacher's digital ink is translated in real-time into audio, movements of a haptic pen that the student holds and the haptic pen leaves a tactile impression of its path on a plastic writing surface.

Following a review of related work, we describe the first version of the prototype (McSig) which included two iterative design cycles and then an evaluation with eight visually impaired children [Plimmer et al. 2008]. Based on these initial results, we designed a second improved prototype: McSig 2.0. Using this prototype, three of the children from the evaluation study deemed by their teachers most likely to benefit from the experience participated in a longitudinal case study. The case study was designed to see if McSig's use could improve the handwriting of signatures over the longer term. Finally, we discuss implications of this work with respect to interaction for visually impaired people and more general design of multimodal systems and suggest areas of future work.

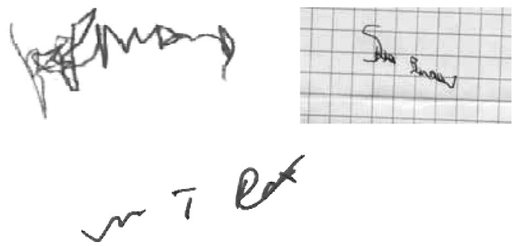


Fig. 1. Examples of three blind adults' signatures.

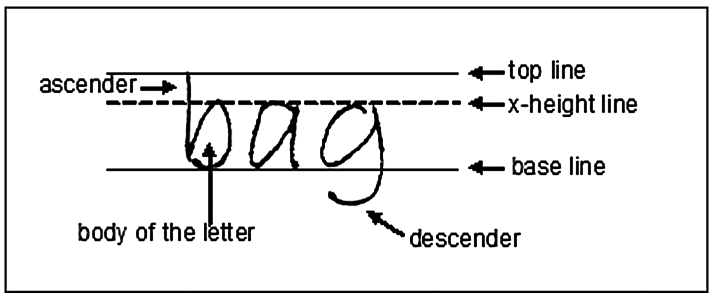


Fig. 2. The spatial features of letters (adapted from Arter et al. [1996].

2. RELATED WORK

Learning handwriting requires knowledge of the character shapes as well as learning the motor skills required to generate the characters. The literature on teaching sighted children to write suggests that a precursor to writing and drawing is to learn to control the writing implement [Arter et al. 1996] and develop a tripod grip [Sassoon 2003; Taylor 2001]. Spatial reference of letters can be guided by using lines (Figure 2). The teacher should provide verbal instructions for concepts such as the shape of a letter (e.g., 'two humps for m' and 'one letter after another'). Repetitive patterns of loops, humps or zigzags are often used to develop flow and motor control [Taylor 2001]. These are all tasks that are difficult for blind learners. Cursive writing, that is normal for signatures, requires additional learning to join the letters together [Arter et al. 1996]; for blind people, this has the advantage of removing the need for spatial repositioning of the pen as it stays in contact with the paper.

When working with blind children, we need to take into consideration that they translate 3D real-world space into 2D drawing space quite differently from sighted people. Using a table as an example, Kurze [1996] described how some blind children drew the table with the legs folded out while others squashed the table flat or presented it in a section view. Writing is the opposite case, and we must be cognisant that 2D writing is created with 3D actions to contact and lift from the paper.

In order to learn handwriting, a visually impaired student must learn the appropriate motor skills, but does not have the visual feedback available to sighted learners. There are two aspects of visual feedback where alternatives have been investigated: means to assist with motor skills learning and means to provide feedback on a visual document. For motor skills training, haptic guidance and haptic constraints have been investigated using devices such as the PHANTOM Omni by SensAble [2010]. Guidance involves pulling the user's hand around a predefined trajectory. This approach has been used for teaching the writing of East Asian characters [Henmi and Yoshikawa 1998; Teo et al. 2002] and stroke patient's arm movement rehabilitation [Amirabdollahian et al. 2002]. Latin character writing practice by dragging the user around the letter trajectory, that is held in a library, at a fixed speed was investigated in Mullins et al. [2005].

Several alternative modalities have been investigated for visualizing documents. Haptic constraints can be used to form a "virtual stencil" where the user can explore spaces with the hand holding the device held within virtual boundaries formed by the constraints. Yu and Brewster [2003] used a haptic constraint approach to allow visually impaired people to explore line graphs and bar charts. Users were constrained to move within grooves in each bar, for example, which made them easy to feel and follow and stopped the users getting lost in the workspace. Results showed that such a technique enabled blind users to get a good understanding of different data sets (especially when combined with nonspeech audio).

A virtual surface was used by Rassmus-Gröhn et al. [2006] with visually impaired people for line drawing. A PHANTOM device was used to create a black and white line drawing that was in turn used to create a virtual surface. Two calligraphy systems have also used virtual surfaces for sighted users. Teo et al. [2002] provided "brush" like feedback as a haptic device was moved over a virtual surface, while Henmi [1998] gave a feeling of friction to improve the drawing process and add some of the key features of drawing on paper back into virtual tools. Sallnäs et al. [2007] paired sighted and visually impaired children in a two PHANTOM collaborative environment to explore 2D and 3D geometric principles.

Numerous tactile aids such as pipe cleaners, sand, or flour trays have traditionally been used with blind learners [Taylor 2001]. Passive tactile surfaces created with cardboard and thermal plastic are used to represent spatial information such as graphs or maps in teaching resources. Pins and rubber-bands on cork boards are used for creating graphs and charts. Special teaching techniques are required for the blind child to learn to interpret this information [Wells 1986]. Tactile drawing surfaces are also available, including "Dutch Drawing Boards", plastic sheets over a rubber mat that, when drawn on with a pen, leaves a physical tactile line on the surface that can then be felt.

Both speech and non-speech audio are often used to replace visual displays for blind people. Synthetic speech output of text has been available for many years and comprehensive voice presentation of complex documents such as Web pages is readily available in screen-reading tools such as JAWS [Freedom Scientific 2007]. Synthetic speech has also been used to generate verbal output of nontextual data for visually impaired people. TDraw [Kurze 1996] gives speech when the user touched particular lines or shapes on a tactile drawing, as did Rassmus-Gröhn et al.'s [2006] drawing application.

There has been significant work on the use of non-speech sound to present information in a more accessible form. Sound graphs [Mansur et al. 1985] are the simplest form of sonification where the value on the y-axis of a graph is mapped to pitch and the x-axis time. A graph of data can then be heard as a sequence of rising and falling notes. These have been studied in detail and are very effective at presenting graph-based data [Brewster et al. 1993; Flowers and Hauer 1995]. Other approaches include the iSonic system [Zhao et al. 2008], which sonifies map navigation with five violin sounds to indicate numeric data and stereo pan for left-right movement. Yu and Brewster [2003] used the pitch of musical notes to indicate data values in a graph. Other parameters such as sound position, timbre and tempo have also been used for the presentation of information nonvisually [Hoggan and Brewster 2007].

3. OUR APPROACH

We developed a multimodal, collaborative handwriting and signature training tool which we call McSig. The scenario envisaged for McSig is that a teacher and student

Fig. 3. SensAble Technologies PHANTOM Omni force-feedback haptic device (www.SensAble.com).

Fig. 4. The McSig system in use. The teacher (on the left) draws on a Tablet PC to create a shape and the student (on the right) can feel, explore and be moved around the shape.

will be working together in a shared environment, with the teacher guiding the student towards learning the letter shapes using words and actions. The McSig system uses stylus input on a Tablet PC for the teacher's interaction and kinaesthetic, tactile and audio for student's interaction. This section starts with an overview of interaction in the McSig system. Section 3.2 describes the implementation and 3.3 the usability testing of the first prototype.

3.1. Interaction in the McSig System

When the teacher is demonstrating writing to the student, he/she writes on a Tablet PC and the student holds a pen attached to the arm of a SensAble PHANTOM Omni haptic device (Figure 3). The PHANTOM pen is then dragged through an approximation of the teacher's path using the PHANTOM's motors. To draw, students rest the tip of the PHANTOM pen on a surface and move the pen over the surface, or follow its movement as it is being moved by the PHANTOM's motors. A permanent record of the PHANTOM pen's path, which can be felt with the non-pen hand during writing, is scored on a tactile writing surface.

When working collaboratively in Playback mode, the teacher forms a letter shape on the Tablet PC (on the left in Figure 4), the student (on the right) gets simultaneous parallel feedback in all of the modalities. The student's hand is guided around the path of the letter shape by the moving haptic device. This takes the ideas of Mullins [2005] one step further by allowing the teacher to demonstrate writing at varied speeds. A

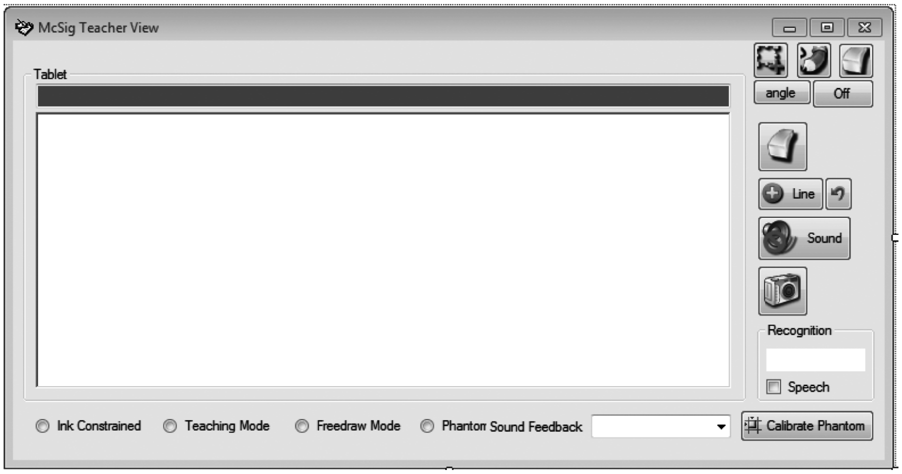


Fig. 5. Screenshot of the teacher's display from McSig 2.0.

continuously playing tone alters to express the movement of the pen. As the pen moves along the y-axis, the pitch of a tone changes (low to high from bottom to top). As the pen moves along the x-axis, the tone is panned from left to right across a pair of loudspeakers. A distinctive Earcon is played at the start and end of each stroke so that the student knows when a letter shape is being drawn. Synthetic speech output of both the teacher's and student's writing is generated by recognizing the characters using the Microsoft Windows handwriting recognition engine. The teacher can also verbally provide information about the letter shape being formed to assist the learning.

The teacher controls the system by a user interface on the Tablet PC. The teacher can switch between three modes. In Playback mode, the student is guided through movements by a teacher in real-time, as described above. In Freedraw mode, the students can draw and write with no restrictions, practicing what they have learned. In Stencil mode, the teacher draws a letter shape on the tablet which forms a virtual stencil in the student's drawing area. In this case, the student is first moved by the PHANTOM to the start of the letter shape. The pen is then constrained to the line drawn by the teacher, without the student being dragged through the shape as previously. This allows students to move through the letter shapes themselves with constraining forces to guide the movements. Initially, the constraining forces can be made strong such that the student is forced to follow the letter shape closely. As the student becomes more proficient at creating the letter shape, the constraining forces can be made weaker to provide less guidance eventually allowing the student to form the shapes unassisted.

A screenshot of the teacher's display is shown in Figure 5. The white rectangular area represents the drawing space where the teachers can draw and also see the shapes drawn by students. They can choose between the different modes and also it has buttons to turn the speech and sounds on or off.

3.2. Implementation of First McSig Prototype

The Playback and Stencil modes of McSig take input from the Tablet PC and translate this into movement (Playback) or constraints (Stencil) of the PHANTOM and associated audio. The Freedraw mode translates movements of the PHANTOM into ink on the Tablet PC screen so that the teacher can see the student's drawing. In the following sections we describe the haptic, audio and tactile feedback available to the student from the teachers writing. After this the teacher's interface and PHANTOM generated visualization for Freedraw mode are described.

3.2.1. Haptic. McSig contains haptic trajectory playback that is part of the Playback mode and haptic constraints that are used for Stencil mode. Haptic trajectory playback is not a trivial problem. The two main issues in creating an effective playback system are the stability of the algorithm and the safety of the user, particularly when some haptic devices can apply enough force to cause injury. Loss of control of the end effector is a particular problem when the user may not be able to see the device. In our software, the implementation of a playback system based on the bead pathway developed by Amirabdollahian et al. [2002] is combined with a PID Controller [Astrom and Hagglund 1995].

A proportional-integral-derivative (PID) controller is a standard algorithm from the control engineering literature [Astrom and Hagglund 1995]. The purpose of using the controller is to minimise the error between the current value of a system and a target value. In this case, we control forces sent to the force-feedback device in order to minimise the distance between the user's current cursor position and the target position on the trajectory of the letter shape drawn by the teacher. As the user's cursor approaches the target position and gets within a threshold distance, the target position is moved along the trajectory by a preset amount. This is repeated until the target position is the end point of the trajectory. By carefully tuning the parameters of the PID controller and the playback system, the user will be dragged through a close approximation of the trajectory in a smooth and stable manner.

The trajectory playback system used for McSig was based on an open source library [Crossan et al. 2006]. The preset PHANTOM Omni settings available in the library were used for the playback controller. Forces from the playback controller were capped at a maximum of 3 Newtons for safety reasons.

Haptic constraints are used in Stencil mode, where a virtual stencil is created from the teacher's pen path. The bead pathway mechanism does not drive the user's movements along the path as in Playback mode but creates virtual stencil walls to keep their pen on the current position in the stencil. The user progresses along the path by moving the pen in the correct direction. This was adapted from Yu and Brewster [2003].

3.2.2. Audio. Work from Crossan and Brewster [2007] indicated that multimodal playback of a shape could help visually impaired people to recreate the shape. Using the audio feedback from that previous study, we mapped the pitch of a sinusoidal tone to vertical movements, and audio pan to horizontal movements. The audio feedback is present when the teacher draws for the student. A high pitch indicates that the PC user's cursor was near the top of the drawing area, and a low pitch indicates it is near the bottom. Similarly with pan, as the teacher moves further left or right in the drawing area, the audio is panned to the appropriate side. Distinct sounds are played at the start and at the end of the teacher's trajectory to clearly indicate to the student the beginning and end of the gesture. The drawing area is restricted by the reach of the PHANTOM pen to a rectangle 150 mm wide by 100 mm high, the sinusoidal tone is calibrated to this space. In addition, voice output is generated using standard Microsoft Windows text-to-speech components by recognizing the handwritten characters with the Windows handwriting recognition engine.

3.2.3. Tactile. A tactile drawing board is used as the writing surface for the PHANTOM. This is a standard Dutch Drawing Board used by people with visual impairments. It consists of a rubber mat over which a plastic drawing sheet is placed. As a pen (or sharp object) is drawn across the surface the plastic buckles leaves a

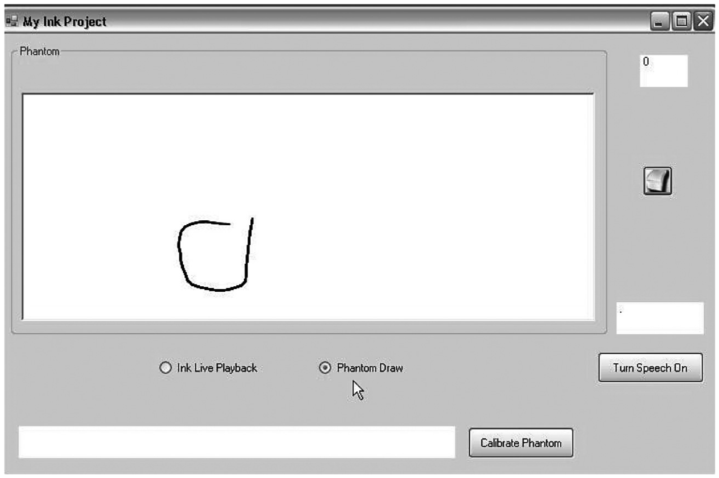


Fig. 6. Teacher's interface showing student writing.

permanent tactile line on the plastic sheet. As the drawing board is A4 size (larger than the drawing space the PHANTOM can support), the drawing board can be rotated to use different sections of the plastic sheet for different periods of drawing.

3.2.4. Teachers' Interface. The teacher's interface is deliberately minimalist. The ink space is used for the teacher to write in and displays the student's ink in Freedraw mode. The canvas is automatically cleared after each letter. However, characters are formed with either one stroke (like "c", "o", or "e") or multiple strokes (like "t", "f", or "i"). To disambiguate between the situation where a character is formed by multiple strokes and the teacher is drawing multiple repetitions of the same character, we use a time-out. If the teacher forms a new stroke within one second, this is counted as a stroke from the same character. The time-out value was set through an iterative trial-and-error process. There are also mode control radio buttons and buttons for turning audio on and off, as previously described.

3.2.5. PHANTOM to Tablet PC Visualization. When the student is drawing in Freedraw mode, it is useful if the teacher has a visualization of the pen stroke. In this mode, when the student holds either of the PHANTOM pen barrel buttons down, movements of the PHANTOM are translated into digital ink and displayed in the teacher's interface on the drawing panel (Figure 6).

3.3. Usability Testing

To refine the design of McSig we iterated development through a series of prototypes. A first informal usability test was conducted with one visually impaired adult, early in McSig's development. When drawing with the PHANTOM she tried to feel the pen stroke on the surface with her other hand to explore the shape drawn. This was not possible on the smooth paper pad we were using, so we switched to a Dutch Drawing Board so that strokes were raised above the surface and could be felt with the nondominant hand.

In a second formative study, four visually impaired adults were recruited to test a further developed version of McSig: three were totally blind and one partially sighted. The usability test was modeled on the planned scenario of a visually impaired child and his/her teacher working together. They would start in Playback mode with the teacher drawing a letter on the tablet and use this mode until the student was confident with

Fig. 7. A partially sighted participant using McSig.

the basic shape. They would then move on to the Stencil mode and the student would trace around the virtual stencil. Finally, the student would draw the letter unsupported in Freedraw mode and the teacher would perform a visual check to see how well it was drawn. Through this testing, a number of refinements to the initial design were made.

—Participants preferred Playback to Stencil mode, as it proved difficult to follow the shape of the letter in Stencil mode. The forces forming the groove of the stencil were strengthened and retested in order to provide a clearer path for the user. However, the letter shapes were still felt to be unclear;
—The audio playback cues were used more by some participants than others. Verbal feedback from the teacher during the playback was appreciated by the participants. The teacher would describe the movements as they were made and at the same time as a participant was feeling the shape of the character drawn;
—The handwritten character recognition was unreliable, frequently misrecognising the characters. This severely affected the visually impaired users' confidence so a toggle button was provided for the teacher to turn it on or off (and the feature was not used for the evaluation study described in this article);
—The PHANTOM Omni pen was not ideal for the task. The pen is larger than a normal pen and awkward to hold near the tip. Users were required to hold a button on the pen barrel as they drew in Freedraw mode, which meant that they held the pen further from the tip than was usual. We decided that training in holding the pen was essential before training started.

The final design for the first prototype can be seen in Figure 4, Figure 6 and Figure 7. Both show a teacher interacting with a visually-impaired student by drawing on the Tablet PC and having feedback echoed on the PHANTOM. The teacher and student sit next to each other to allow for easy verbal communication and to provide a similar frame of reference such that the teacher's left is the same as the student's.

4. EVALUATION OF MCSIG

The aim of this evaluation was to assess the efficacy of McSig for improving visually-impaired children's handwriting performance. The physical setup is shown in Figure 4 and Figure 7. The sessions were recorded using Morae™(www.techsmith.com) and the time-stamped x, y, and z co-ordinates of the PHANTOM were logged.

The task devised was based on introductory handwriting skill learning as our discussions with teachers suggested that visually impaired children's handwriting skills vary from almost none to being able to produce an adequate signature. The evaluation test plan was evolved from our experiences with visually impaired adults in the usability testing phase and discussion with teachers.

Participants were recruited through the local education centre for visually impaired children in Auckland, New Zealand. In discussion with the teachers, we set the following criteria for participant selection: over 10 years old and still at school; Braille reader; no other major disabilities. Drawing from the local population of 1.4 million, this gave us a potential participant pool of about 15 (visual impairment is a low-incident disability in the young). Eight of these students participated in the study; some were totally blind while others had a small amount of vision. As there was no consistency in their existing skills and with such small numbers, we rely on qualitative analysis of the results.

The first stage of the study allowed participants to be familiarized with the experimental set up. The key aims of this stage were to:

—familiarize the children with the physical environment, allowing them to feel the Dutch drawing board, the PHANTOM Omni and the computer;
—get the children to establish their spatial orientation on the drawing board by outlining the limits of the space;
—get the children to draw a circle, horizontal line and vertical line to familiarize them with the interface.

A letter set of "o, c, a, d, e" was selected in discussion with the teachers as they were all variants of a circle and formed with a single stroke. We opted for simple, single stroke shapes for this initial evaluation as we wanted ones that were not too difficult for our young participants to draw. For each letter there was a pretest, a training phase and a post-test (we did not pretest "o" as it is the same as the familiarization circle). All of a child's writing was with the PHANTOM and drawing board. For each letter, the child was asked if he/she knew how to write the letter, and if so, were invited to write it (pretest phase). He/she was then shown how to write it by the teacher (in this case, one of the experimenters) writing the letter on the Tablet PC with the movement echoed by the PHANTOM. The number of repeats of training strokes depended on the child's confidence (training phase). When the child was ready, we retested (post-test phase). If the child could not form the letter correctly, he/she was retrained and retested. A session ran for a maximum of 20 minutes, stopping earlier if all the letters were completed (which only happened with the partially sighted group).

4.1. Results of the McSig 1 Evaluation

Of the eight participants, three had a small amount of useful vision. These partially sighted students used both Braille and super-enlarged print. They all had deteriorating eye conditions and had learned to write when their eyesight was better, but did not write now as they could not see what they had written. Of the five totally blind students, one had lost her sight at three years old, the others had been blind since birth. The results were quite different for the two groups, so they are presented separately.

4.1.1. Partially Sighted Participants. The participants with partial sight quickly familiarized themselves with the devices and drawing space. They could all form the circle, horizontal, and vertical lines without difficultly. One participant formed all the pretest letters correctly. Both of the others formed the "d" by starting at the top and created a

Fig. 8. Pre- and posttraining ‘d’ by a partially sighted student (red dot is the start point of the pre-training stroke).

Fig. 9. A totally blind participant using the PHANTOM—Note the nonwriting hand used to feel the tactile line that has been drawn on the drawing board.

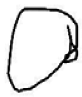
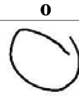
letter than looked more like a mirror image “6” (Figure 8). One of them also formed a visually correct “e” but formed it in the opposite direction to normal.

These participants interacted with the drawing space in a very similar manner to a sighted user except that they often had their eyes very close to the surface so that they could see the lines drawn on the drawing board (Figure 7); they did not feel the tactile letters. It was very quick to retrain the partially sighted users to form letters correctly. We completed the study with these three students within 20 minutes. These participants made very few comments about the system. Their general attitude was that they already knew how to write and they simply followed our instructions

4.1.2. Blind Participants. The familiarization and spatial orientation processes took considerably longer with the blind participants as they needed to explore the different devices by touch and trace around the drawing space at least twice to gain orientation. They also interacted with the drawing space quite differently. Typically they used both hands, one to hold the pen and the other to retain their orientation within the space and feel the tactile marks made by the pen (Figure 9). One of these participants (Mae,[1]) used so much pressure that the pen could not move over the surface and another (Tam) did not use enough pressure to create a tactile line. We taught them to use the appropriate amount of pressure before continuing with the study. All but one participant completed the basic circle and vertical and horizontal lines without difficulty. Table I shows the pre- and posttest letters for each of the blind participants along with their age and roughly in order of worst to best performance. All of the participants had no concept of the shape of some letters: when we asked them to draw the letter in the pretest they often said something like “I don’t know how to do that one”; we have marked these cells in the table “unable to do”. The blind participants were excited about the study, making comments like “Wow, this is neat” and “This is really cool”.

[1]Names changed for anonymity.

Table I. Pre- and Posttest Letters Drawn by the Blind Participants (Size Reduced 4:1)

Mae Age 14	**o**	**c**	**a**	**d**	**e**
Pre-test		Unable to do	Unable to do	Out of time	Out of time
Post-test				Out of time	Out of time
Sue Age 19	**o**	**c**	**a**	**d**	**e**
Pre-test	No data		Unable to do	Skipped	Unable to do
Post-test	No data			Skipped	
Tam Age 13	**o**	**c**	**a**	**d**	**e**
Pre-test		Unable to do		Unable to do	Out of time
Post-test					Out of time
Nik Age 11	**o**	**c**	**a**	**d**	**e**
Pre-test		 Formed back-wards		Unable to do	Out of time
Post-test					Out of time
Ann Age 17	**o**	**c**	**a**	**d**	**e**
Pre-test		Unable to do	 In name		Unable to do
Post-test					

There was a considerable difference in the existing skills of the blind participants. The worst, Mae, could not create a reasonable pretest circle “o” and had no knowledge of any of the letters. Her fine spatial orientation and skills were very poor. We did two rounds of training with the “c” before she felt that she could remember the shape and three rounds with the “a”, the third round was at the 20 minute time limit and at the limit of her concentration. In contrast, “Ann”, the best of the blind participants could form an accurate “o” and “a” and quickly learnt the other letters. She also scaled the letters accurately; while the training letters created on the PHANTOM were large, about 6 cm high, she drew her letters at about 1cm in the tests. Ann was the only blind participant who was not congenially blind (she had sight until she was 3), it is likely that she had developed normal spatial cognition before she lost her sight. All of the blind participants had a very limited knowledge of letters and had only been taught letters in their names—hence, the better knowledge of “a” by Tam and Ann.

The results in Table I show some substantial improvements in writing performance. Mae was unable to draw any of the letters successfully in the pre-test but was able to draw a recognizable “o” “c”, and “a” at the end. Sue also improved significantly, able to do a recognizable “c”, “a”, and “e” after the test. Ann was able to do a good version of all of our letters after the test. These results suggest that McSig was able to help the participants learn to draw the letters successfully. The blind participants all expressed enjoyment and excitement about the experience. Within the first few minutes, unprompted, they would make comments like “cool”, “fantastic”, “this is neat”. Tam said “I like how I learnt it from the computer, after the computer did it lots of times I could do it!” This suggests that McSig may be a motivating way for them to learn to handwrite, giving them active guidance for learning and dynamic, direct feedback on how they are doing. The blind participant’s responses were very different to the partially sighted group who were politely interested but not captivated.

The results suggested that McSig was a successful teaching tool and that in a short period of time new writing skills could be leant. However, the study was only 20 minutes long and only trained on a small set of letters. The aim of McSig was to teach users to write cursive signatures. From these initial results, it was not clear how learning would continue over a longer period of time and whether students would be able to learn cursive signatures. During the study, we identified a number of areas where McSig could be refined. The next iteration of McSig, described here, included major enhancements to the system and a longitudinal study to test performance over a much longer period of time. This would show if learning continued when any novelty effect had worn off and whether useful cursive signatures could be learned with such a training tool.

5. DESIGN AND IMPLEMENTATION OF MCSIG 2.0

We identified the enhancements for McSig 2.0from three sources: the evaluation study described above, the general requirements for learning handwriting and the record keeping requirements for a longitudinal study. Experience with the first prototype suggested that we needed input from congenitally blind people during design and implementation. We asked a blind adult, Eliza, who had been a usability test participant for McSig, to be our design partner for the redevelopment. She is totally and congenitally blind, thus matching the intended user group as closely as possible. We undertook progressive user evaluations with Eliza during the redevelopment. She visited the lab on three occasions and trialled variations of the setup each time. In this section, we describe the changes to the audio output, haptic device, pen interaction, writing surface, teacher’s interface and screen capture we made to create McSig 2.0.

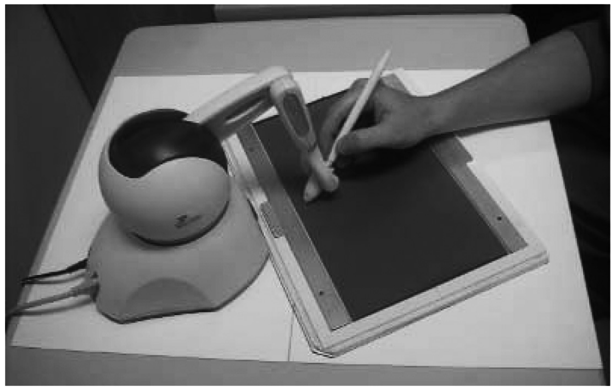


Fig. 10. New pen attachment to replace the large PHANTOM Omni pen shaft.

Fig. 11. Point A (the gimbal) is the standard point of control when using the PHANTOM, rather than the tip of the pen on the writing surface.

5.1. Haptic Interaction

Participants in the evaluation study often had problems holding the PHANTOM's pen. As blind children do not often write, they do not have the pen skills of sighted children. This meant that they often gripped the pen incorrectly, or used inappropriate levels of pressure for the pen tip on the drawing surface. We identified four difficulties with the PHANTOM pen.

First, the button press required when drawing in Freedraw mode so that the PHANTOM pen path is visualized on the teacher's display was difficult to maintain and distracting (particularly as these children have little experience with gripping a pen so pressing and gripping was difficult). To alleviate the button press, we incorporated height sensing into Freedraw mode, using the z-axis coordinates from the PHANTOM. When the pen tip was on the drawing surface it was assumed to be writing and generated digital ink on the teacher's display. This automatic height sensing meant that there was no need for a button on the pen, enabling us to solve the second problem: the fat pen shaft. Some of the participants had struggled with the PHANTOM pen's 20-mm diameter. We replaced the upper section of the pen with a normal pen cover (see Figure 10, with Figure 11 showing the size of the original pen) making it much easier to hold.

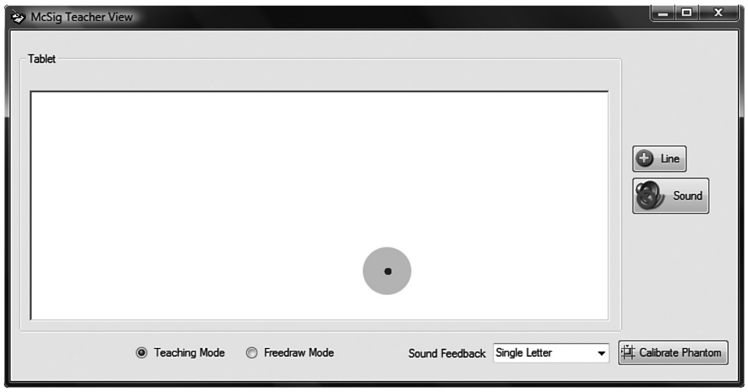


Fig. 12. The blue dot (highlighted with orange here for clarity) shows the position of the student's pen to the teacher.

Third, the reflection of the teacher's stylus path onto the PHANTOM did not take account of changes in the PHANTOM pen tilt angle. The actual point of control is the gimbal (see Figure 11) where the pen hinges on the arm, rather than the pen's tip. By calculating and adjusting for the change in tilt, the tip more accurately reflects the teacher's stylus path, making the letter shapes clearer. Because of the complexity of calculating the exact correction, a simplified correction was carried out. As the pen is typically facing forwards, we applied an offset in the direction of the z-axis (vertical movement). Changes in the angle of the pen are obtained from the haptic device and used to calculate the required offset.

Finally, the teacher could inadvertently jerk the PHANTOM by starting a new stroke a long way from the current position. A blue dot was added to the teacher's display to indicate the current position of the PHANTOM (see Figure 12). The teacher, by aiming to make first contact with the tablet close to the dot, can ensure that the student's pen will not have to move a large distance to begin following the teacher's trajectory.

The PHANTOM position is polled every 10 ms to obtain x, y, and z coordinates for the vertical plane facing the device. These are translated and adjusted appropriately to get the x and y coordinates for the writing surface plane. Once scaled to fit the teacher's viewing area, the dot can be rendered in the correct position. So that the primary task of the teacher is not interrupted, the dot disappears when the teacher is drawing an ink stroke.

5.2. Audio Feedback

Stereo panning of sound maps well to movements in the x dimension. However, small changes in stereo pan are difficult to discern and there is a range of writing widths that need to be supported: useful feedback must be produced for single letters, but also for wider signatures.

The change in stereo pan was maximised by providing variable panning widths. The soundscape is visualized for the teacher from where the stylus touches the screen until it is lifted off. Color shading shows where the panning reaches its left and right extremes, allowing the teacher to write at a size that produces the largest possible change in stereo pan for the duration of the stroke (see Figure 13). For a single letter, when a stroke begins the sound plays at a centred pan position, and panning moves sharply towards the left and right relative to this starting point. Many letters fall entirely to the left or to the right of their starting point; this can be reinforced by the panning occurring relative to the starting point. The width that the pen stroke must

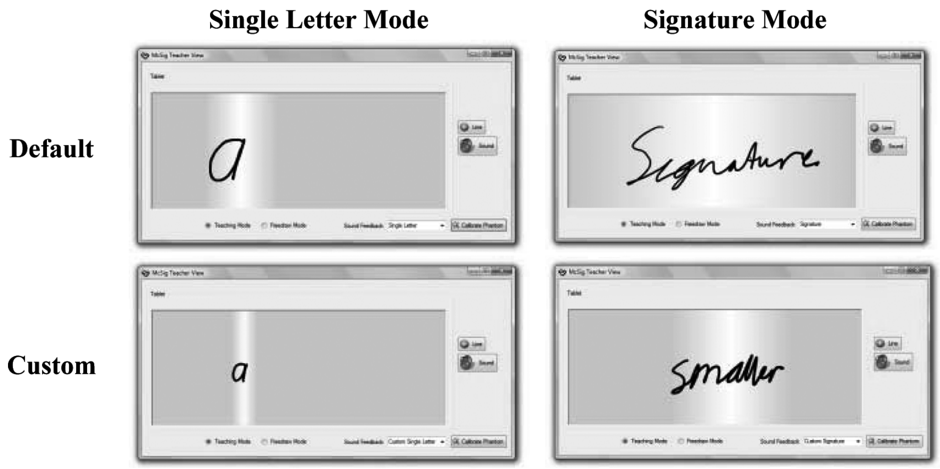


Fig. 13. The teacher can select suitable stereo panning behavior. The grey regions show where the panning has reached its leftmost or rightmost extremity.

cross before panning reaches its left or right extremity can be customised. The teacher selects “custom single letter” and then draws an example letter. The stereo pan will be adjusted so that the most useful feedback is provided for strokes the same width as the example stroke.

When writing signatures, it is necessary to change the stereo panning to the width of the signature to give meaningful feedback to the student over the full range of movement in the x axis. A signature will usually be carried out with one primary stroke, with a width almost as wide as the writing area. In signature mode the stereo pan will start close to the left extremity. The small offset allows the first letter to move to the left before movement is towards the right. The width of the signature mode can also be configured by providing an example signature.

The two modes were tested with Eliza, our adult participant. She said that the single letter modes made it considerably easier to hear the change in stereo pan. On her suggestion, the same sound feedback was added in to the Freedraw mode to provide consistency. This also simplifies learning in the early stages of use when the sound feedback is vital. We also asked Eliza to try headphones as opposed to speakers because the positions of the speakers on the desk can vary and effect how panning is heard. She found the headphones less satisfactory for discerning stereo pan and they also prevented her from hearing verbal instructions from the teacher, so we continued with loudspeakers.

5.3. Tactile Surface

The literature about learning to write identifies lined paper as a requirement for learning spatial positions [Sassoon 2003; Taylor 2001]. No equivalent to lined paper was provided in the first McSig prototype, but is needed for students to grasp the important spatial concepts that visual lines reinforce (see Figure 2). A nonvisual implementation of lines was a key requirement for the second prototype—we considered a range of solutions. Virtual haptic lines were dismissed as our experience with virtual stencils suggested that the line had to be physical: a virtual line would only be accessible to the hand holding the PHANTOM. Our observations from the first McSig evaluation showed that the tactile feedback to the non-pen hand was a critical part of spatial orientation.

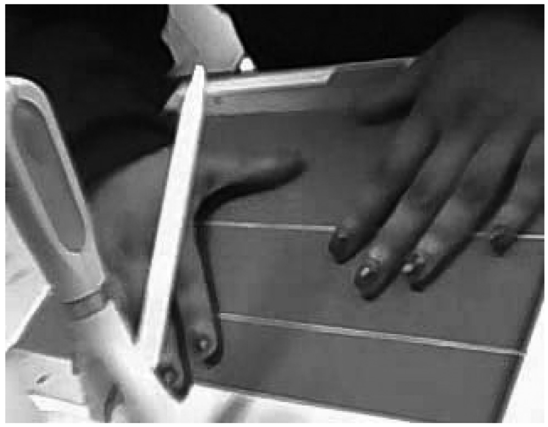


Fig. 14. Tactile lines created with rubber band under plastic mat.

Manually drawing lines on the tactile surface is possible, but tiresome. Overlays such as sticky-notes are often used by blind people as writing guides, and could have been used but were problematic as the overlay would need to be repositioned for each new sheet. We then considered putting something between the rubber mat and plastic writing sheet. Eliza tried fishing nylon and rubber bands. The fishing nylon gave a rather abrupt change in contour that was hard to write over. Rubber bands worked well (see Figure 14), as they lie flatter and have some give, yet stayed in place between the mat and the plastic sheet. They also come in different widths so thicker bands can be used for the writing line and thinner ones for the other guide lines. To visualize the line positions on the teacher's display, we added a calibration function: a button click creates a line on the teacher's display from the current PHANTOM position.

5.4. Screenshot Capture Tool

In the longitudinal study, we planned to track students' progress by taking screen shots during lessons. We tried this with Eliza and found that we had difficulty quickly collecting and organizing screenshots. To avoid delays, a custom screenshot tool was added into the teacher's interface. On the first click of the "screenshot" button, the teacher is prompted for the name of the student and from this information the system creates a folder named with the student's name, date and time. After this, whenever the screenshot button is pressed, the software takes a screenshot of the writing area and automatically saves it as a .png file in the folder using the same naming convention.

6. LONGITUDINAL CASE STUDY

To evaluate the McSig 2.0 prototype and the idea of multimodal support for handwriting over the longer term, we conducted a longitudinal study with three of the congenitally and totally blind children. This was the group identified in the first evaluation who most benefited from the multimodal environment. A longitudinal study overcomes the limitations of the initial 20 minute evaluations and would show if there were longer term learning benefits from such multimodal handwriting training.

Case studies are "research in the typical" [Nagappan et al. 2008]. They do not attempt to isolate variables and control the environment but are conducted in the real-world. This has advantages and disadvantages. On the one hand, as in this case, they can continue for a period of time and be used to gather rich information. However, this means that reliability, validity and repeatability are not guaranteed. A small number

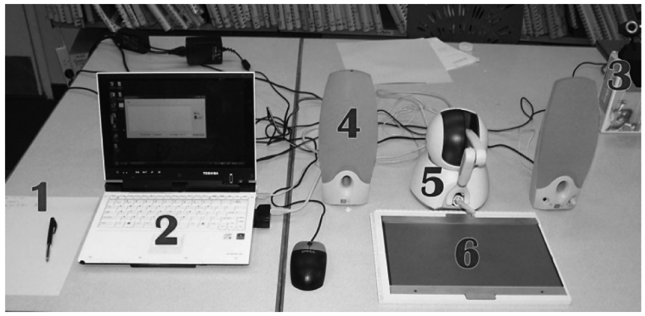


Fig. 15. Experiment setup for the McSig V2 evaluation.

of case studies, as in this case, is not enough to draw specific conclusions, but can provide data for general guidelines.

While we could not, and did not try to control all variables, the children had no other formal instruction on writing at school during the period of the study. Furthermore, we did not constrain our training to the use of McSig; if a child was struggling with a concept, we supplemented McSig with other tactile resources to help learning. We reasoned that other resources that proved useful might provide interesting areas of future investigation. At all times, ethical practice guided the study—our overarching concern was that the children had the best possible learning experience, thus we traded experimental purity for participant learning.

The three children who took part were selected from our initial group of participants by the local vision education centre as children that could benefit from the study. Consent was obtained from the children, their parents, and their teachers (the students all attended mainstream schools). Further information was gathered about the students who took part in the longitudinal study. Each of the children had different pre-existing skills and varied in their academic ability. The lessons took place either at their homes or schools depending on what was most convenient for them. One of the experimenters played the role of teacher, thus consistency was maintained between participants. Background information on the students' academic level and learning was obtained from discussions with their teachers and parents.

Each child received ten individual lessons over 14 weeks. We followed an A-B methodology [Drew et al. 2008]: taking baseline data, applying a treatment and measuring progress. Progress was defined as: "attractiveness" of signature (this highly subjective measure was judged by the teacher); reproducibility (consistency demonstrated between signatures); and retention (that the writing skill was retained over time).

Figure 15 shows the setup for the experiment. The experimenter has a paper notepad (1) and the Tablet PC (2), a webcam is positioned to record the student's hands and the writing surface (3), the two loudspeakers are placed approximately 50 cm apart in front of the participant (4), the PHANTOM is placed between the speakers (5) and directly behind the tactile drawing board that is in a comfortable position for the student (6).

The lessons were tailored for each student according to skill level and current progress. Each lesson lasted for about 40 minutes; we took breaks or stopped early if the student's concentration waned. During the first lesson we re-evaluated the students' baseline skills. We asked them to write a signature and then checked their knowledge of basic prewriting skills. Spatial concepts (up, down, beside, etc.) were tested and taught when missing. The students were encouraged to explore the experimental equipment (by touch) and their pen grip and pressure checked and corrected. We also discussed the Earcons and auditory feedback.

Over the following lessons, we progressively taught each student all the letters required for their signatures (we did not teach them the entire alphabet). A progress chart was kept for each student, with each lesson starting with a recap of the previously taught letters and then the introduction of a new skill. Exit strokes were added to the letters that required them, slowly transitioning to cursive writing by joining two, three, and more letters together. As the students gained confidence, the rubber-band lines were added to the drawing space and the writing size reduced. In the final phase, we moved between McSig and pen and paper so that the students could learn to write with reduced tactile feedback and independently remember the letter sequence and spatial relationships. In the next figures, all blue ink is a photo of writing with a standard pen on paper, all black ink is a screen capture of characters drawn with McSig 2.0.

Participants. Mae was 15 years old at the time of the longitudinal study, she was familiar with Braille and a number of tactile learning aids including thermoform plastic diagrams and “Wikki Stixs” (short flexible wax-covered wire sticks similar to pipe cleaners, www.wikkistix.com). Her academic ability was described by her teacher as below average for her age. She was one of the worst performers in the first McSig study. Mae’s goal signature was “M Kumar”.[2]

Nik was 13 years old, with good Braille skills and she had used a tactile drawing board. Nik’s teachers considered her an able student with good academic ability for her age. We had planned a signature of “N Te Paa” for Nik, but she immediately decided she wanted “N J Te Paa”. Nik had a good grasp of all the basic spatial concepts and her initial writing skills were at a relatively high level.

Tam, the third participant, was 14 years old. He had basic Braille skills and his teacher said that he had some learning difficulties, often having problems with recall and retention. Tam showed no preference for a writing hand so we started with his right hand holding the pen. His target signature was “T Pearse”, while he could verbalize the letters, he had no concept of moving his hand across the page when writing (perhaps because with a keyboard the keys stay in the same position) and he did not realize that the “ar” contraction in Braille was two separate characters.

6.1. Results

Table II shows a visual summary of each child’s progress from his/her first “o” in the pretest of the first evaluation McSig, a signature created on paper at the beginning of Lesson 1 of this second study and a final signature from Lesson 10. With the exception of Tam’s final signature, these were all made without assistance or prompting. We report on the different phases of the longitudinal study: the first lesson; learning individual letters; joining letters together; and transitioning to paper. The ten lessons took place over 14 weeks with breaks for holidays, illness, and general business.

Lesson 1. In each participant’s first lesson, we recorded a base signature on the PHANTOM. Each was then refamiliarized with the PHANTOM setup. We then checked on whether they understood spatial references and correct pen pressure.

Mae’s signature in the first lesson, as Table II shows, was an “M” formed without the first down stroke. In this lesson, we assessed that she had a good understanding of left and right. She quickly grasped top, bottom, vertical, and horizontal. As during the first evaluation study, she had difficulty achieving appropriate pressure for the PHANTOM on the tactile surface. She was very interested in the tactile trace and initially she applied so much pressure that the PHANTOM pen could not be moved by its motors. In this first lesson we extended the M of Mae’s signature to a hump pattern and then transitioned this to an “r” (Figure 16). We took this approach as

[2]Participants and parents gave us permission to report their real family names.

Table II. Visual Summary of Progress by Three Longitudinal Study Participants

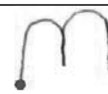
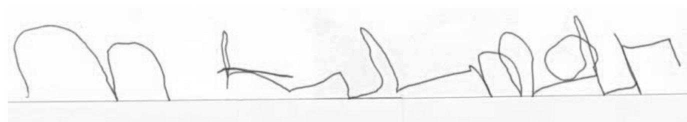
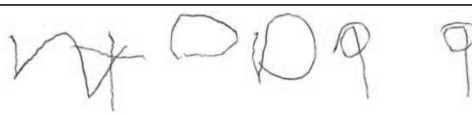
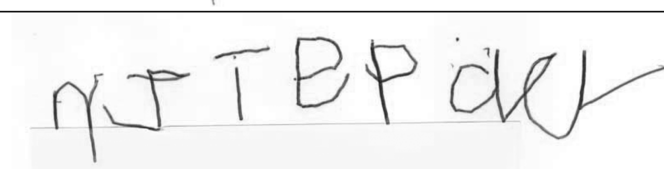
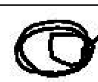
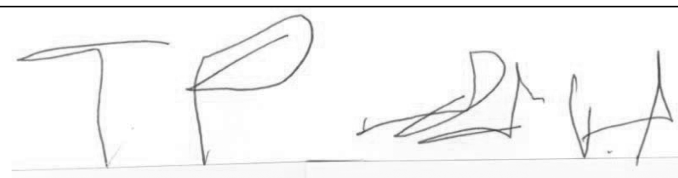
Mae Evaluation study ‘o’	
Longitudinal study Lesson 1 signature	 (Note: the red dot indicates the starting point.)
Lesson 10 Signature	
Nik Evaluation study ‘o’	
Lesson 1 signature	
Lesson 10 Signature	
Tam Evaluation study ‘o’	
Lesson 1 signature	
Lesson 10 Signature (Note: verbal prompting provided)	

Fig. 16. Lesson 1 Hump pattern and r.

Fig. 17. Mae's 'K', she liked the "curvy bit at the base".

teaching patterns such as humps is a standard technique for teaching writing to sighted children.

Nik had a good grasp of all the basic spatial concepts and her initial writing skills were at a relatively high level. In Lesson 1, she confidently engaged with the researcher asking questions about what he was doing with his pen and commenting on the range of the musical tones used for the y-axis movement. We explored the letters "N" and "J" in this lesson. For "J", where we described the bottom as a little tail, she said "a bit like an umbrella".

Tam had a good understanding of the concepts up, down, left, right, vertical, and horizontal. Tam initially did not use enough pressure with the PHANTOM to make a tactile mark on the drawing board. He was interested in the arm of the PHANTOM, it was pointed out to him that he needed to be more interested in the tip of the pen! We concentrated on this and started with the letter "e" during Lesson 1. Tam commented that he liked the sounds and enjoyed the lesson observing that "it was very good".

To summarize, two of the students needed to adjust the pressure they were exerting on the surface. Of the modalities that the system affords, Mae found the tactile surface the most engaging while Nik and Tam were more interested in the audio.

Learning Letter Shapes. Over the next lessons each participant learnt the letters required for their signatures. As each of the students had different learning abilities and preexisting knowledge the duration of this phase varied from four, for Nik, to eight lessons for Tam. Mae, the first to commence the longitudinal study, found repetitive patterns used for sighted children confusing so we did not persist with this strategy.

The haptic guidance in Playback mode was the primary sense used for learning new letter shapes. For example, when learning "a", Mae held the pen with her left hand as it moved synchronously with the teacher's pen and followed the tactile trace her pen made on the tactile surface with her right hand. After numerous demonstrations, Mae asked "Can I try now?". We then moved between Freedraw and Playback modes to refine the letter shape.

Some letters are more difficult for blind people to form, for example the standard formation of K is difficult because it is two strokes that should touch in the middle which is very difficult to line up correctly—using Playback mode, we taught Mae an alternative formation which can be formed with one stroke. Mae decided she liked having a "curvy bit at the base" (Figure 17). She went on to design her own version of K in Lesson 10.

Fig. 18. Lesson 3: Tam's early attempt at an "a" then again after retraining.

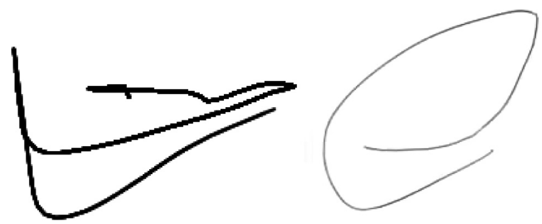


Fig. 19. Lesson 9: Tam's remembered "e" on McSig2 and later with pen after retraining in the same lesson.

Fig. 20. Mae lesson 3 Two U's before wiki stick use and one after.

Tam's concentration span and retention were significantly lower than those of Nik or Mae. He would frequently wander off task, asking about the sounds or other things. He also relied heavily on little chants he made up such as "e, right-up-round-down-across". The chants were not always accurate or meaningful. He would make significant progress during a lesson, for example, Figure 18 shows his "a" after initial training, then later in the lesson. However, this knowledge was not well retained, each lesson included significant retesting and training of letters already learnt. Figure 19 shows an example of this in Lesson 9. We did note, however, that retraining became quicker over the lessons.

Both Mae and Tam struggled with some letter shapes. Mae had difficulty with the concept of the hump being at the bottom of a "u", rather than the top in Lesson 3. We used wikki stixs to make a tactile "m" and "u" to help her with this spatial concept. Figure 20 shows her 'u's before and after using the wiki stixs. With Tam we used pipe cleaners for the "T", which worked fairly well. However, his attempt at "P" after a pipe cleaner exploration was badly malformed. We then demonstrated the letter again with McSig and Tam said "Oh! I get it", he was then able to write a well formed "P" (Figure 21).

The concept of baselines and varying letter heights was also introduced in the latter part of this stage. Nik had difficulty with the width of "N" and slope of letters; the guidelines were helpful for this (Figure 22).

Fig. 21. Tam's 'P' with pen after pipe cleaner and McSig2 training.

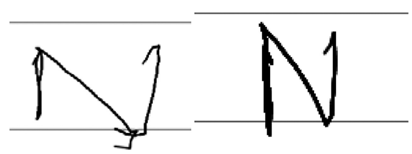


Fig. 22. Nik's "N" before and after slope correction.

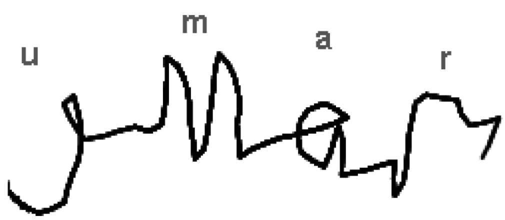


Fig. 23. Mae's first joined letters.

Fig. 24. Nik joining 'a's in Lesson 3.

To summarize, the Playback mode was the primary teaching and learning tool during this phase. The tactile lines were useful to reinforce concepts of letter heights and slopes. The tactile letter feedback was very important to Nik, while Tam was more interested in his little chants and the audio feedback.

Joining Letters. The importance of being able to join letters for a signature varies depending on the letter combinations. As with the individual letters, the PHANTOM Playback mode was used as the primary teaching and learning modality. The signature audio pan width was used during this stage to emphasise the horizontal movement.

Mae spent Lesson 6 on joining the letters together. We needed to correct her formation of "m" so it could be joined from the previous stroke (Figure 23). Apart from this she had little difficulty with this stage.

Nik had relatively good initial concepts so she also quickly moved from single letters to cursive writing. For example, in Lesson 3, she worked on joining "a"s (Figure 24). Tam took longer to learn the individual letters so did not have time to learn to join them.

Transitioning to Paper. For the training to be useful to the participants in their everyday lives, they had to be able to form a signature without McSig or a tactile

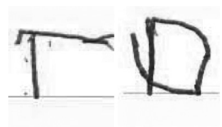


Fig. 25. Nik's writing on paper from Lesson 6.

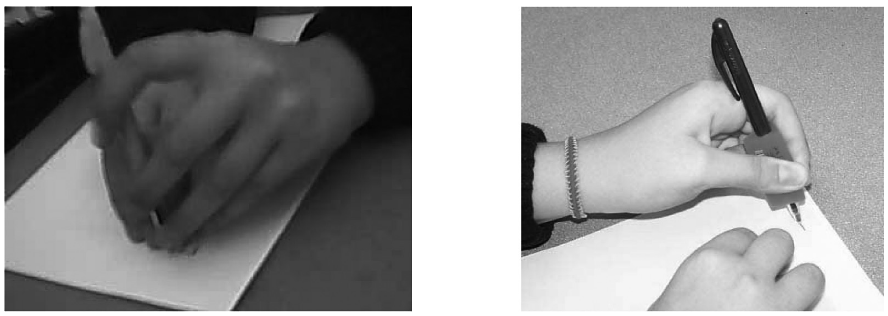


Fig. 26. Correction of Nik's pen grip. Top shows her initial grip, bottom her corrected grip.

surface. Once Mae and Nik could form a complete signature on McSig, Lesson 7 and 6 respectively, they started to transition to paper. For Tam, only his final lesson was on paper.

We started this process by alternating between McSig and paper. By Lesson 9, Mae could form a complete signature without prompting, we then worked more on aesthetics, size and letter joining, using a sticky-note for a baseline guide.

Nik struggled with paper, in Lesson 6, she commented that she could not tell when the letters were intersecting or overlapping when using the paper. At times, she was concentrating so hard that she would forget the sequence of letters. Nik's progress slowed, she was constantly looking for tactile feedback and relied heavily on the top and bottom sticky-note guides provided (Figure 25). We also noted that she was using excessive pressure to try to get some tactile trace. This emphasised to us again just how limited the feedback is for blind children when writing on paper and how hard this makes the learning task.

By Lesson 9, Nik could make all of the letters, however the heights were very variable. We realized that part of the problem was her pen grip which made control of the pen very difficult (Figure 26, left). In the final lesson, we used a standard triangle grip on the pen, while Nik initially found this difficult to hold she quickly realized she had better control (Figure 26, right).

Of note, during this stage was that alternating between the McSig system and paper allowed Mae to quickly transfer her skills, while Nik's heavy reliance on the tactile feedback caused her progress to slow.

Final lesson. In the final lesson, we asked the participants to sign multiple signatures on paper. A sample of each participant's final signatures is shown in Table II. Mae's final lesson was notable as she demonstrated advanced spatial awareness, on one occasion repositioning the pen to ensure a letter was correctly placed (Figure 27). Both Mae and Nik demonstrated a set of six repeated signatures without assistance. Mae's teacher was extremely pleased with the progress Mae had made. The researcher and Nik's parents agreed that hers showed good consistency, although greater differentiation of letter height was required.

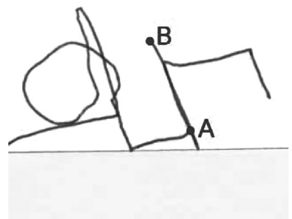


Fig. 27. Mae repositioning the pen for a new letter moving it from A to B to start the new letter.

In Tam's final lesson we transitioned quickly and frequently between McSig and paper for Tam to get some feeling of putting the letters together in sequence on paper. His final signature (Table II) was produced with some verbal prompting from the teacher. Considering his starting point and learning difficulties, we, and his teachers, were impressed with the progress Tam made.

7. DISCUSSION

Learning handwriting and creating an individual signature is a normal part of education for sighted children. For blind children, learning to create a signature is a separate and difficult task. Our interactions with blind children and adults during this project have reemphasised the many subskills that are required for making a signature such as pen grip and pressure, fine motor and spatial concepts and knowledge of letters. We have shown that students can learn new writing skills and that our system supported learning over a long period of time, from gaining initial pen skills all the way to the transition to writing with a standard pen on real paper.

The evaluation of the first McSig prototype showed that this approach could help visually impaired, and particularly blind, children to learn to make better character shapes. The partially sighted students had a reasonable knowledge of letter shapes before our study. They did produce some letters in mirror image and form other letters incorrectly. We were intrigued by the incorrect formation hypothesising that it could be because they had been taught incorrectly or that their poor vision meant they did not pick up the subtleties of letter shapes. We discussed the cause of misformed letters with their teachers but they had no better ideas. With the McSig system, we could quickly re-train these students to form letters correctly.

The blind students all made significant progress in their writing skills during their short training session in the first evaluation study. Existing writing competence did not appear to have any association with age or general academic performance. The evaluation study reinforced the difficulty, for visually impaired children, of learning to write. Even the most basic skills, such as how much pressure to exert, must be specifically learnt. Our discussions with the participants and teachers suggested that it was dependent on the interest of students, their parents or individual teaching assistants as some saw learning a signature as a higher priority than others (students in integrated schools have a teaching assistant with them for many hours a week). We concluded that McSig could perhaps make it easier for the teachers (or parents) to teach handwriting as it appeared to be motivating for the students.

None of the blind participants in the first evaluation knew all of the letters in the training set. The least competent writer, Mae, improved her spatial orientation, adjusted her pen pressure and mastered a basic circle. She required significant training to be able to create the "o, c, a" and these were very large and jerky, but she was unable to write them at all before the training. Of the three middle performing students, in the pretest we noted two misformed letters, one reversed "c" (Sue), and the other misformed "c" and an inaccurate "a" (Nik). These students corrected misunderstandings and learned the basic shape and formation of one or two letters they did not know before the study. Student Ann with the best existing skills could form an appropriate "o" and "a" and a reasonable "d". The training did not significantly change her performance of the "o" and "a", but she did learn "c" and "e" and improved her "d". The most interesting aspect of this student's performance was that she could scale the examples to an appropriate size for handwriting. While scaling is trivial for sighted people, it is not obvious for visually impaired people due to the lack of feedback. Of note is that Ann lost her sight when she was about 3, it is likely she had already developed good spatial concepts by this time.

The first evaluation study considered only a small set of single stroke letters, due to the skills of our participants. McSig supports multistroke letters and multiple letters. Even finer spatial orientation is required to create some multi-stroke letters, for example "K" requires careful positioning to connect the two strokes. Likewise the spacing between letters and words is critical to the visual appearance of words and sentences.

Of the three modes in the first McSig prototype, Playback and Freedraw worked reasonably well, but Stencil did not. It took us some time to understand why the virtual stencil did not work. We believe it is because visually impaired people use two hands to write, one holding the pen and the other for spatial orientation on the paper. The stencil was virtual, only discernible from the hand holding the PHANTOM. We considered using a second PHANTOM for the other hand, but two such devices in a small area is problematic due to clashes between the armatures and each would only give a single point of contact where our participants typically used several fingertips (as they do to read Braille).

We identified a number of aspects of the system that could be refined. A second prototype was developed before the longitudinal study in which the accuracy of the haptic guidance was improved by correcting for the tilt of the PHANTOM pen, the tactile surface had physical lines added where appropriate and the soundscape panning was of variable width with different start points in the space for single letters and signatures.

The literature on learning to write suggests that it involves three subtasks: learning letter shapes, developing motor skills and learning the spatial relationships between the letters [Sassoon 2003; Taylor 2001]. Sighted children rely heavily on visual instruction (watching the teacher form a letter, seeing the letter) and feedback from seeing the ink they have laid down. McSig supports the learning of these skills with three non-visual modalities. Learners can be moved through letter shapes and then explore them on their own, allowing the letters to be felt again through the marks made on the drawing board, supporting the learning of spatial relationships between letters. The soundscape reinforces the spatial information and the teacher can draw on everyday concepts that may not necessarily relate to writing (e.g., hump or umbrella handle).

Results from the longitudinal study with Mae and Nik showed that they maintained these skills over time, suggesting that they had learned the new skill deeply and could make a consistent and repeatable signature as would be needed in everyday life for the signing of legal documents, etc. Several months after the completion of the study, Tam's father told us that Tam had used his signature on several occasions and although it is still oversized, Tam gets a feeling of independence being able to sign for himself.

The writing instruction literature suggests prewriting pattern exercises [Taylor 2001] (e.g., drawing zigzags or lines of humps) but we found that these were unhelpful for our students. We hypothesize that, with only a subset of the alphabet to learn, they simply caused confusion. The literature also refers to spatial skills in terms of letter placement with the writing lines. We found that our blind children also needed to develop their spatial orientation skills to write signatures. Mae demonstrated considerable improvement in her spatial skills over the training period. By Lesson 10, she was able to use her newly devised “K” (taught in Lessons 5 and 6) that was spatially correct and easier for her to construct. She was also able to reposition the pen to join letters in the correct place (see Figure 27), this demonstrated good fine spatial skills. Tam advanced from placing all the letters on top of each other to moving along the line in a correct spatial sequence.

McSig’s haptic guidance has extended that provided by other similar projects [Mullins et al. 2005]. It provides rich instruction to the student for learning shapes and motor skills. The pen-tip position correction for pen angle improved the accuracy of the haptic guidance. While the position correction is an estimate, it seems to be adequate given the granularity of control available on the PHANTOM. The tip height sensing introduced into McSig 2.0 removed the button press requirement in Freedraw mode; this solved the problems experienced with pen/button interaction seen in the original McSig study. It also allowed us to replace the pen shaft; however the PHANTOM pen is still bulky and difficult to hold for those with small hands. A device specifically designed as a pen might solve this problem.

The need for tactile feedback was evident from the first informal evaluation we undertook with a blind adult early in the development of the first prototype. It was very important to Mae and Nik during learning, both requiring a clear writing space for each new letter or signature. Nik had difficulty with the removal of this feedback when she transitioned to paper, making comments such as she could not tell whether the letters were overlapping or at the right heights. The tactile sheets are less sensitive than pen on paper, requiring a little retraining of pressure when moving to paper. One interesting solution to support the transition to paper might be to use the tactile pen proposed by Lee et al. [2004]. This included a vibration actuator within the pen shaft, so could provide some tactile feedback when handwriting on paper. The inclusion of an accelerometer would allow the pen to give some dynamic feedback on letter shapes as they were drawn. We will investigate this in a future research project.

Our simple solution of using rubber-bands to create tactile lines worked exceptionally well and set up an appropriate transition to the use of sticky-note guides for paper writing. We also used wiki stixs and pipe cleaners as tactile aids. Both of these could be replaced by an active, controllable tactile surface which would have the advantage of being quick to create new shapes. With such a surface it is likely that the stencil mode would also be more successful. One of the authors is part of a project investigating the design of a tactile pin array that could be used for this purpose. It is based on MEMS technology and, if successful, would provide a low-cost solution to providing fine-grained, dynamic tactile feedback over a large area.

McSig maps the x,y position of the pen to audio pan and pitch. The variable width sound pan developed for the second prototype was particularly useful for single letter teaching and used extensively by Mae and Nik. Earcons for the start and end of a stroke completed the audio feedback. We could add further Earcons to indicate switching between Playback and Freedraw modes as students would often ask what mode they were in or try to work it out from the teacher’s verbal comments.

Under the longitudinal study conditions the students’ progress cannot be fully attributed to McSig. It is possible that if the students had been given the same amount of training with traditional methods they may have made similar progress. However, this is not commonly provided in integrated education and Eliza and the other blind adults that we have interacted with during this project have all told us their horror stories of learning to write. They described the frustration and hours of practice in derogatory terms. The teachers also commented on how much easier and more pleasurable McSig had made the task for the students. In the future, students could use McSig with recorded examples when they liked (at home, school or work) to practise their handwriting and signatures to keep them consistent and repeatable over time, without the need for a sighted helper. Some of the concepts the students mastered would also be useful in other contexts, such as for developing fine motor skills, or in mathematical subjects such as geometry where understanding spatial concepts and relationships is very important.

8. CONCLUSIONS

We have shown that McSig, a multimodal haptic and audio tool, can be used teach blind children handwriting and the development of cursive signatures. The students in the longitudinal study made significant progress over the ten lessons. The skills they learned were developed over a 14-week period and two of the students showed that they maintained their skills over time, suggesting that they had learned the new skills deeply. They were able to make a consistent and repeatable signature and so would be able to sign legal documents, bank loans, cheques, etc.

These techniques and the software could be applied to other two-dimensional drawing tasks. The teachers of visually impaired students were particularly keen to try it for geometry. These teachers currently spend hours making two-dimensional drawings of simple geometric figures such as triangles to help their students. While general mathematics teachers often use three-dimensional blocks to demonstrate geometry, the teachers of visually-impaired students involved in this study told us that when 3D blocks are used to represent a 2D figure it confuses the students. They suggested that McSig may be useful to help students construct a better understanding of 2D geometric principles.

In conclusion, it is possible for visually-impaired people to handwrite a consistent signature, but it is extremely difficult for them to learn to make a visually "normal" signature. The learning task is both difficult and not very fulfilling because of the limited of feedback. McSig takes an innovative approach combining virtual haptic guidance and audio cues with a physical tactile rendering of the pen strokes to enrich the interaction experience. By allowing a student and teacher to work together with haptic guidance we have shown that it is possible to improve children's handwriting performance after a short 20-minute session with our system. The blind participants that carried on to the longitudinal study learnt, over 10 lessons, to form a full signature. The blind students, in particular, enjoyed the enriched feedback of McSig. This suggests that students can learn new writing skills and that our system supported learning over a long period of time, from gaining initial pen skills all the way to the transition to writing with a standard pen on real paper.

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