# A Collaborative Multimodal Handwriting Training Environment for Visually Impaired Students

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## ABSTRACT
The spatial motor skills used for handwriting are particularly difficult for visually impaired people to develop. These skills are required in order to sign an aesthetically pleasing and repeatable signature, which is often required for documents such as legal agreements and job applications. Our multimodal system with haptic guidance, sonification and tactile feedback is designed to assist when teaching visually impaired students to form letters, and eventually, a signature. As tactile technologies become commonplace, appearing even in mobile phones, our system may also provide useful insight into the use of non-visual feedback for a variety of applications.

## Categories and Subject Descriptors
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

## General Terms
Design, Human Factors

## Keywords
Visually-Impaired, Handwriting, Signature, Haptic Guidance, Sonification, Tactile

## 1. INTRODUCTION
A personal signature is necessary for many everyday scenarios. Business letters and legal contracts are important examples. Learning how to create an aesthetically pleasing signature that can be successfully repeated is difficult for visually impaired people.

Using tactile aids, such as plastic letters, stencils, or pipe cleaners, visually impaired students can become familiar with letter shapes. However, the motor skills to form these letters must still be developed. A teacher physically holding and guiding a student's hand is a conventional approach. Haptic guidance technology offers possibilities for more accurately controlled guidance that can be combined with other non-visual feedback.

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"McSig" is an interactive teaching and learning system designed with the goal of teaching visually impaired students to write a signature. The system combines haptic guidance, audio and tactile feedback to provide visually impaired students with rich multi-modal feedback relating to the formation of letter shapes. During an initial study [16], the system showed great potential, but several shortcomings were identified.

This paper discusses the development of new features for McSig 2.0. By looking at the problems with McSig 1.0 [16] and findings from literature on teaching children to write, we devise requirements for an upgrade to the system. We describe the development of new features using a participatory design method with a visually-impaired adult. We then evaluate the many facets of the interactions in the system using the Cognitive Dimensions Framework [9].

## 2. RELATED WORK
Information can be displayed for visually impaired people using conventional static tactile representations. Braille and paper or plastic sheets with raised sections are commonly used. Information stored in digital form can be edited and displayed in a more dynamic manner. Screen readers are a popular example. However, learning to write presents several unique challenges, including gaining an understanding of the shapes of letters, spatial skills, and the development of the motor skills necessary to form the letters.

### 2.1 Non-Visual Drawing
"TDraw" [13] is an interactive drawing system for visually impaired people. The system allows users to create drawings on swell paper using a thermal pen. A digitiser beneath the swell paper is used to obtain the position of the pen. The user is able to feel the lines that have been drawn on the swell paper. The user can record a related piece of information verbally as a pen stroke is carried out. A separate mode allows the user to touch lines and shapes with the pen in order to hear the corresponding verbal information played.

The system created by Rassmus-Gröhn et al. [17] allows visually impaired users to freely draw pictures on a virtual writing surface, using the Sensable Technologies PHANTOM haptic device [19]. The drawings are stored as grayscale images, where a black denotes a positive relief, and white denotes a negative relief. The user is able to move the haptic device around the virtual writing surface to experience the changes in relief.

## 2.2 Non-Visually Displaying Spatial Information

Providing access to spatial and graphical information for visually impaired people has been carried out using a variety of techniques. The Talking Tactile Tablet [14] uses a touch sensitive tablet, overlaid with paper which has raised regions. The raised paper can be touched by a user and plays audio upon various parts being touched. This system is proposed for educational and game applications. Although the mapping of areas of the tactile surface to audio is configurable, custom raised paper sheets must be made for each new application.

The TeDUB project [12] involved the processing of diagrams in order to allow them to be comprehended in non-visual modalities. It can process several types of input file, including image bitmaps and recognise the underlying semantics contained in diagrams of particular domains. The user can then explore the data, receiving various audio or haptic feedback appropriate to the diagram domain.

Wall and Brewster [22] presented a system to help visually-impaired people gain access to information in bar graphs. The user uses one hand to move a stylus around a graphics tablet. The fingers of the other hand can touch two small tactile pin arrays which are incorporated into a mouse. As the user moves the stylus over the tablet, the pixels close to the corresponding mouse cursor position are monitored. Pixels which are darker than a specified threshold value cause the pins to be raised. As the cursor moves over features of a graph, such as a line forming the edge of a bar in a bar graph, tactile feedback is provided for the fingers touching the pin arrays.

A system developed by Yu and Brewster [24] allows users to access information from graphs and tables using a haptic device. The user can retrieve information about the values of data in the form of synthesised speech and musical notes with a pitch corresponding to the magnitude of a value.

## 2.3 Haptic Guidance for Learning Motor Skills

Literature in the area of teaching sighted users using haptic systems provide some useful insights for developing systems to teach visually impaired students. Haptic guidance is where the user's hand or arm is guided through a trajectory using forces provided by a force feedback device. This approach has been used to teach users how to carry out basic physical movements [23]. Haptic guidance has also been applied in the medical domain to train medical personnel in carrying out injections [6].

There are a number of systems that have been created to assist users in learning how to form Japanese and Chinese characters [10, 21]. One study [1] used a robot arm to guide a user's hand and arm through reaching movements. The system was designed to help rehabilitate stroke patients developing the ability to reach directly for a target, or reach through a curved trajectory. A similar system developed by Mullins et. al. [15] is to aid stroke patients in rehabilitating their handwriting skills. The system displays text using a font which resembles handwriting. A PHANTOM Omni haptic device is used to guide the user's hand through the motion of letter formation at a fixed speed. Another study showed that haptic guidance can be used to teach users to move through complex 3-dimensional motions [7].

Teaching similar motor skills to visually impaired learners presents some quite different challenges. Non-visual modalities must be effectively utilised to train the user in a motor skill.

A study by Crossan and Brewster [4] tested a haptic guidance system for teaching shapes to sighted and visually impaired users. The study showed that visually impaired users found this much more difficult than sighted users. With the addition of audio feedback, an improvement was seen in user performance compared to using haptic guidance only. The letter shape was recorded by a teacher and the student was then guided through the motion at a set rate. This was found to be problematic, as the teacher could not slow down the rate of playback for difficult parts of a shape.

## 2.4 McSig 1.0

The original McSig system used kinaesthetic, tactile and sound modalities to provide feedback to students. The system was designed for the teacher and student to use together. The teacher uses a Tablet PC and the student holds a pen which is attached to the mechanical arm on a PHANTOM Omni haptic device [19]. As the teacher forms a letter shape on a Tablet PC, the student experiences 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. A continuously playing tone is altered to express the movement of the student's pen. As the pen moves along the y-axis, the pitch of the tone changes. As the pen moves along the x-axis, a stereo panning effect occurs between the two speakers playing the tone. A distinctive sound is also played at the start and end of each stroke. Such sounds are known as "earcons".

**Figure 1. A teacher and student using the McSig 1.0 system.**

The student's pen moves over a tactile writing surface. This consists of a plastic tactile sheet resting on top of a rubber surface known as a Dutch drawing board. As the tip of the student's pen moves over the plastic tactile sheet, the sheet is scored, leaving a tactile ridge that the student can feel with their non-dominant hand. The teacher can verbally provide information about the letter shape being formed to assist the learning.

Teacher interaction is made possible by means of a software GUI. The teacher can switch between two modes. In "teaching" mode (originally named "Playback" mode), the student is guided through movements by a teacher. In the free drawing (“freedraw”) mode, the student is able to attempt forming letters or a signature without being guided through the motion by the haptic device. The student presses a button on the side of the PHANTOM pen to cause ink to appear on the teacher’s display. The option was given to provide speech feedback to the student upon the completion of a letter. Once recognised, the letter is read aloud using synthesised speech.

The software in McSig 1.0 which controls the haptic device draws on the approach taken by Amirabdollahian et al. [1] to create a haptic guidance system for stroke rehabilitation. This is used in conjunction with a PID Controller algorithm [3]. This algorithm dynamically alters the forces applied by the device in order to move the user’s hand along the trajectory smoothly. A library which had been created to enable the haptic device to move its end effector through trajectories [5] was used in the development of McSig.

## 2.5 Teaching Handwriting

There is extensive research into understanding how people learn a motor skill and from the domain of teaching sighted children to handwrite. This work provides useful guidance when teaching the same skills to visually impaired students. The importance of recognising and catering for the needs of the individual child is recognised [2].

Ergonomics are important during writing. The literature emphasises the need to maintain an appropriate posture while writing [2, 18, 20]. Consideration of the angle of the paper and the student’s grip on the pen ensures that the student can write comfortably. Paper which is angled slightly allows for a natural writing position. Right-handed students should work with the paper slanting leftwards. For left handed students, the paper should slant in the opposite direction [2]. The way that a student holds the pen is important to ensure that they can comfortably write and easily produce letters. The “tripod” grip is a commonly taught holding technique [18, 20]. This grip develops students’ hold from three fingers rigidly pressing against the pen, into a more fluid hold with the pen held between the thumb and forefinger, and resting on the middle finger [20].

Lined paper can be used to provide a spatial reference while students learn the height and relative vertical positions of letters. This also helps the student understand that some parts of letters hang below the baseline, parts of most lowercase letters are of a uniform height, and that some strokes in letters rise above this height to the top line [20]. A teacher can use a single baseline, double lines or four lines as a tool to help the students master these concepts [18].

These considerations from the general learning to write literature, together with problems identified with McSig 1.0 [16], form the design requirements for enhancements to the McSig system.

# 3. DESIGN REQUIREMENTS

These requirements are drawn from the shortcomings of McSig 1.0 [16] and the additional requirements from the literature on teaching handwriting, described above. From the McSig 1.0 system [16] the following weaknesses were identified:

- Changes in stereo pan feedback for the x-axis movement are sometimes difficult to discern. A large change in the position of the pen is needed to create any discernable change in stereo pan. This means that no useful feedback is provided for small movements.
- In the student freedraw mode the student is required to push a button on the side of the PHANTOM pen for the ink to show on the teacher’s display. Having to hold down a button can distract the student from the primary task, namely, moving the pen around the intended trajectory. It may also introduce forces which interfere with the writing motion and prevent the student from maintaining a conventional and ergonomic grip of the pen. These difficulties are exacerbated by the PHANTOM pen being thicker than a typical ballpoint pen, making it relatively difficult to hold while writing.
- The position of the student’s pen within the working area is not always clear to the teacher. When the teacher’s stylus first contacts the tablet screen, the PHANTOM pen moves to the corresponding position within the student’s writing area. If this initial point is a significant distance from the previous position of the student’s pen, it causes a sudden jerking movement of the student’s pen. This is uncomfortable for the student and can cause disorientation.
- The ability of the pen to rotate about an axis (figure 2) can lead to inaccuracy in the trajectory playback. In McSig 1.0, the point that is moved around the trajectory is part way up the pen (where the pen is attached to the mechanical arm). The pen is able to tilt, so the pen tip below this attachment point can deviate from the trajectory. As an example, the teacher may scribe a straight line, but because the student changes the tilt on his/her pen during the motion, the student’s pen tip will scribe a curved line on the tactile surface.

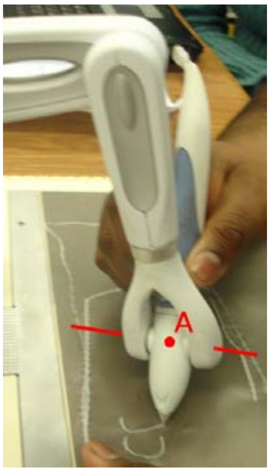


**Figure 2. Point A is moved about the trajectory and the student can rotate the pen about the axis indicated.**

The literature about learning to write identified some key areas for improvement. No equivalent to lined paper was used in McSig 1.0, making it difficult for students to grasp the important spatial concepts that lines reinforce. A non-visual implementation of lines is a key requirement. The technique of slanting the paper slightly leftwards or rightwards for writing is also an important ergonomic consideration. A suitable way should be found to apply a similar technique in McSig.

# 4. PARTICIPATORY DESIGN AND DEVELOPMENT

Enhancements were made to the McSig system to address each of the design requirements formulated in the previous section. This was carried out using a participatory design and development approach. The extremely limited pool of visually impaired children makes it unfeasible to have child participants. Informal evaluations were carried out with a visually impaired adult, ‘Sue’, who was one of the participants in the previous McSig usability study [16]. The target user group for McSig is congenitally blind children and the previous study showed that congenitally blind people interact differently than those who have seen [16]. From among those who participated in the previous study, Sue was the closest match to the target user group because she is congenitally blind.

On three occasions during the enhancement implementations Sue helped to evaluate different design options relating to the blind user’s interaction. For example, while refining the sound pan feedback, she trialled the use of headphones and the various stereo pan options in order to refine the interaction experience for a blind user.

## 4.1 Button-Press Removal

The button-press problem was addressed by obtaining the height of the pen tip. The ink can be displayed on the teacher’s display when the student’s pen tip is moving along the writing surface. This eliminates the need for the student to hold down a button on the pen to switch into an inking mode, and allows for a more natural interaction. The student will need to learn that they must only touch the pen on the paper when they intend to write a letter. However, this is also necessary for ordinary writing with a ball-point pen to avoid drawing unintended marks and lines on paper.

## 4.2 Visual Feedback for Teacher

Visual feedback was added to make the teacher aware of the current position of the student’s pen. A moving blue dot was added to the teacher’s display to indicate the current position of the student’s pen. The teacher, by aiming to make first contact with the tablet close to the dot, can make sure that the student’s pen will not have to move a large distance to begin following the teacher’s trajectory. By polling every 10ms, the position of the student’s pen is read from the haptic device and displayed on the teachers’ view. From the phantom pen, x, y and z coordinates for the vertical plane facing the device were obtained. These were translated appropriately to get the x and y coordinates for the writing surface plane. Adjustments then needed to be made to the coordinates. The PHANTOM coordinate system places the origin in the centre of the dimension, with positive and negative values proceeding from this point. To display this position on the teacher’s software, the coordinates need to be adjusted to fit within a rectangle, with the origin at the top left corner. 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. CursorDown and Stroke events represent the time when the stylus first touches the tablet and leaves the tablet, respectively. These events are used to toggle the visibility of the trailing dot.

## 4.3 Non-Visual Lines

Several options were considered for a suitable non-visual equivalent of lines on paper. One option is to alter the character of sound that is playing according to the position of the pen in the y axis. As the pen moves past a certain y axis position, a change in the character of the sound feedback could indicate that a line is located at that position. A second option to consider is the use of a virtual haptic ridge. As the student’s pen tip moves over the location of the line on the writing surface the z coordinate could be altered to lift the pen off the page slightly, causing a bump sensation. Both of these options have the significant disadvantage that no tactile feedback is available for the student to touch with their non-dominant hand. This is considered an important part of the interaction [16].

Physical tactile lines are able to be felt by the user, and a number of options exist for implementing these. A calibration step is required for some options, as the teacher needs a view of the lines on their writing area which corresponds to the placement of the lines on the student’s writing area. Plastic sheets could be thermally pressed to form physical ridges, and placed on the writing surface. Because they could be placed in predefined positions, no calibration with the teacher’s view would be necessary. A problem is that they are static and unable to be configured. Another option is that the teacher could rule a straight line while in teacher mode, causing a line to be drawn on the tactile sheet of plastic. This would require no further calibration or equipment, but it could be time consuming and also lacks flexibility. This was trialled with Sue, our adult participant and was found to be difficult to carry out accurately and quickly. Nylon threads placed beneath the plastic tactile sheet are a promising alternative, but easily slip out of position beneath the plastic sheet when touched. The chosen option was rubber bands placed beneath the tactile sheet. Rubber bands of two different thicknesses can be used in order to show lines of differing importance. For example, if three lines were used, the middle line could be thinner. The rubber bands were found to be effective with Sue.


**Figure 3. The teacher view of McSig, showing lines that are calibrated to the position of the student’s tactile lines.**

| | Signature Mode | Single Letter Mode |
|---|---|---|
| **Default** |  |  |
| **Custom** |  |  |

**Figure 4. The teacher can select suitable stereo panning behaviour. The solid grey regions show where the panning has reached its leftmost or rightmost extremity.**

When using rubber bands, a calibration step is required, however this allows the flexibility to add, remove and position lines as necessary for teaching sessions. Because lines are always horizontal, that is, parallel to the x-axis of the writing plane, only the position of the line in the y axis needs to be considered during calibration. The student's pen is placed with the tip on a line, and the teacher pushes an "Add Line" button on the teacher view software interface. This causes a line to appear on the teacher's writing area for the duration of the teaching session (figure 3). The teacher can add multiple lines and remove lines using an undo button.

## 4.4 Angling the Writing Area

Another enhancement was to angle the writing area, to replicate the idea of slanting a sheet of paper while writing with pen and paper. In order to keep the writing area on an angle during teaching sessions, a cardboard template was devised. This has outlines that show where to place the drawing board and the haptic device. Sue indicated that turning the writing area on an angle could potentially disorientate a student. However, she suggested that it may be of use, particularly for long teaching sessions, where discomfort may be prevented by keeping the ergonomic writing posture encouraged by angling the writing area.

## 4.5 Improving Stereo Pan

Two unique challenges are faced in providing feedback with stereo panning in the x dimension. First, small changes in the stereo pan are difficult to discern. We should seek to provide the largest possible change in panning. Second, there is a large range in the width of strokes that we would like to provide feedback for. Useful feedback must be produced for small thin letters, but also for large wide signatures.

The positions of the speakers on the desk are variables that affect how panning is heard. If the speakers are sufficiently close together while being distant from the student, sound from these two speakers may appear to be coming from a single source, even when significant panning occurs. During any teaching session, the speakers need to be placed a suitable distance apart. We asked Sue to try using headphones instead of standing speakers, to see if this could make it easier to hear a change in pan. However, she found the headphones less satisfactory for discerning stereo pan. Headphones also prevented her from hearing verbal instructions from the teacher. Although headphones may potentially prove useful for some, it appeared that a more serious alteration of the sonic feedback approach was required.

We decided to maximise the change in stereo pan by providing different panning feedback for single letters and entire signatures. By providing a single letter mode, the stereo pan can be made to pan more sharply to the left or to the right even when a small letter is drawn. Teacher feedback is vital here, so the teacher is provided with a visualisation of the panning on their drawing area from when the stylus pen touches the screen until it is lifted off. Colour shading shows where the panning reaches its left and right extremes, allowing the teacher to draw the letter at a size that would produce the largest possible change in stereo pan for the duration of the stroke (figure 4). When a stroke begins the sound plays at a centred pan position, and panning moves towards the left and right relative to this starting point. Many letters in the English alphabet fall entirely to the left or to the right of their starting point, and this can be reinforced by causing panning to occur relative to the starting point of a letter.

The width that the pen stroke must 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 entire signatures, it is necessary to change the stereo panning to the entire width of the signature, so that meaningful feedback is given 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. A signature mode is provided which provides a change of pan for a greater width of the writing area. At the starting point of the stroke the stereo pan will be near the left extremity. This starting point is slightly to the right of the left extremity, to allow change in stereo pan to occur even when the signature stroke moves slightly to the left before moving predominantly towards the right. The signature mode can also be configured by providing an example signature.

The teacher can customise the signature and single letter modes to produce a range of differing behaviours, in order to provide the best possible change of pan for the student, while also considering the width of strokes being carried out. Customisation of the modes can be carried out during teaching sessions when the lesson moves on to learning and repeating a new stroke with a considerably different width to previous strokes.

The two modes were tested with Sue, our adult participant. She considered that the single letter modes made it considerably easier to hear the change in stereo pan. Sue suggested the same sound feedback be added in to the freedraw mode, in order to provide consistent feedback. This also reduces the learning curve in the early stages of learning when the sound feedback is vital.

## 4.6 Pen Ergonomics

The thick standard PHANTOM Omni pen was replaced by a thinner pen shaft. The pen included with the device had a relatively large diameter, making it difficult to hold and noticeably different to handle in comparison with a standard ballpoint pen. The standard pen was detachable, and a thinner plastic shaft was attached as a substitute. Sue found this pen much easier to hold.

## 4.7 Pen Tip Position Correction

There are two approaches that could be used to correct the position of the pen tip during trajectory playback. First, the pen could be held at a fixed angle. However, this makes the pen difficult to hold and constrains the user more than we would like, as the student is not free to tilt the pen. The alternative is to indirectly alter the position of the pen tip by considering the angle of the pen. The angle of the pen can be obtained from the PHANTOM hardware, although it can not be mechanically altered. We can only control the position of the gimbal point (Point A in Figure 2), and not the pen tip. With this information we could dynamically calculate the position of the pen tip in relation to the gimbal point using trigonometry, and adjust the position of the gimbal point to give a new resulting pen tip position. This offset is complicated by the fact that the gimbal that holds the pen can also rotate.

Due to the complexity of calculating comprehensive correction accurately, a basic version of this correction has been implemented. We had observed that the angle of the pen varied the most along the y axis, as the user tends to tilt the pen with the pen facing forwards, approximately parallel to the y-axis. By storing the original angle, the difference in angle between the original and current angle can be calculated. This value can be used to calculate the distance that the pen tip needs to be offset. When this simple offset is applied the effect on the trajectory of the pen is sufficient for normal use.

## 4.8 Screenshot Capture Tool

We planned to track students' progress by taking screen shots during lessons. We trialled this with Sue and found that we had difficulty collecting and organising screenshots of her attempts at letter shapes. It was difficult to capture, name and save the example quickly, while still keeping the flow of the lesson. To avoid delays, a custom screenshot tool was added into the teacher's software interface. On the first click of the 'screenshot' button, the teacher is prompted for the name of the student and the software then creates a folder named with the student's name, date and time. After this setup step, 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.

# 5. COGNITIVE DIMENSIONS EVALUATION

Because of the very small user population we could not consider a standard usability test. As an alternative we have taken a two-pronged approach. We have carried out participatory design with a visually impaired adult as described above and have used the well known Cognitive Dimensions Framework [9]. This framework allows the developers of visual environments to use independent measures to discuss aspects of a system. In this section we examine McSig in light of each of Green and Petre's dimensions, where necessary, adapting the visual criteria to the sound and tactile interface. There are five different interaction modalities for the visually impaired user (earcons, pan, pitch, haptic and tactile) that we considered.

Green and Blackwell's tutorial on Cognitive Dimensions [8] says: "Giving names to concepts (lexicalisation) is essential to serious thought and discussion. Once names are given, discussants do not have to explain each idea every time they use it; they can refer to the idea knowing that the other party will understand it. Paradigmatic examples help to make the concepts concrete. Comparisons of trade-off costs become easier. Above all, a checklist can be constructed, to make sure that an evaluative discussion has not overlooked important aspects."

The framework proposes fourteen standard dimensions to examine such aspects as abstraction, mapping and dependencies; visibility, consistency and error-proneness. For each dimension the designer can consider aspects of the interaction. For example, for the interaction "Manually changing US spelling to UK spelling throughout a long document" [8], a designer may observe that the cognitive dimension *viscosity* is apparent. The dimension *viscosity* encapsulates the idea of resistance to change. Use of the framework has been shown to be an effective way to review interactive design in a range of systems [9].

We conducted a full review of the system in terms of the dimensions. This allowed us to profile the cognitive aspects of the interaction. A summary is presented below. For most systems visual feedback is the most important so the Cognitive Dimensions concentrate on this. Our needs are different because all of the modalities used with the student are non-visual. Therefore we have interpreted and applied the dimensions non-visually.

It can be expected that the task of learning to write with only non-visual modalities for feedback will be a difficult task, requiring careful concentration. Here the dimension of *hard mental operations* characterises the interaction. By providing feedback with good *closeness of mapping* between the feedback and the real world, and suitably using *abstraction* mechanisms we seek to minimise the cognitive load required.

Earcons are used as an *abstraction* to indicate the start and finish of a stroke. *Error-proneness* is reduced by using two distinctive sounds for the start and finish. This helps the user to realise whether a stroke is currently being carried out or not. The *role-expressiveness* of each sound is demonstrated in that its role can be easily inferred from its order. A start sound is followed by a tone, followed by an end sound, followed by silence.

The pan and pitch feedback simplify the idea of position in space into two single dimensions, creating an *abstraction*. *Consistency* is ensured by providing the same sound feedback in freedraw mode as is provided in the teaching mode. This allows the student to receive rich aural feedback as they make attempts at forming letter shapes and signatures in the early stages of learning. The speech output of recognised letters that was tested in the McSig 1.0 usability study [16] can only be carried out in a discrete manner, on a fully formed and accurate letter. This proved to be very disruptive and was not used for the McSig 1.0 evaluation study with the children. In comparison to this feedback, pitch and pan feedback offer better *progressive evaluation*, in that the user can obtain feedback on the formation of the letter for the duration of the stroke. The feedback is given in a continuous manner, regardless of the accuracy of the letter.

The *viscosity* of the stereo pan is low as stereo panning is readily changed between signature and single letter modes. The option to create custom versions of signature and single letter panning also demonstrates low *viscosity*. Each of these *abstractions* give a characteristic label to a set of behaviours for the stereo pan. Because custom versions require teacher input, the GUI dictates that the type of panning must be selected within teacher mode. This requires *premature commitment*, as the type of panning can not be changed once in freedraw mode. The stereo pan is a spatial movement – moving between left and right extremes. This maps closely to the spatial concept that it seeks to reinforce, which is movement along the x-axis. This demonstrates *closeness of mapping*. There is a problem with *consistency* because in single letter mode the starting point of the stroke is the centre of the panning, whereas with signature mode the starting point of the stroke is close to the left extreme of the panning. This is a trade-off between *consistency* and *visibility*. The signature and single letter modes employ different starting points in order to maximise the non-visual equivalent of *visibility*. The single letter mode makes discerning stereo pan easier by causing panning to move sharply to the left or right when a single letter is drawn. The signature mode ensures that panning occurs across the full width of a signature, by extending the panning scope across the width of the workspace.

Even a small change in the pitch is noticeably discernable, giving this modality good "*visibility*". Low *closeness of mapping* and *role-expressiveness* is apparent as change in pitch has no inherent relevance to the concept of movement in space along a y axis; the changing pitch is an *abstraction*.

Haptic guidance demonstrates *juxtaposition*. The movement of the student's pen is juxtaposed with respect to the movement of the teacher's pen in order to mitigate *hidden dependency* of the student's pen movement upon the teacher's pen movement. The system shows resistance to change, or *viscosity*, because the device has physical constraints; the writing area size is defined by limits of the device.

The tactile surface allows all of the strokes that have been carried out so far to be touched, increasing a tactile equivalent of *visibility*. Because the raised letters are persistent, and not erasable, the tactile surface has high *viscosity*, and *provisionality* is low. As a stroke is being carried out, the student can touch the tactile representation. This allows a measure of *progressive evaluation*. Two types of rubber band of different thickness can be used to show two types of line, demonstrating *diffuseness*.

# 6. DISCUSSION

The new features provided in McSig 2.0 alleviate problems observed in the initial version of McSig. The implementations of key concepts for teaching children to write are implemented in a non-visual manner. The upgrades were carried out using a participatory design and development approach, involving a visually impaired adult. The new system improves the core feedback that the student receives during the training sessions by improving the sound feedback and the accuracy of the trajectory playback. Teacher tools were included to ensure that teaching sessions are able to run smoothly. While the accuracy of the pen-tip positioning was improved, further development of the position correction or exploring the use of alternative hardware may prove to be beneficial.

The evaluation of the system using the Cognitive Dimensions Framework highlights the benefits provided by some of the new features. The stereo panning feedback is made more useful, and tactile lines are an effective solution for providing a spatial reference. Investigation into the intuitiveness of the mapping between sound feedback and movement in the x and y axes, with a focus on visually impaired people, could provide valuable insights.

The upgrades carried out provide a richer and more accurate multimodal interface as we look towards carrying out a longitudinal study with visually impaired students. The longitudinal study will test whether use of the McSig system over a number of training sessions can be helpful to a visually impaired student learning to create a signature. The concepts used in learning to write are closely related to the spatial concepts used in mathematics and geometry. The McSig system, and lessons learned from using the system, may also be applicable to teaching mathematical concepts such as fractions or angles to visually-impaired students. These concepts can be difficult to master without visual feedback.

# 7. CONCLUSIONS

Developing spatial and motor skills for handwriting is a difficult task for visually impaired people. These are the skills required to repeatedly form an attractive signature. McSig is a multimodal system utilising haptic, audio and tactile feedback to assist visually impaired students to learn letters shapes and a signature. Similar non-visual feedback is being developed for personal mobile devices [11], and work carried out with McSig may also provide findings which can be utilised in the development of these devices.

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