Design and evaluation of a technology-driven intervention to represent graphical data in a non-visual form

Abstract

Visual representation of data in graphical form is ubiquitous in science teaching. However, this is often inaccessible to visually impaired students, with few alternative formats available. Where alternatives exist, they are often expensive, complex, and limited in scope.

This research aimed to design and build an inexpensive system that could take real-world data typical in chemistry degree courses, in this case from a high-performance liquid chromatography (HPLC) or gas chromatography (GC) instrument and present it in a form that engaged visually impaired students could engage. Several methods were used to achieve this. 3D CAD using a visual programming language was used to convert data into 3D models for 3D printing. A resistive touchscreen, simple electronics, and a voice synthesiser were used to "read" the 3D prints. Participants under simulated blindness conditions evaluated the system in two sessions. The initial results were promising. The evaluations showed it was possible to analyse data holistically, spot trends, and drill down to extract discrete values. Further development opportunities leading towards a viable production version were identified.

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

Phillip Marsh 17/8/23

Division of Natural Sciences

Word Count 15,000

1. Contents

2. Abstract

Visual representation of data in graphical form is ubiquitous in science teaching. However, this is often inaccessible to visually impaired students, with few alternative formats available. Where alternatives exist, they are often expensive, complex, and limited in scope.

This research aimed to design and build an inexpensive system that could take real-world data typical in chemistry degree courses, in this case from a high-performance liquid chromatography (HPLC) or gas chromatography (GC) instrument and present it in a form that engaged visually impaired students could engage. Several methods were used to achieve this. 3D CAD using a visual programming language was used to convert data into 3D models for 3D printing. A resistive touchscreen, simple electronics, and a voice synthesiser were used to "read" the 3D prints. Participants under simulated blindness conditions evaluated the system in two sessions. The initial results were promising. The evaluations showed it was possible to analyse data holistically, spot trends, and drill down to extract discrete values. Further development opportunities leading towards a viable production version were identified.

3. Introduction

Traditional science teaching relies significantly on visual instruction, making many areas of science where concepts and information are presented visually inaccessible to students with visual impairments[1]. It is widely understood that students with visual impairments have the same cognitive abilities as sighted students and, with adjustment in the teaching, can master higher-order scientific concepts[2,3,4]. However, in higher education, science educators may lack experience with visually impaired students and often struggle to provide quality instruction to them[1,3]. Furthermore, the proliferation of visualisation technology, much of it inaccessible to the visually impaired, continues to disenfranchise these students[5].

Figures recorded by the World Health Organisation show 2.2 billion people with some form of vision impairment.[6] These are classified, according to the International Classification of

Diseases 11 (2018), into two groups; distance and near vision impairment. These can be further classified as

Distance vision impairment:

- Mild –visual acuity worse than 6/12 to 6/18
- Moderate –visual acuity worse than 6/18 to 6/60
- Severe –visual acuity worse than 6/60 to 3/60
- Blindness –visual acuity worse than 3/60

Visual acuity is assessed using the Snellen scale. On this scale, normal visual acuity is called 6/6, which corresponds to the bottom line of the standard eye test chart. The first number is this distance from the chart; the second corresponds to the number of lines read off the chart. For example, if only the top line can be read, then this would be recorded as 6/60, which means that what can be seen at 6 metres is what someone with standard vision can see at 60 metres.

More than 2 million people in the UK have sight loss severe enough to impact their lives significantly, defined as best corrected visual acuity of (BCVA) <6/12. This figure is predicted to double by 2050[7,8].

The Royal National Institute of Blind People (RNIB) highlights that despite legislation, there is an experience of inequality for blind and partially sighted people. Most visually impaired children are taught in mainstream education; however, a variation in provision deprives many of them of specialist support[9].

This inequality continues into the workplace. The barriers to visually impaired people entering the workplace can be separated into three categories: personal barriers, societal barriers and programmatic barriers. Personal barriers include low confidence, lack of independent mobility and lower-level qualifications. Societal barriers include a limited understanding of visual impairment and employers' unwillingness to make adjustments. Pragmatic barriers include a lack of employment support and a perceived benefits trap[10].

In 2020 the employment rate for visually impaired people of working age was 48%. (Overall employment rate is 78%, non-disabled 81% and other disabilities 53%)[11]. The RNIB survey[11] identified that similar to people without a disability, the situation improved with qualifications. (73% for visually impaired people with a degree) 90% of employers state that it would be “difficult” or “impossible” to employ a visually impaired person.[12]

Employer attitudes to visually impaired people vary. Only 60% are willing to make adaptions despite the employer's obligations to the equality act. 62% of visually impaired people in employment have special aids or equipment to help them at work.[13]

An RNIB study found that science, along with engineering and technology, had the lowest number of employment outcomes (5%) for Blind and Visually Impaired (BVI) people[14] compared to other occupations such as administration.

4. Literature Review

Scientists typically are visual communicators and thinkers[15], as Miller[16] states, "the history of scientific thought incontestably bears witness to scientists' desire for visual imagery". Therefore, it is no coincidence that the teaching of science is not only through the written word but relies significantly on visual forms such as diagrams, charts, illustrations, schematics and plots.

The use of modern technology continues this trend facilitating the introduction of these are incompatible with accessibility devices such as screen readers[17].

4.1 General overview of assistive technology for BVI students

Tactile and haptic interactions

Presenting data and information in a form accessible by BVI students has resulted in many different haptic/tactile approaches. Tactile is generally defined as being “connected or perceived by touch”. Haptics is derived from the Greek word *haptikos*, which means “concerning the sense of touch”. Fourney and Carter[18] found there is little consensus on the definition of tactile and haptic interactions. They found that some researchers used haptic as a special case of tactile and others vice versa with tactile used in reference to static touch and haptics as dynamic.

Several authors use the term haptic to describe either dynamic or static feedback. Specifically, Gabbard and Hix[19] and Durlach and Mavor[20] suggest that there are two types of feedback kinaesthetic and tactile. Tactile feedback generally refers to sensing an object by nerve endings in the fingers, such as vibration, friction or deformation. In contrast, kinaesthetic feedback refers to the dynamic manipulation of an object where the object is felt through joints and muscles. For instance, sensing weight, amount of stretch and joint angles of the arm, hand, wrist and fingers. A haptic interface, therefore, by this definition, is a device that reproduces the sensation of contact and manipulation of an object found in a remote or virtual setting.

Different technological approaches to teaching BVI students

Many different techniques have been employed in teaching BVI science students. Some of these interventions rely on touch, such as Braille-labelled magnetic letters and numbers and molecular geometry using magnetic Lewis dot structures[21], tactile drawing boards and graphics[22], tactile drawings using hot glue guns and tactile pens[23] to make raised letters and diagrams. Inkjet printing has also been evaluated as a device for printing tactile graphics[24,25].

Other devices convert information to audio outputs, such as text-to-speech screen-readers[26], however, although there has been an increase in electronically available textbooks, Burch and Pawluk[27] suggest that visual images within 70% of these do not contain any accompanying description in the text.

Laboratory instruments with speech synthesis outputs[28,26,29] are available however, these tend to be expensive. As an example, the Sci-Voice TM Talking LabQuest 2 package is $2500 - $3000.

Research has been undertaken using more complex technology. Haptic devices, such as PHANToM, are used. *(fig 1)* This pointing device has a range of motion that simulates the lower arm connected to a passive stylus and gimbal. It provides positional sensing and force feedback. Through this, PHANTom users “feel” their way around virtual objects[4,30,31].

Figure 1 PHANTom stylus and gimbal in use

Sequential tracking is required with these types of point probe devices. Within the literature reviewed[4,30], although users could describe features of the virtual model, it was unclear if they had a concept of the overall shape and form. Despite researchers' comments that the devices are not expensive, this is subjective, and at well over £1000 for the PHANToM Omni, it is possible that educational establishments would find this prohibitive. As with other interventions, significant prior preparation would be required to provide virtual models.

Other interventions using pointing devices have been explored, such as a tactile display system that raises and vibrates pins[32] and force feedback tablets for recognising shapes[33].

3D printing technology has been utilised to produce tactile models either as full 3D or 2.5-dimensional models (bas-relief)[34,35]. Other uses of 3D prints have been investigated, such as using a 3D print as an overlay that can provide an audio description on a smartphone or tablet[36]. Using tablets coupled to vibrating gloves to "feel" images has been explored[37].

4.2 Data visualization

A central tenet of scientific literacy is the ability to visualise and interpret data in the form of graphs and charts[38,39]. Within this review the existing possibilities to represent data in non-visual form interactions such as audio, sonic and haptic/tactile will be explored, specifically on the representation of numerical or abstract mathematical concepts.

Data analysis is an essential requirement in science and many other professions. Much use of spectra and graphical data is used to portray visually numerical information. In these formats, it is easy to identify trends, spot maxima and minima and drill down to discrete values. Although there are exceptions, screen readers that convert text to speech cannot "read" charts and graphs[40]. Portraying this information for a BVI person is problematic, resulting in the disenfranchisement of screen reader users[41,42,43]. Watanabe and Mizukami found that BVI users that used tactile graphs could identify relationships between two variables quicker than through electronic tables, read by screen readers, or haptic tables[44].

Several low-tech methods have been employed to provide tactile representations of standard data visualisations, such as pie charts, bar charts and line graphs. Pins stuck into cork boards and joined by rubber bands have been used to represent line graphs[31,45,46]. Other methods use heat-raised paper, such as "swell paper". This type of paper can be printed on a standard laser printer. It is then put through a machine that heats the paper. Where there is black ink, it swells and creates a tactile image[47,48]. Watanabe and Mizukami, as noted above, used a braille embosser to produce tactile scatter graphs.

Several projects have used haptic interface devices, such as PHANToM, to provide force feedback. Ramloll & Brewster[49] used primitive line graphs represented as virtual cylinders. These are "read" using the PHANToM force feedback device. The research found that limitations of force feedback, such as the pointer slipping of cylindrical objects, resulted in a distorted perception of the line graphs.

Other researchers have combined force feedback with sonification. Grabowski and Barner[50] evaluated a multimodal visualisation system. They used the PHANToM interface to navigate a tri-mesh surface created from datum points or mathematical functions. Basic sonification was added by assigning the pitch of a sine wave tone to represent the height of the surfaces. They found that the addition of sound in this way was an improvement on solely haptic visualisation. The enhanced orientation created less ambiguity than touch alone. In a similar vein, Ramoll et al.[31] used the Phantom device to investigate a line graph. In this case, two computers were used, one for PHANToM and a second to produce an audio output. y values were represented by pitch and positive and negative x values by the position of the sound within the stereo soundscape. Speech synthesis was also utilised to give exact x and y values. Although this combined sonification and force feedback seems promising, the authors of these studies provided little in the way of evaluation.

Another example of multimodal data visualisation is a “data” glove with vibrating actuators. The glove gives haptic feedback when the fingers touch graphical elements on a touchscreen. The touchscreen also provides an audio output that is attached to graphical elements[37]. This method had some success, especially in allowing BVI users to understand the shapes of the graphics and their relative positions to each other. However, it still requires prior preparation of the accessible graphics[51].

Converting online data to sound can be achieved using text-to-speech screen readers. However, most of these applications will only read out tables of data[43]. As remarked above, data tables are challenging to interpret, whereas, in contrast, graphic forms are easier to understand[42]. However, there has been some progress in this area with the creation of open source software such as VoxLens[52] that can interpret JavaScript visualisations, a data visualisation library for creating basic line and bar charts from data sets, and convert to speech. The audio output allows users to interact with the information and drill down into the discrete values with voice commands. An added feature of VoxLens is to allocate musical notes to data. This approach has been trialled in other research, converting CSV files to midi data[53] and combining haptic pointing devices to produce spatial soundscapes[31]. There are limitations with VoxLens, such as compatibility across browsers and reliance on preprepared Javascript visualisations.

Touchgraphics[54] produces a tablet that allows tactile graphic overlays to be placed on top of the screen. The tablet recognises the overlay by using QR codes. The user can explore the graphic content by pressing down to hear a spoken description.

Although this has much promise, it is currently limited to a small range of in-house produced materials. Price is another factor, with the initial costs around $750 for the tablet and resources at $250 per pack.

4.3 Conclusions

Current research highlights some of the limitations of technology-driven solutions. Haptic graphics can be produced using a range of methods; however, on their own, they are less effective than using multimodal methods. Force feedback is a complex and expensive solution that has not yet been shown to be effective. Most methods require material and graphics to be prepared in advance. With some exceptions, screen readers are unable to interpret graphic content. The most promising multimodal technology appears to be touch screens and graphical overlays. The Touchgraphic system is the most developed but has limited material and no provision for user-generated content. It is also relatively expensive. Tangible circuits[36] has a similar and inexpensive solution but only works with data parsed from a single application.

5. Aims and objectives

A key area of science teaching considered essential is the visual presentation of data[55]. Graphs are abstract spatial representations that illustrate the relationship between variables. Predominantly this is presented in cartesian graphs, where the variables are plotted against orthogonal axes[56,57]. These graphical resources can be inaccessible to blind and visually impaired (BVI) students unless presented in an alternative format. Cahill *et al*. found that blind students particularly found graphical spatial elements such as graphs to be the most challenging[58].

In line with key issues identified in the RNIB Teaching STEM subjects report[59], this research project aims to evaluate the efficacy of a technology-driven intervention to represent graphical data in a non-visual form and allow the BVI user to gain qualitative and quantitative data to draw conclusions.

The objective was to design, develop and construct a working prototype and evaluate effectiveness. A secondary consideration was to do this cost-effectively and explore the feasibility of developing an enterprise project providing affordable devices to other education providers.

As previously stated, graphical data is ubiquitous in science teaching, communicating information visually and highlighting patterns and correlations. The project's focus was to consider a specific task/problem requiring graphical interpretation that an undergraduate BVI student may typically face while studying chemistry. In this case, chromatography. The objectives were to design, build and evaluate a multimodal assistive device enabling a BVI student to interpret chromatogram outputs. Drawing on the literature review findings that many interventions were expensive and required significant preparation; the secondary considerations were to keep the cost of the apparatus low and to produce a workflow that requires limited instructor/teacher preparation.

HPLC and GC overview

Chromatography is an essential part of chemistry teaching. It is the technique used for separating and analysing chemical mixtures. There are two main types, liquid chromatography and gas chromatography.

In liquid chromatography, the analyte, the mixture under analysis, is introduced to a column. The column contains the stationary phase, typically bonded silica. The mobile phase, the solvent, flows through the column. The various components of the analyte have varying degrees of interaction with the stationary phase. This interaction results in different times for the components to pass through the column, also known as retention times.

High-performance liquid chromatography (HPLC) is a common analytical technique. A pump pushes solvent through a column at a high pressure into which a sample is injected. *(fig 2)*

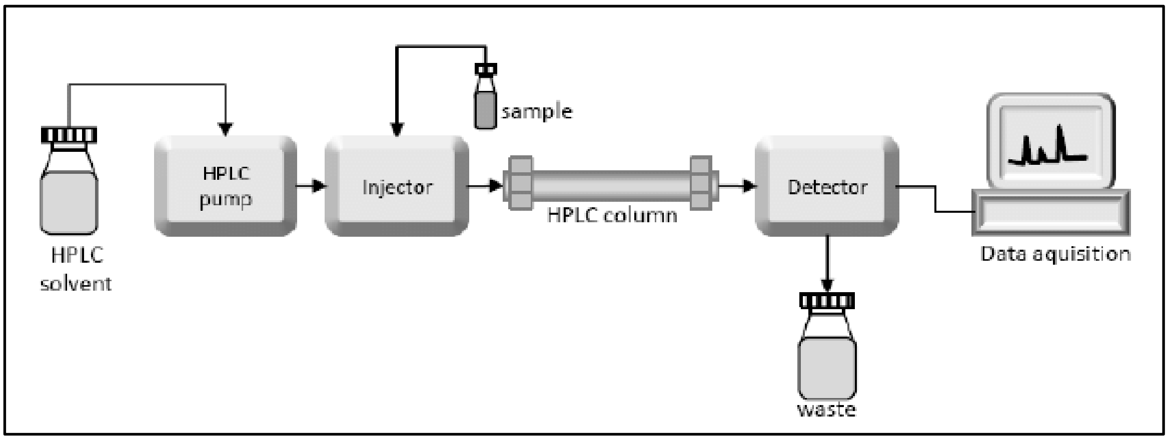


Figure 2 High-performance liquid chromatography (HPLC) description

In gas chromatography (GC), the mobile phase is usually an inert carrier gas such as helium. The stationary phase can be a solid or liquid contained within a separation column. Samples are injected using a syringe. The injector is contained within a heater block. The sample, if not already in the gas phase, vaporises and is passed along with the mobile phase through the stationary phase. *(fig 3)* As with HPLC, retention times for the different components are measured. In addition, both GC and HPLC are frequently connected in tandem to a mass-spectrometer, a technique which gives information on the molecular mass of components.

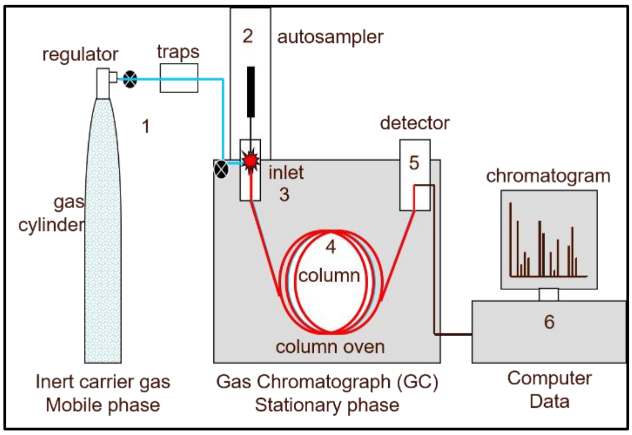


Figure 3 [60] Gas Chromatography description

A chemistry undergraduate would typically study both techniques.

The visual output from the GC and the HPLC instruments is in the form of a chromatogram. The chromatogram is plotted as an x/y graph. Retention time is plotted on the x-axis and intensities or peaks of analytes are on the y – axis. *(fig 4 & 5)*

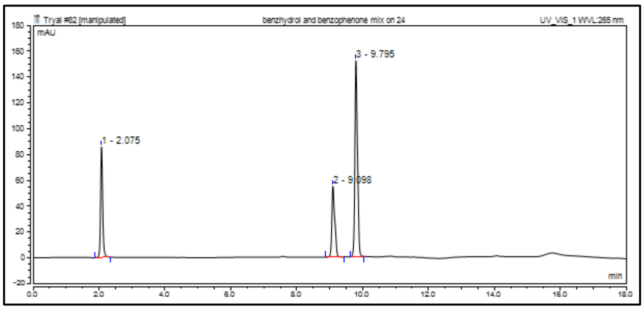


Figure 4 A HPLC chromatogram of two components (benzhydrol and benzophenone)

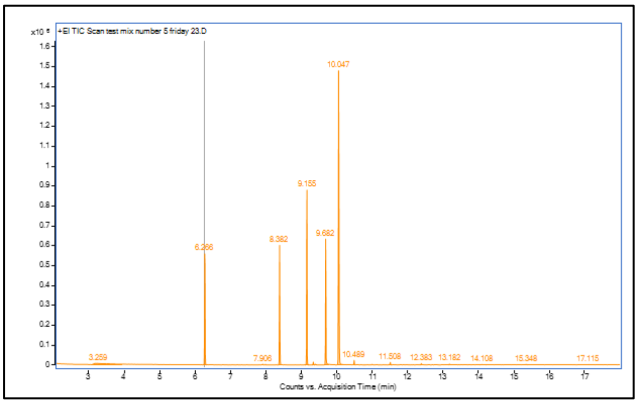


Figure 5 Mass-spectrum from a GC-MS chromatogram of a variety of analytes

Graphical information presented this way is not easily accessible to a BVI student. As noted in the literature review, numerical data presented in this graphical form makes it easy to identify trends, spot maxima and minima and highlight discrete values. The intention was to maintain the efficacy of the graphical information.

As explored in the literature review, there are various ways in which this data could be presented to BVI students. The main finding from the literature is that there are indications that multimodal interfaces are preferred. The interface should combine voice, haptic/tactile and graphics since the participants wanted to interact differently depending on functionality and context.

Ideally, the data needs to be presented holistically, whereby the BVI student can get a sense of the overall detail of the chromatogram and drill down into discrete values.

Different methods to produce comprehensive data in an accessible format, introduced in the literature review, were considered.

6. Design and Development

6.1 Producing the 3D print model

To provide the tactile feedback 3D printing was used to produce chromatograms.

Initially, 3D-printed models were produced by tracing the chromatograms using Rhinoceros Computer-Aided Design (CAD) software. GC and HPLC chromatograms were digitally scanned and imported into Rhino as a background image. The chromatograms were manually traced using the spline and line tools. 3D models were created by extruding the lines. The models were then scaled to a suitable size and exported as a .3mf file for printing. Using Cura 3d print slicer software, 3D print files were prepared and printed in polylactic acid (PLA) using an Ultimaker 2+ 3D printer

Other types of models were investigated. 3D prints were produced using the following methods.

- Solid background with the chromatogram in relief
- Solid background with the chromatogram sunken
- Isolated chromatogram

These are shown in the figures below. Figure 6 illustrates the chromatogram raised above the solid base. Figure 7 shows the chromatogram subtracted from the background material. Figure 8 shows the chromatogram without any base.

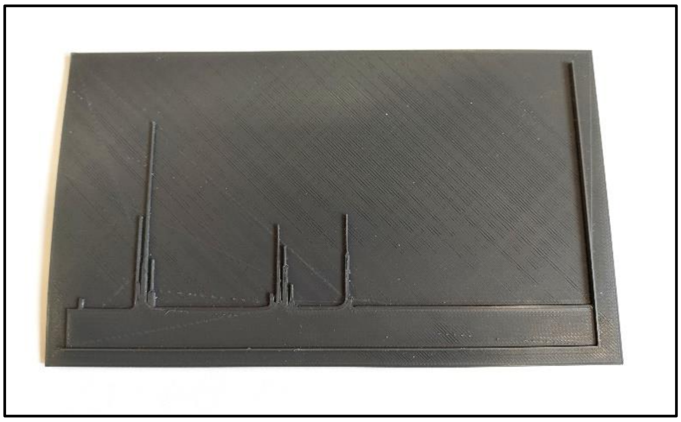


Figure 6 3D print solid background with chromatogram in relief

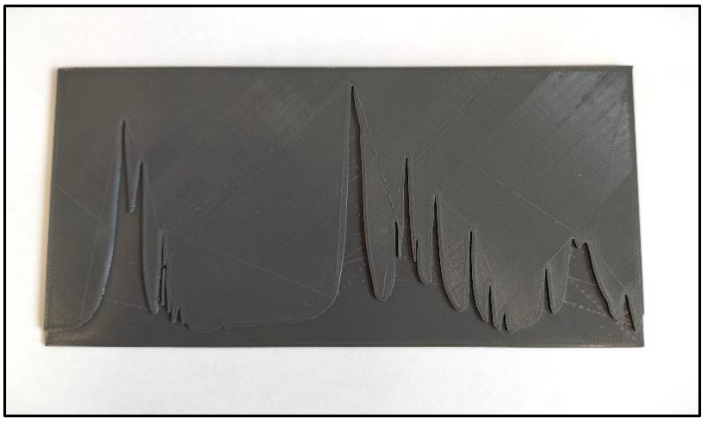


Figure 7 3D print solid background with sunken chromatogram

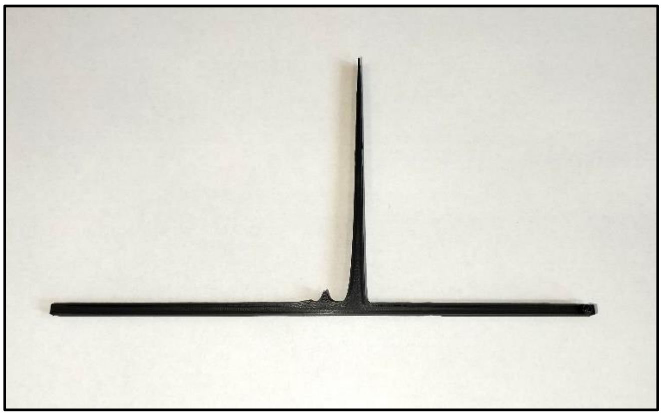


Figure 8 3D print isolated chromatogram

Although all three models had potential, the isolated chromatogram was eventually developed further following the design and testing of the reader. The graph reader required space around the 3D print to trace with a stylus. The chromatograms with solid bases blocked the stylus.

6.2 Design of the chromatogram reader

Having produced a range of 3D prints, attention was turned to designing a device capable of reading the data captured in the 3D print.

Audio output (Labtalk unit)

Audio output was required to read out values from the chromatogram reader. The ubiquitous Arduino open-source electronics platform was used as the basis for the speech synthesis.

The Arduino platform[61] consists of easy-to-use hardware and software. The Arduino hardware is a range of programmable circuit boards (microcontrollers) that breaks down the functions of a microcontroller into an accessible package. The Arduino software (Integrated Development Environment IDE) uses a simplified version of the C++ program language. Using Arduino in a project like this has some significant advantages; it is inexpensive and straightforward to program.

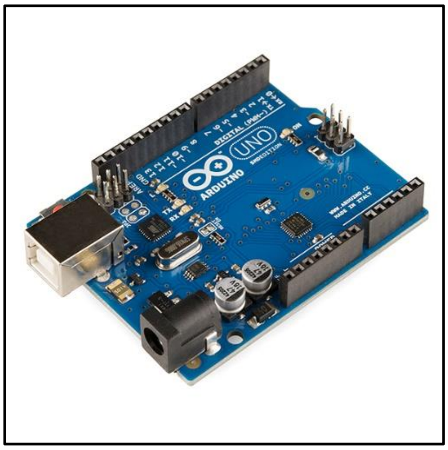


Figure 9 Arduino Uno microcontroller

The "Talkie" speech library for Arduino [62] was used to generate speech. Talkie traces its roots back to the Texas Instruments speech synthesis architecture. Its 100 words of data were adequate for reading out graph data values. Anybody familiar with the "speak and spell" *(fig 10)* range of educational products would recognise the artificial voice. It was also used in other products, such as Atari arcade games.

Figure 10 Speak and spell [63] educational game

The audio output circuit

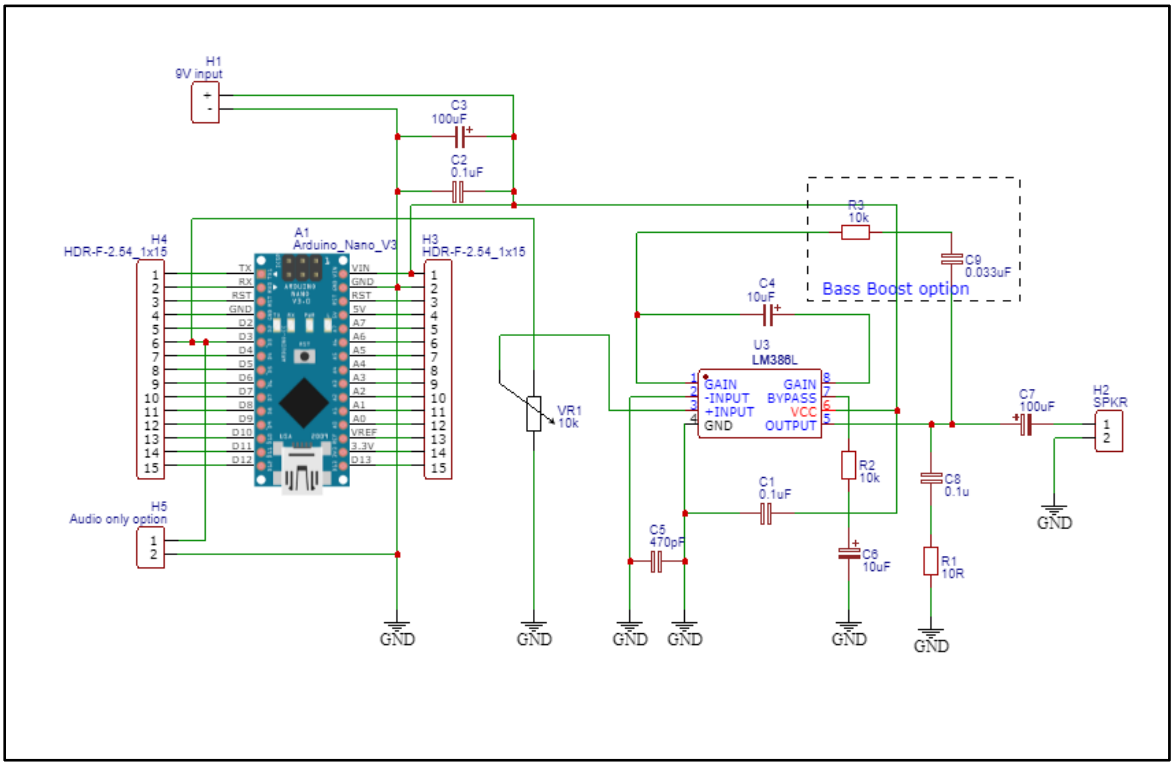
A simple circuit was designed around the Arduino Uno. Initially, a prototype was constructed on a breadboard to test for correct operation. Once the circuit was finalised, a PCB design was created using the online Easy EDA PCB design tool. The Arduino Uno was changed to an Arduino Nano to make the design smaller.

The circuit consists of an Arduino Nano and an LM386 low-voltage power amplifier (see schematic 1). The Texas Instrument LM386 data sheet and web-based resources[64,65] provided a reference audio amplification circuit. This data sheet was used as the basis for the circuit design. The LM386 amplifier is designed for use in low-voltage consumer devices. It's ideal for devices that require battery operation due to its low power drain.

The audio signal from the Arduino pin D3 is connected to pin3 of the amplifier via a 10kΩ potentiometer to control audio volume. The gain of the amplifier is set at 20 within the device; however, with the addition of a 10µF capacitor across pins 1 and 8, this is increased to 200. Capacitor C5 filters out radio interference affecting the input wires. Capacitors C1, C2 and C3 decouple the power supply from the LM386, filtering high and low-frequency noise. Resistor R2 and Capacitor C6 decouple the audio input signal.

The output pin 5 is passed through a “Zobel Network”, essentially a capacitor C8 and resistor R1 creating a filter circuit to adjust the impedance to match an 8Ω speaker. Capacitor C7 is used to remove any DC component from the signal.

A low pass filter consisting of a capacitor and resistor across pins 1 and 5 removes higher frequency noise providing a “bass boost“ at the output.



Schematic 1 Arduino Nano circuit schematic.

Arduino sketch

To test the Labtalk device: the Arduino sketch provided with the talkie library[62] was used and adapted. The Arduino measures the floating voltage levels on pin (5) and outputs as speech.

The test sketch calls the Talkie library and initially sets up the output pin (3), which routes to the amplifier circuit. Pin (3) is used as it allows Pulse Width Modulation (PWM). Because the Arduino does not have a digital-to-analogue converter, PWM is required to convert the digital signal to a pseudo-analogue output.

Varying the duty cycle can provide analogue-like voltages. The voltage is determined by:

PWM voltage = (Duty cycle/256) x 5V

256 is the number of digital 0 and 1 levels available, and 5V is the max available voltage supplied by the Arduino.

```
#include <Arduino.h>
#include "Talkie.h"

int SPKpin = 3; //PWM pin for spk/radio output
const int pinVolt = A5;
int voltageAnalogue = 0;
```

Code snippet 1

When running, the floating voltage is measured on pinA5 and converted to speech through the Talkie *sayNumber* function.

```
void setup()
{
  Serial.begin(9600);

}

void loop(){

  voltageAnalogue = analogRead(pinVolt);
  Serial.print("Voltage = ");  //Print voltage
  Serial.println(voltageAnalogue); // Print value
  delay(1000);
  sayNumber(voltageAnalogue);
```

Code snippet 2

The prototype Labtalk unit

The prototype Labtalk was housed in a 3D-printed enclosure. Adding a 7-Pin DIN socket and a momentary switch allowed the future provision of connections to various devices with a simple change to the circuit. For instance, a pH meter was “hacked” by locating the voltage output proportional to pH. This voltage was then measured and mapped to pH within the code. Labtalk was then able to provide spoken pH readings. *(fig11)*

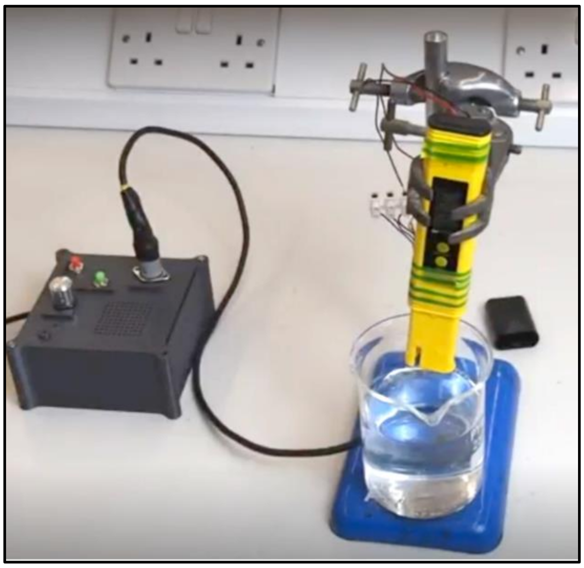


Figure 11 PH Meter with LabTalk unit.

Resistive paper experimentation

The initial ideas for being able to “read” the 3D printed chromatogram were around the use of Teledeltos paper. Teledeltos (Western Union Telegraph Company registered tradename) is an electrically conductive but somewhat resistive, coated paper initially produced for use on chart recorders and fax machines. [66]

It is often used in physics education to plot electrical fields, typically using probes to plot equipotential lines. The paper has isotropic resistivity in all directions. The idea was to measure the electrical potential difference across the x and y directions to plot x and y coordinates. By placing the 3D-printed chromatograph on the paper, points could be plotted anywhere around the object.

Testing

The Teledeltos conductive paper was cut into a square. Metal rules were placed on the left and right edges, leaving 10 cm of paper between them. A 5V supply was connected to the metal rules using croc clips. The voltmeter was connected to the supply ground, and a probe was used to make the connections on the paper. *(fig 12)*

Initial measurements showed the voltage to be roughly linear 0-5V across the paper. Marking in equipotential lines showed deviations in the Y direction rather than the parallel lines expected. Further measurements showed a deviation from a linear voltage across the paper in differing Y positions; it was noted that pressing down on the metal rules so that they pressed firm on the paper changed the readings. Looking closely at the paper, it was obvious that the coating was not homogenous. This was further investigated by taping multimeter probes together to create a fixed distance between the probe tips. This was applied to the paper at various points, showing changes in the resistance of +/- 20KΩ.

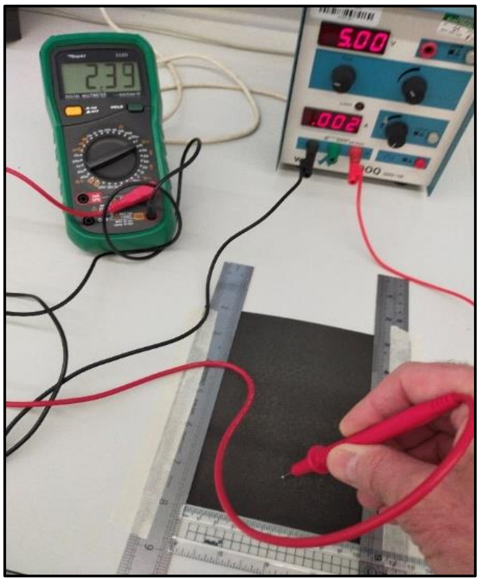


Figure 12 Testing Teledetros paper with voltmeter

Given that Teledetros resistive paper* should exhibit isotropic resistivity in all directions. It can be assumed that the sample was defective.

* *Teledetros paper has a resistance of 6 KΩ/square The reason for "ohms per square" is that a square sheet with a sheet resistance of 6 KΩ/sq has an actual resistance of 6 kΩ regardless of the size of the square.*

Sorting through the Teledeltos paper, a more evenly coated example was chosen. Silver conductive “glue” was applied in vertical strips to the paper on both the x and y axis to improve the connections. The rules were then placed over the silver glue and the circuit connected across the x-axis. Equipotentials were then plotted across the x-axis. This time the lines were parallel and there was no change in voltage when pressure was applied to the metal rules.

The paper was then prepared by painting on the Y axis and square cut-outs on each corner. On testing voltage across the x-axis, it was immediately apparent that the equipotentials were not going to be parallel to the x-axis. *(fig 13)*

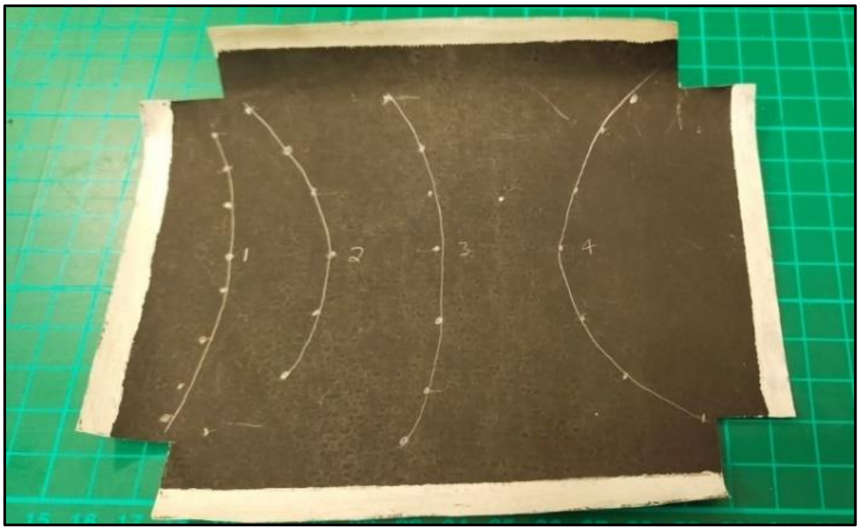


Figure 13 Plotted Equipotential on Teledeltos paper

Resistive paper experimentation part 2

Given that the field lines across the x and y directions were not going to be linear because of the presence of the conductors, a second design was investigated. By cutting the Teledeltos paper into two strips, the x and y potential differences could be examined separately. A simple mechanical system was devised and built to allow a stylus to draw around the 3D print.

5V was initially supplied by a power supply unit (PSU). The voltage was applied vertically across the y-axis strip and horizontally across the x-axis strip. Silver conductive glue was used to coat the paper at the edges. Copper strips were used to connect the conductive glue to the electrical connections.

Using a multimeter probe that could slide vertically up and down within a sliding plastic guide, the voltage in the y direction was read. The probe could also move in the x direction. Using a fixed probe that travelled along the separated Teledeltos paper in parallel with the y probe voltage in the x direction was read. *(fig 14)*

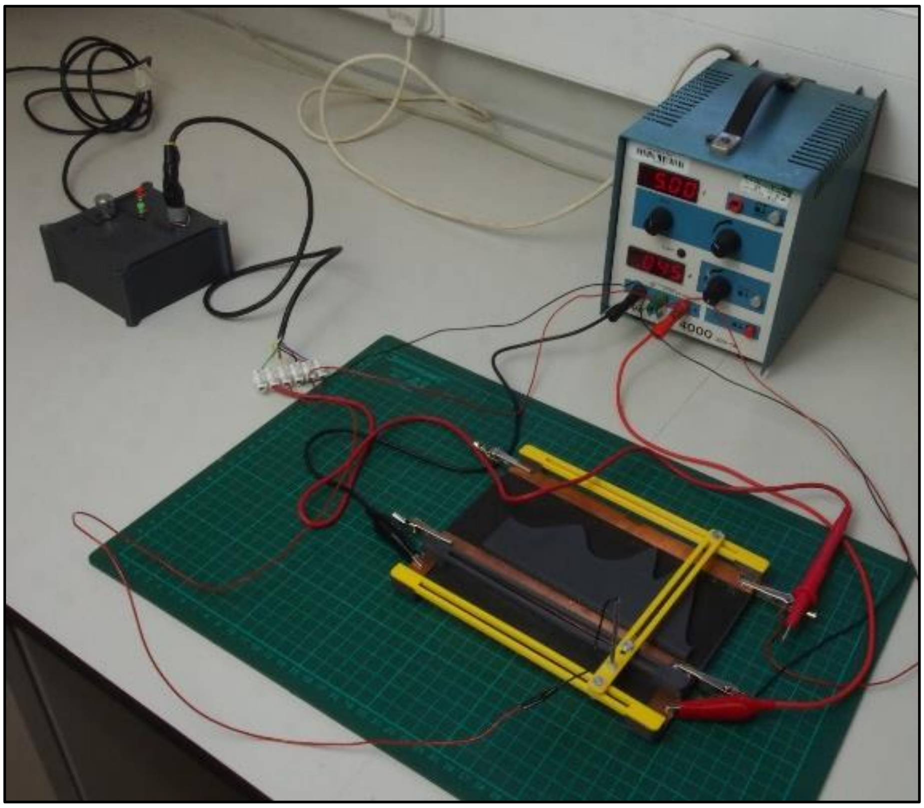


Figure 4 Prototype graph reader connected to power supply and LabTalk unit

Updated Arduino code

The code was adapted so that x and y voltages were read from the A5 and A7 inputs respectively (snippet 3). The momentary pushbuttons were connected to the D9 and D10 inputs. Because the Arduino has a ten-bit analogue to digital converter, it reads the voltage 0-5 into discrete 2^{10} (1024) digital values. The voltage on pins 9 and 10 was measured at 5.015V. Dividing this by 10.24 gives readings in millivolts.

```
int voltageY = analogRead(A5) * 5.015 / 10.24;
int voltageX = analogRead(A7)* 5.015 / 10.24;
```

Code snippet 3- reads x and y voltages.

```
const int buttonPinX = 9; //sets digital pin number
const int buttonPinY = 10; ////sets digital pin number
```

Code snippet 4 – sets up pushbuttons.

Initially, power was supplied by PSU; however, in subsequent tests, the voltage was provided by the Arduino. This was achieved by setting digital pins 2 and 5 to HIGH when the x or y button was pressed (snippet 5). These pins were connected via the DIN lead to the copper strips on the device.

The device was connected to the LabTalk unit via the DIN lead. When the x button was pressed, the voltage was set to HIGH on pin 2 and the *voice.say* command was used to say "x". After a 250ms delay, it then says the x voltage read through the A7 input. Output 2 is then set to LOW again.

```
 buttonStateX = digitalRead (buttonPinX);
 buttonStateY = digitalRead (buttonPinY);
 //Serial.println(buttonStateX);
 //Serial.println(buttonStateY);

 if (buttonStateX == 1)
 {digitalWrite(2, HIGH); // sets the digital pin 2 high
   voice.say(sp2_X);
   delay(250);
   sayNumber(voltageX);
   //voice.say(sp2_MILLI);
   //voice.say(sp2_VOLTS);

   digitalWrite(2, LOW); // sets the digital pin 2 low

 }

if (buttonStateY == 1)
{digitalWrite(5, HIGH); // sets the digital pin 3 high
  voice.say(sp2_Y);
  delay(250);
  sayNumber(voltageY);
  //voice.say(sp2_MILLI);
  //voice.say(sp2_VOLTS);
}
  digitalWrite(5, LOW); // sets the digital pin 3 low

}
```

Code snippet 5 – reading x and y voltages

Although this concept worked, it could have been more robust. It was challenging to move the slider whilst maintaining parallel movement. The multimeter probe gave reliable and consistent readings; however, the sliding x-axis probe did not. The pressure required on the x probe for a reliable connection resulted in marks on the paper that affected subsequent readings.

Because of the problems encountered with the prototype, a more refined and advanced reader was envisaged. CAD software was used to draw the design. The design uses polished steel rods and linear rail slide bearings to provide improved, accurate movement. *(fig 15)*

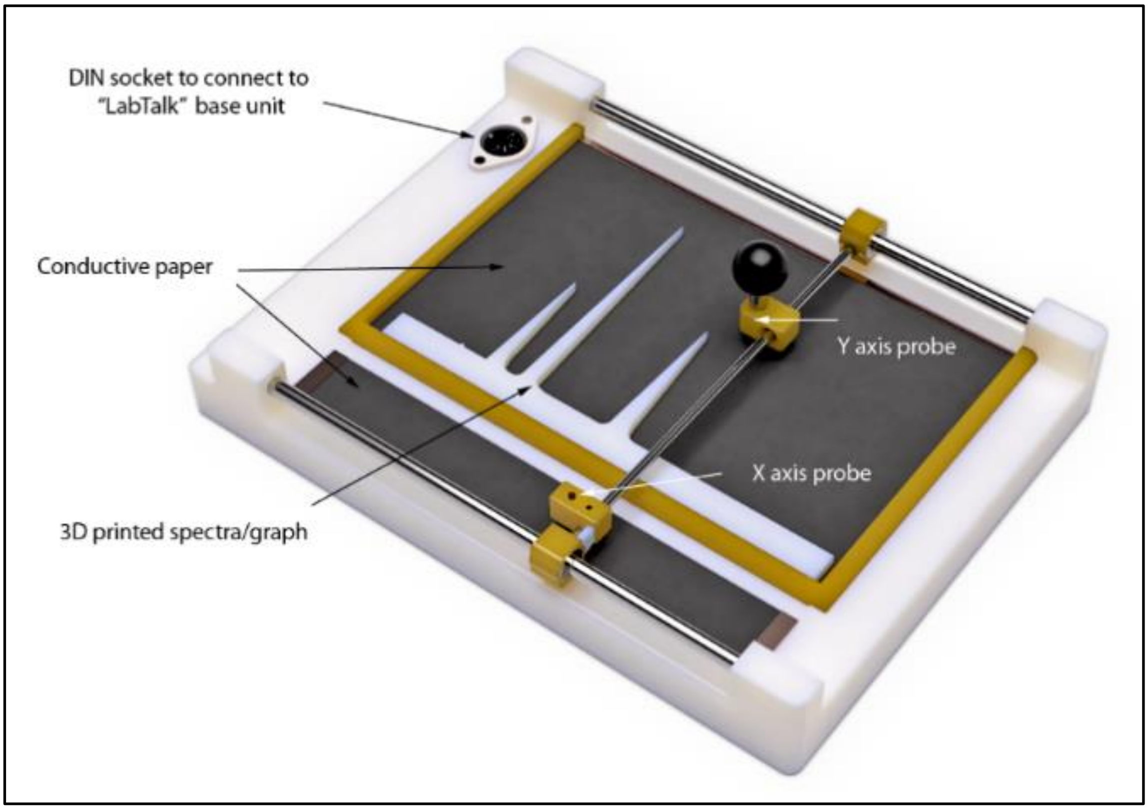


Figure 5 Improved graph reader concept.

The improved design promised better results; however, it was challenging to source Teledetros paper and given the initial problems encountered with the paper's inconsistency and mechanical design's complexity, a more straightforward, less mechanically complex solution was sought. The use of touchscreens to replace the paper was therefore investigated.

6.3 Touchscreen technology

There are four main types of touchscreen technology available, resistive, capacitive, SAW (Surface Acoustic Wave) and IR (Infrared). These are described below with their advantages and disadvantages.

Resistive touchscreen

The resistive touchscreen (see fig16) typically uses a glass panel (5) overlaid with a film screen (1). Both are coated with a thin metallic layer (2). These layers are separated by spacers (3). When the screen is touched, the metallic layers make contact. This change in voltage then detects the touch.

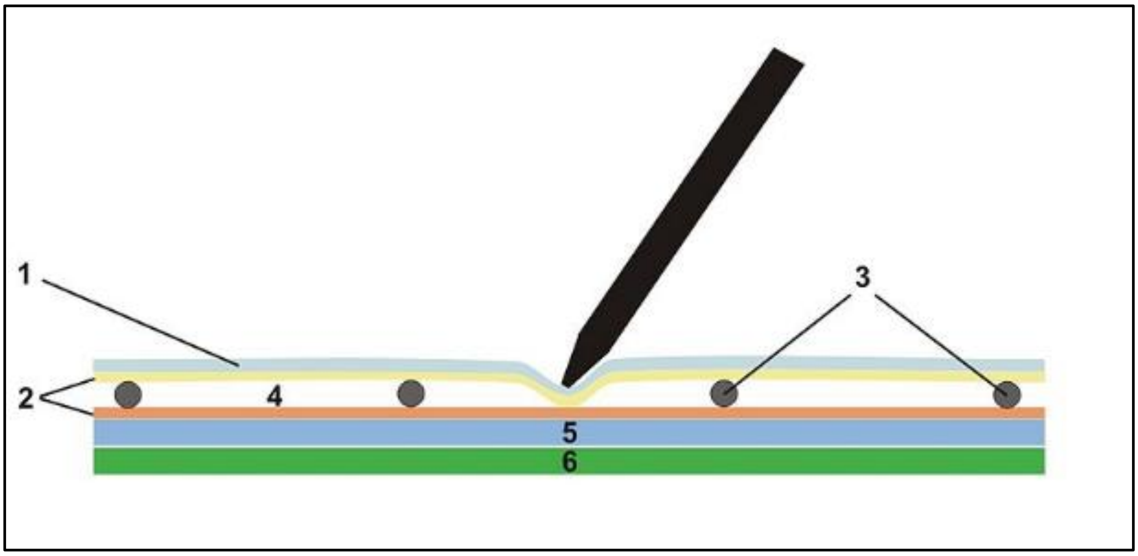


Figure 6[67] resistive touchscreen diagram

Surface capacitive touchscreen

The surface capacitive touchscreen typically consists of a glass panel overlaid with a transparent electrode layer. This layer is covered with a protective cover. When a bare human finger touches the screen, it completes a circuit as some of the electrical charge on the electrode transfer to the finger. Sensors in the corners of the screen detect touch. *(fig 17)* The ratio of the current is measured to determine location. A variation on this is the projected capacitive touchscreen (PCT or PCAP). This allows the user to wear thin gloves in addition to allowing multitouch activation.

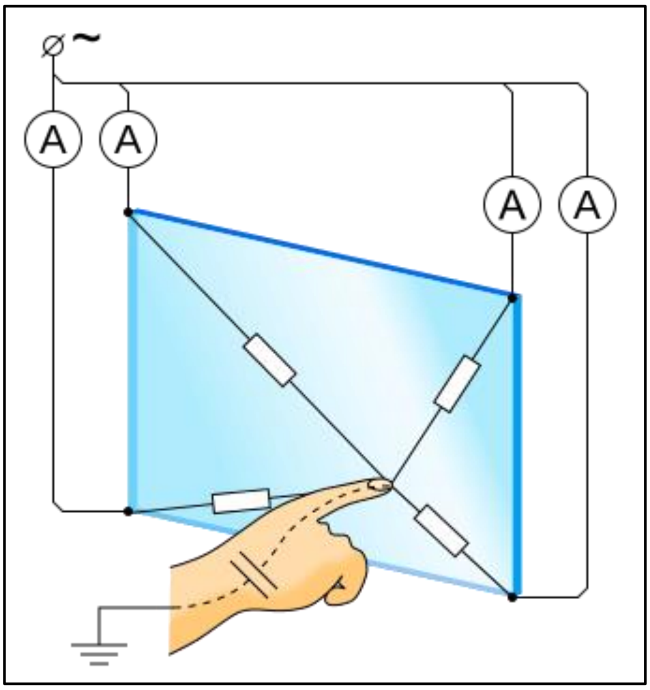


Figure 17 [68] Capacitive touchscreen diagram

Surface acoustic waves (SAW) touchscreen

The SAW touchscreen uses piezoelectric transducers and receivers. It consists of a glass plate with transducers and receivers along the edges. The position of the user's finger is located using a grid of ultrasonic waves as it absorbs the sound wave. *(fig 18)*

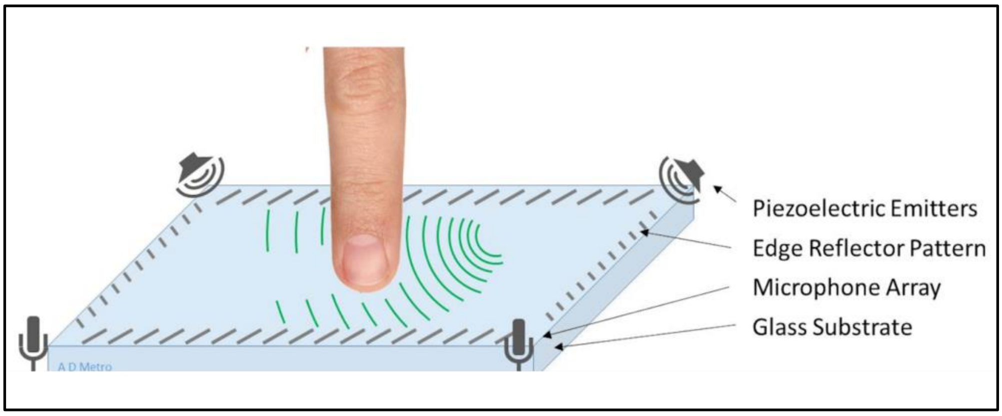


Figure 7 SAW touchscreen diagram

Infrared Touchscreen

The infrared touchscreen makes use of an IR emitter and receiver. The sensors can locate the point through triangulation when a user's finger interrupts the beams. *(fig 19)*

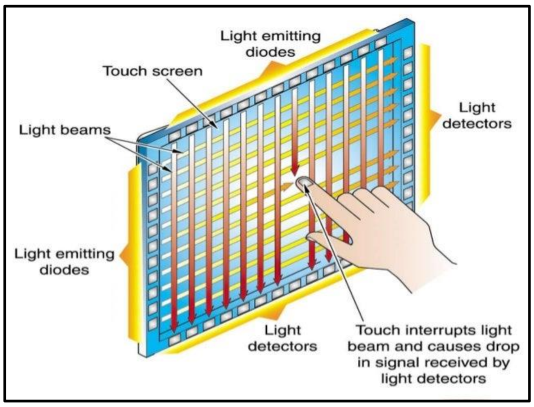


Figure 8 Infrared touchscreen diagram

The advantages and disadvantages were listed in the following table to decide on the touchscreen choice. [69] [70]

Table 1

Type of touch screen	Resistive	Surface Capacitive	Projected Capacitive	SAW	Infrared
Advantages	- Activated by stylus, finger, or gloved hand. -Tactile -Low cost -Low power consumption -Resistant to contaminants	- Good image clarity - Durable - Resistant to contaminants - scratch resistant	- Excellent image clarity - Scratch resistant - Multi-touch - Resistant to contaminants	- Excellent image clarity (better than capacitive) - Scratch resistant	- Highest image quality - Scratch resistant - Multi touch
Disadvantages	-Lower image quality compared to other types -Can be vulnerable to damage	-Requires bare finger or capacitive stylus - Sensitive to EM and RF interference	-Requires bare finger or capacitive stylus - Sensitive to EM and RF interference	- Sensitive to contaminants and water droplets - Will not operate with stylus or hard objects	- Sensitive to contaminants and water - Prone to accidental activation - Sensitive to high ambient light - Higher cost

Touchscreen requirements

Requirements for the touchscreen were defined as follows.

1. It needed to be used with a stylus so that coordinates on the screen could be accurately located.
2. Resistant to contaminants and water because of the lab-based environment.
3. Low cost.

Capacitive screens were rejected because of the need for a capacitive stylus which tend to have a large diameter. The way the SAW and IR screens operate would make them susceptible to interference when the 3D print is placed on the screen and therefore was considered unsuitable.

Because image clarity was not an issue, the chromatogram was going to be placed on top of the screen, and the cost factor and the lab environment it would be operating in, the resistive touchscreen was identified as most suitable.

The resistive touchscreen

A four-wire analogue resistive touch screen was used for testing. *(fig 20)* Two wires are connected to buss bars on the top resistive coating and the other two on the bottom. Pin 4 is set to +5V and Pin 2 to GND to capture the x position. Pin 3 reads the voltage. Pin 1 is set to +5V and Pin 3 to GND to capture the y position. Pin 2 reads the voltage.

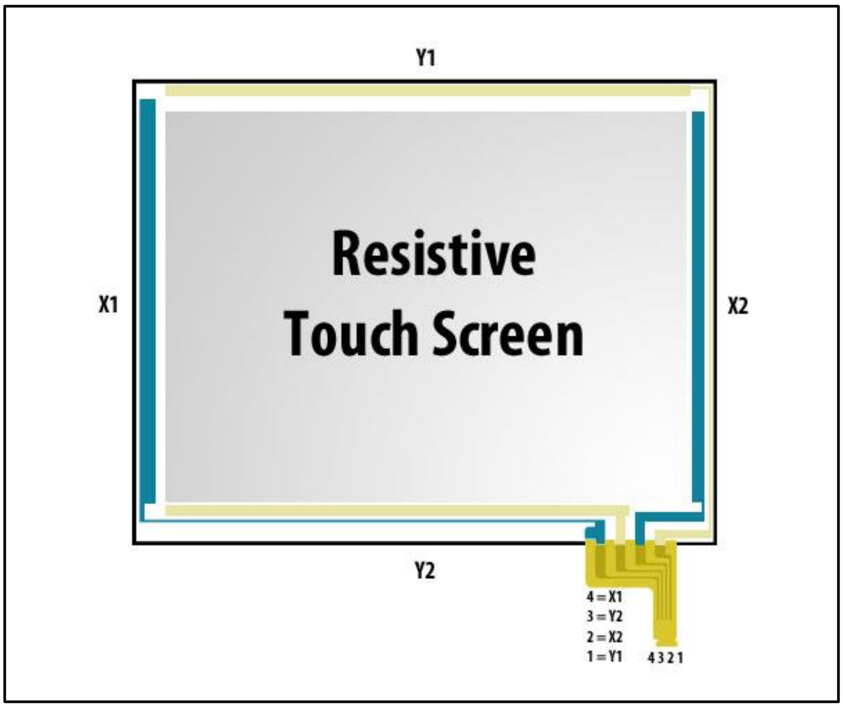
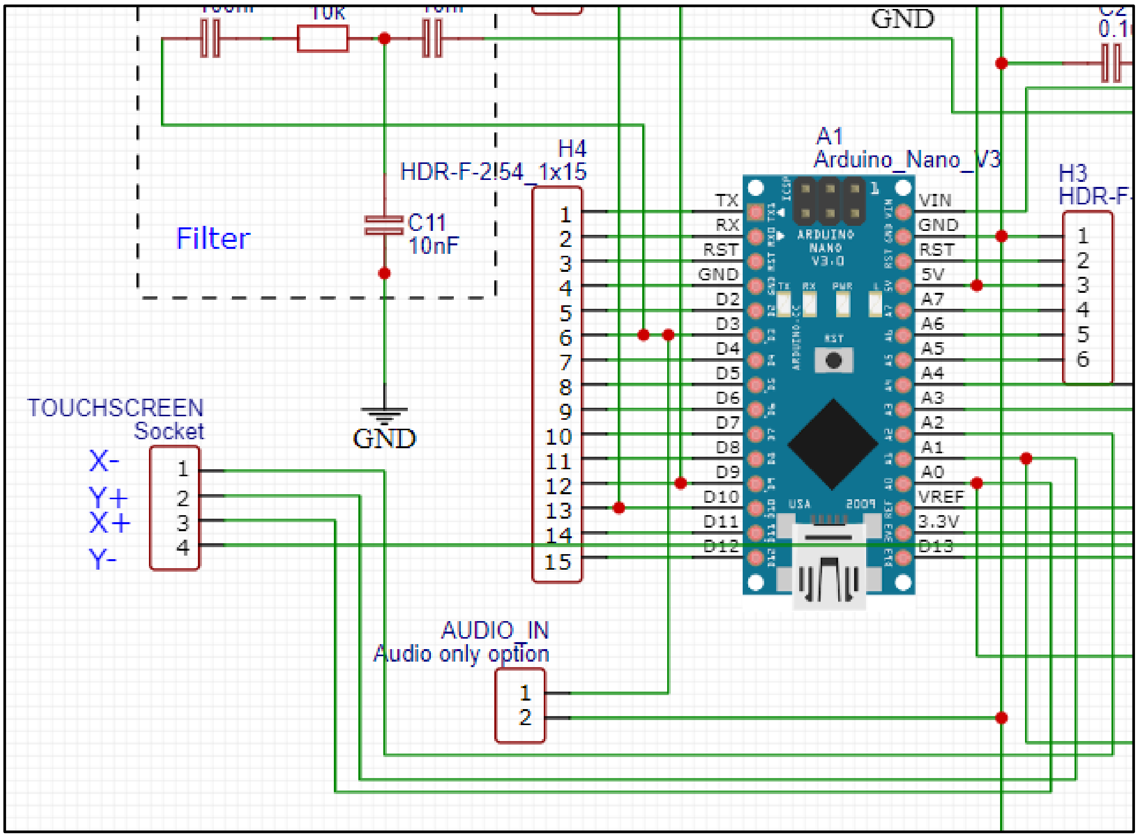


Figure 20 Resistive touchscreen layout and connections

The updated circuit diagram (Schematic 2) shows the connections to resistive touchscreen from an Arduino Nano.



Schematic 2 – touchscreen connection schematic

Arduino sketch

A simple sketch was used to test the touchscreen.

```
#define Xin A0
#define Yin A1
#define Xout A2
#define Yout A3

void setup()
{
  pinMode(Xin, INPUT);
  pinMode(Yin, INPUT);
  pinMode(Xout, INPUT);
  pinMode(Yout, INPUT);


  Serial.begin(9600);
}
```

Code snippet 6 – defines touchscreen connections.

First the analogue input/outputs are defined, and all initially set as inputs. The code then reads x values by setting the Y in/out to outputs and Yin(A1) to low and Yout(A3) to high. This makes pin 2 low and pin 4 high. The value is then read from Xin(A0) which is connected to pin 3. To read y values, Xin/out are set to outputs, then Xin(A0) is set to low and Xout(A2) to high. This makes pin 3 low and pin 1 high. The Y value is read from Yin (A1) which is connected to pin 2. The values are then output using the print function.

```
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Read X
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

pinMode(Yin, OUTPUT);
pinMode(Yout, OUTPUT);
digitalWrite(Yin, LOW);
digitalWrite(Yout, HIGH);
delay(100); // Pause for power up
readX = analogRead(Xin); // Read X
digitalWrite(Yout, LOW); //reset
delay(100); // Pause for power down
pinMode(Yin, INPUT);
pinMode(Yout, INPUT);

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Read Y
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

pinMode(Xin, OUTPUT);
pinMode(Xout, OUTPUT);
digitalWrite(Xin, LOW);
digitalWrite(Xout, HIGH);
delay(100); // Pause for power up
readY = analogRead(Yin);     // Read Y
digitalWrite(Xout, LOW); //reset
delay(100); // Pause for power down
pinMode(Xin, INPUT);
pinMode(Xout, INPUT);

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Output values
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Serial.print(ReadX);
Serial.print("\t");
Serial.println(ReadY);
```

Code snippet 7 – reads x, y coordinates.

Calibration of touchscreen

Due to manufacturing imperfections a touchscreen requires calibrating before use. The quadrilateral method of correction was used[71].

The sketch above was used to read the voltages. Several readings were taken for coordinates at each corner of the screen and the averages were plotted in an excel spreadsheet. *(fig 21)*

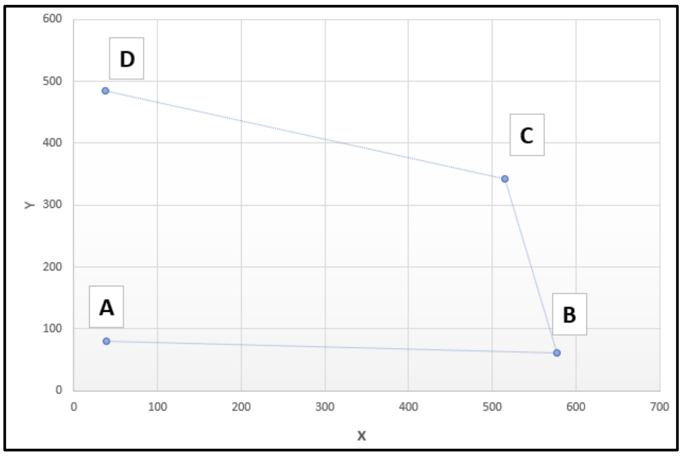


Figure 21 screen corner coordinates

The coordinates when plotted are not square. To calibrate, linear (y =mx +C) functions for the x and y line graphs were calculated.

For the Y axis;

The gradient of AB is calculated.

AB = (80-61)/(578-38) = -0.036

The intercept (offset) is calculated

So C = y -mx

Offset AB = 80 – (38 x – 0.036) = 81.22

The slope of CD is calculated.

CD = (343-485)/(515-38) = -0.299

Offset CD = 485 – (38 x –0.299) = 496.35

A third function is calculated to find the vertical distance between the AB and CD.

Slope CD – Slope AB = -0.036 - 0.299 = - 0.263

The offset is calculated.

Offset CD – Offset AB = 415.12

This gives two functions:

f1(x) = -0.036 x + 81.22

f2(x) = -0.2631 x 415.12

These are then used to correct the Y axis

Y corrected = Y measurement – f1(x) / f2(x)

The same method is then applied to find the X correction

X corrected = X measurement – f1(y) / f2(y)

Arduino sketch

The values required for the correction were calculated in an excel spreadsheet. Within the code they are labelled *slopeA – D* and *offsetA –D*. The actual touchscreen measurements were included as scrX and scrY.

```
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
//Calibration factors (from excel spreadsheet) after running calibration sketch
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
const float  slopeA = -0.035506094;
const float  offsetA = 81.22159134;
const float  slopeB = -0.263055057;
const float  offsetB = 415.1237324;
const float  slopeC = -0.001057828;
const float  offsetC = 38.51304654;
const float  slopeD = -0.222346427;
const float  offsetD = 552.6222118;
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Enter physical screen size here
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
const int scrX = 150; //Screen x measurement in mm used to scale x direction
const int scrY = 85; //Screen y measurement in mm used to scale y direction
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

Code snippet 8 - calibration corrections

The method described above formed the basis of the calibration function within the code. At this point the screen size is also factored in. This generates the correction factors, *correctX* and *correctY.*

```
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
//Calibration function
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

float correctX(int measuredX, int measuredY)
{
  float correctedX;
  float temp;

  temp = (slopeC * measuredY) + offsetC;
  correctedX = measuredX - temp;
  temp = (slopeD * measuredY) + offsetD;
  correctedX = correctedX / temp;
  correctedX = correctedX * scrX;

  return correctedX;
}
float correctY(int measuredX, int measuredY)
{
  float correctedY;
  float temp;

  temp = (slopeA * measuredX) + offsetA;
  correctedY = measuredY - temp;
  temp = (slopeB * measuredX) + offsetB;
  correctedY = correctedY / temp;
  correctedY = correctedY * scrY;

  return correctedY;

```

Code snippet 9

Touchscreen testing

The touchscreen was initially connected to the (Lab Talk) unit using the DIN connector with an Arduino UNO used to control the touchscreen.

To check the accuracy of the screen, a calibration print *(fig 23)* was used. The print measurements were checked using a vernier calliper and written on the model for convenience. A stylus was placed on the screen against the edge of each step corner. The x and y-axis readings were taken. The readings were repeated 10 times. *(fig 24)*

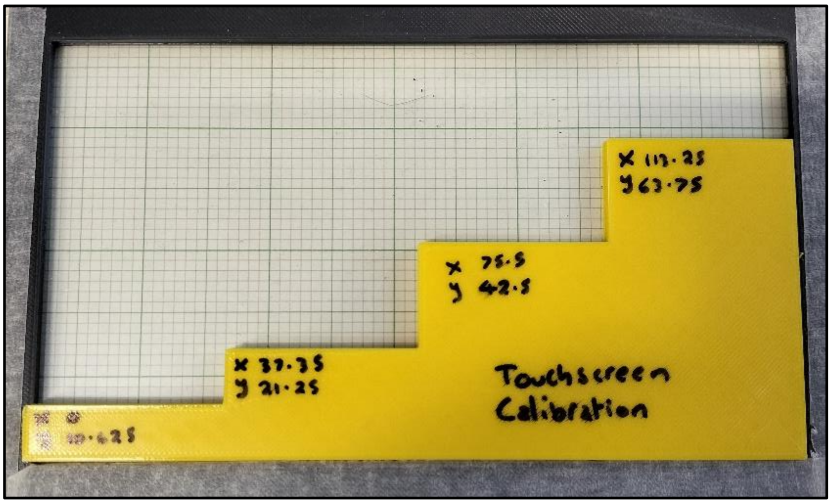


Figure 23 touchscreen calibration

The average error in the touchscreen readings was –2.00mm +/-0.5mm

The error was more significant in the x direction (-4.00mm) than in the y (1.0mm)

The size of the stylus point contributed to the position error. The point measured 0.5mm, so every time a measurement was made, it was displaced by +0.5mm in each axis. More accurate results were obtained by subtracting this value.

In addition, there was a taper on the point that made it challenging to locate the stylus close to the edge of the calibration print.

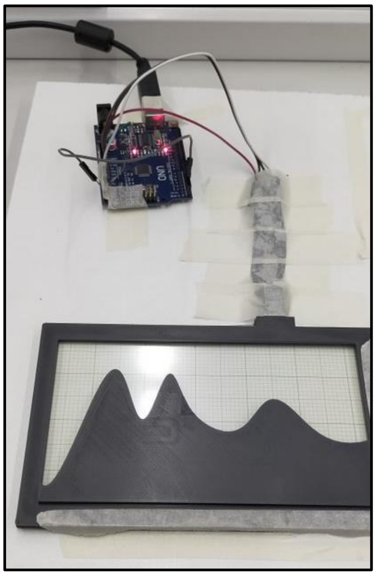


Figure 9 Screen used in initial testing

The code was adapted by including the earlier sketch for synthesised voice output. Various 3D graphical prints were used for testing and a stylus was used to trace around the graphs.

The initial code outputted a continuous stream of data which made the spoken values hard to follow, so code was developed that took a reading on the detection of any pressure on the screen. However, in practice, this gave erroneous readings whilst positioning the stylus, for instance, on peaks of the graphs.

X and Y momentary switches were installed and the code was adapted so that it only gave a reading on pressing either of these axis button.

Audio performance was poor, with audible clicks and pops. Literature[62] suggested that a low pass filter could be incorporated to remove these.

A low pass filter was added to the audio circuit to clean up the audio output. With talkie imitating a male voice, the fundamental vocal frequency range is between 80-180 Hz. However, harmonics are audible above this. Using a 10k resistor and a 10nF capacitor gave approximately a 1.6kHz cut-off. (Fc = 1/2PIRc) On testing, this removed most of the clicks and pops whilst not affecting the voice.

6.4 Graph reader design

Following testing, an improved prototype graph reader was designed. The circuit schematic contains everything needed to control the touchscreen, provide the audio output and include the filter circuit. The schematic was then used to produce a PCB using EasyEDA, an online PCB design tool.

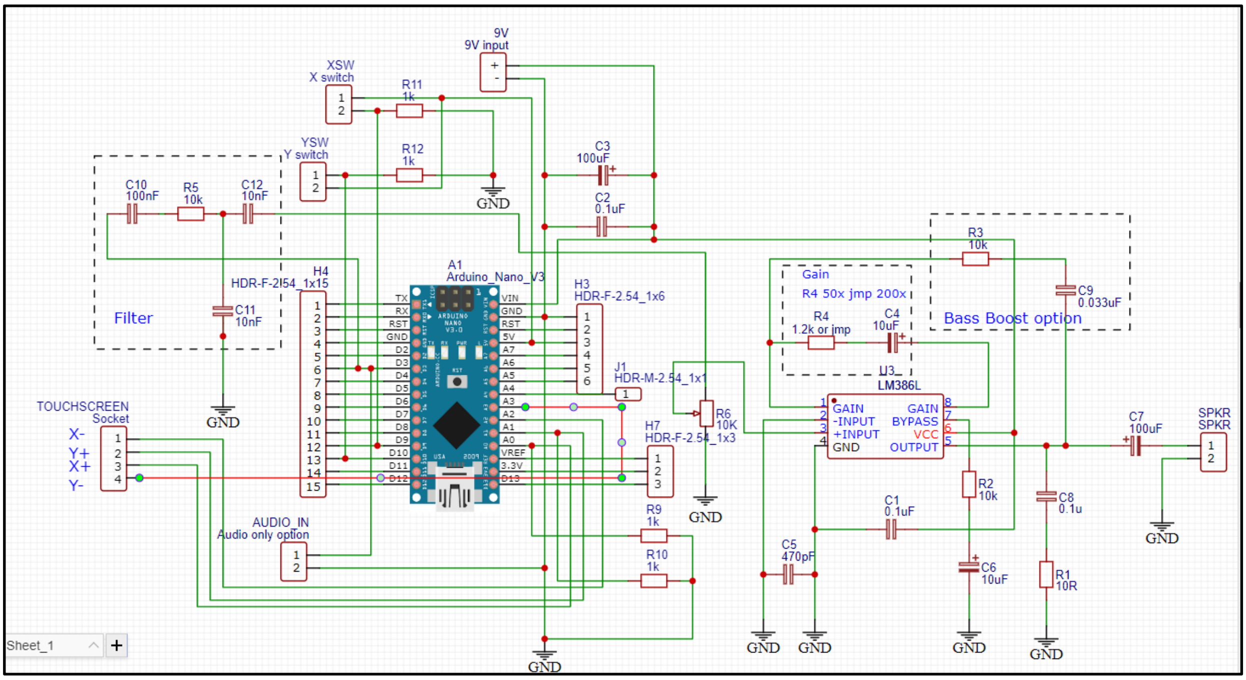


Figure 10 prototype circuit schematic

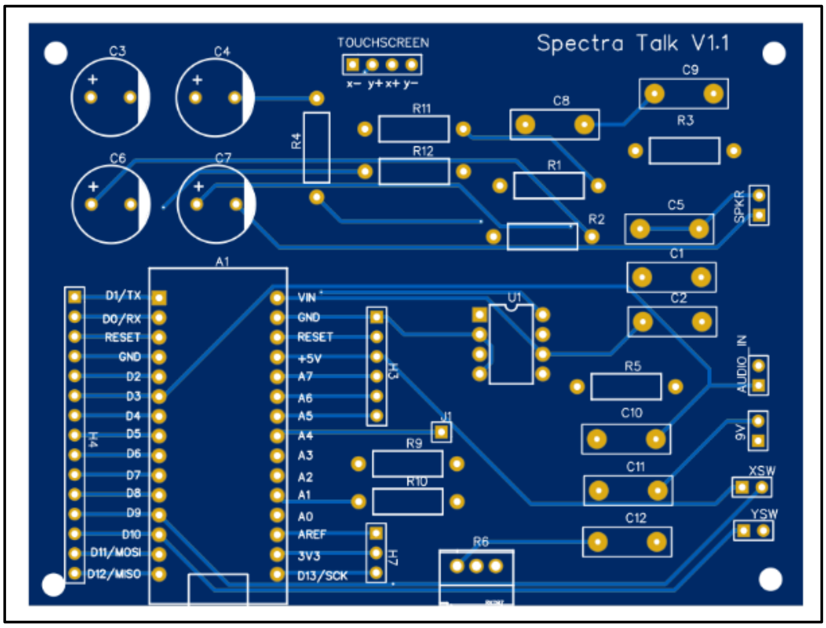


Figure 26 PCB layout

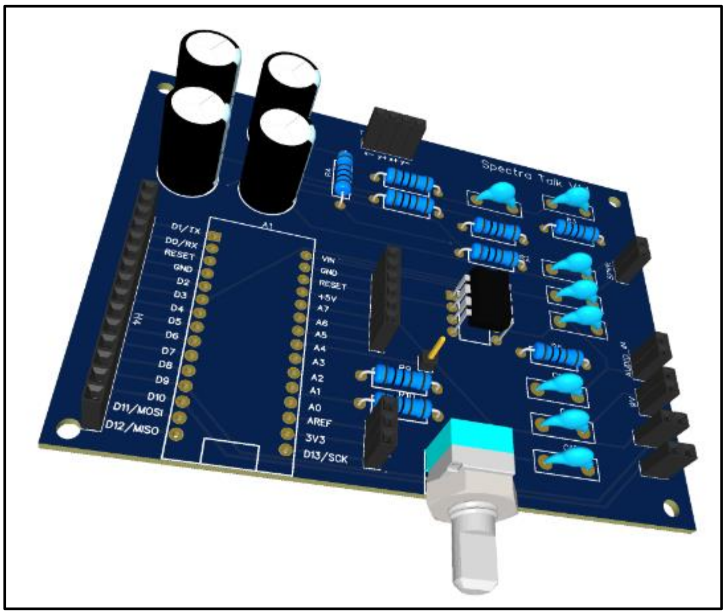


Figure 11 Circuit board layout

A casing was designed, and 3D printed. It houses the screen in a recess and incorporates the x,y buttons, volume control and USB connection.

Figure 12 Prototype graph reader

6.5 Improved method for rapidly producing an accurate 3D print model

Although the tracing method described earlier produced a perfectly usable 3D print, tracing around the chromatogram to match the curves accurately was time-consuming.

The Rhinoceros CAD software package contains the “Grasshopper” plugin. Grasshopper is a visual programming language primarily used for creating generative algorithms. Definition files, a set of automation instructions and rules for Rhino, were created to investigate different methods of creating a 3D print from a scanned chromatogram. Different methods were trialled.

A Grasshopper definition file was created that imported an image file and then used the image sample component to create 3-dimensional geometry. *(fig 29)* This created a “bas relief” model. Although usable as a tactile representation of the chromatogram, it was not possible to use this method to create an isolated chromatogram suitable for use with the graph reader. *(fig 30)*

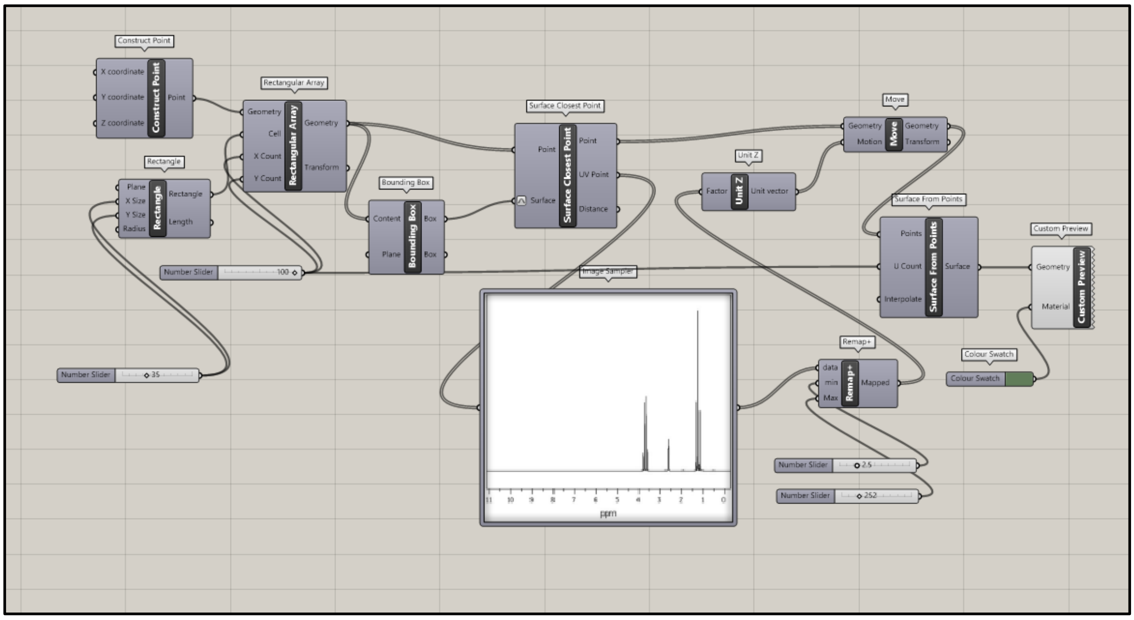


Figure 13 Rhino definition for image sampling

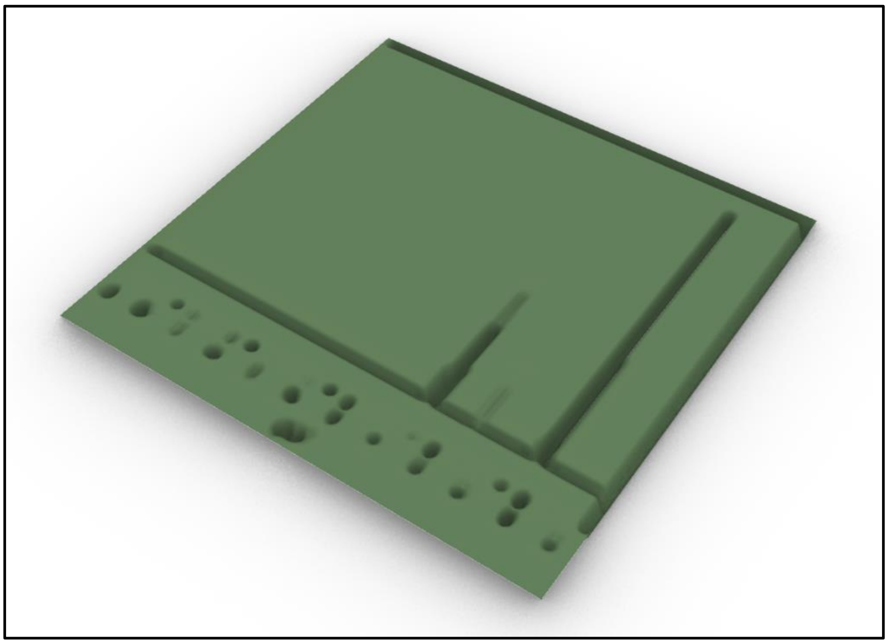


Figure 30 3D geometry for image sampling

Another method used live webcam capture. This gave similar results to the image import, with added immediacy benefit. Although there may be some applications that would benefit from this approach, the 3D print could not be read with the graph reader. *(fig 31 & 32)*

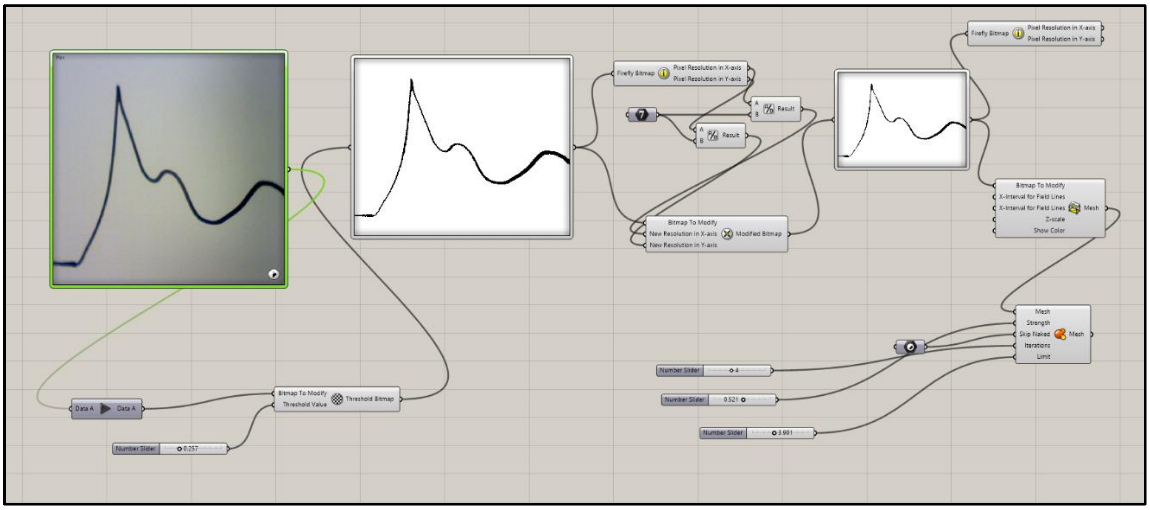


Figure 31 Definition for web cam capture

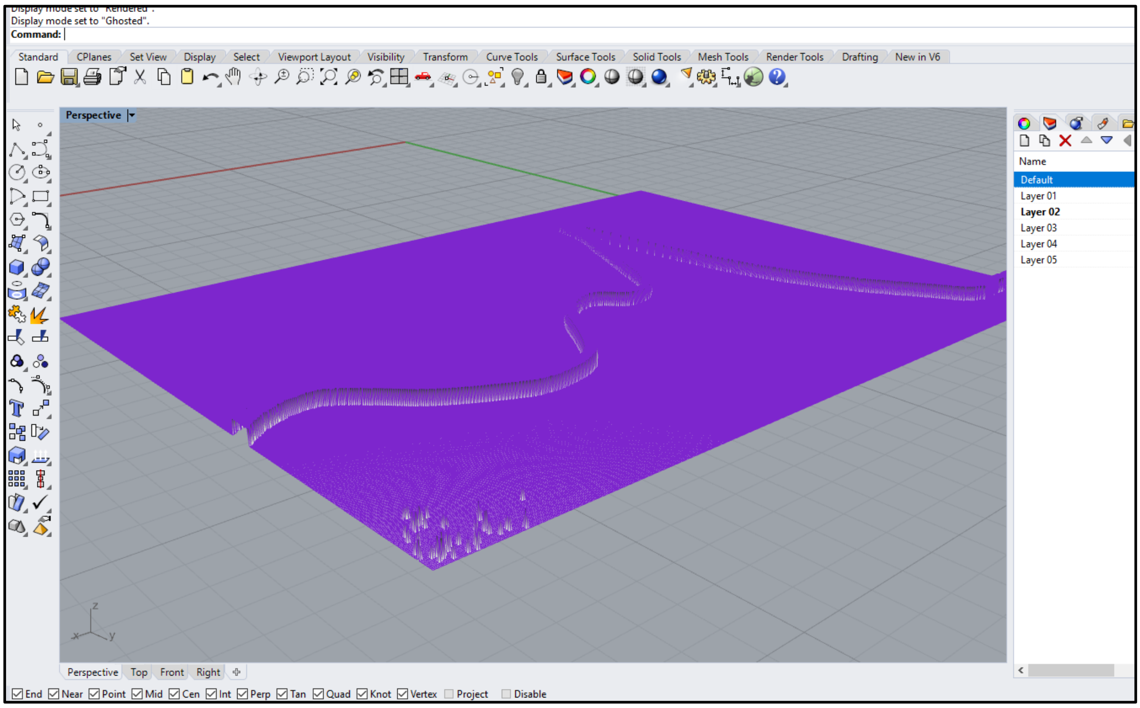


Figure 32 3D geometry for web cam capture

Importing data to Grasshopper

One of the available options is the ability to import excel spreadsheets. Both the HPLC instruments and the GC instrument could export the chromatogram data as a raw text file which could then be imported into excel to create the correct file type for Grasshopper to use.

A grasshopper definition was developed that took in the excel spreadsheet and created a 3D model ready to export for printing. This workflow was found to be the most efficient method of producing a 3D model of HPLC/GC data

Explanation of Grasshopper model

Spreadsheet setup

To create a model, the excel spreadsheet required some adjustments.

1. Two additional worksheets were created for the file. The sheets are labelled 1,2 and 3 accordingly.
2. In worksheet 2, the max and min excel functions were used to extract the extent of the x data. These were placed in the A1 and B1 cells.

3. In worksheet 1, the first and the last y data points were overwritten with a 4-5% lower value than the max value. This increased value created a thickened baseline so that the chromatogram prints correctly.
4. In worksheet 3, the min values were extracted from the previously entered data and placed in the B1 cell.
5. In worksheet 3, instead of the max value, a value was calculated that was 10% higher than the y max and placed in the A1 cell. The reason for this will be explained and become apparent later.

The grasshopper definition

Figure 33 below shows the complete grasshopper definition.

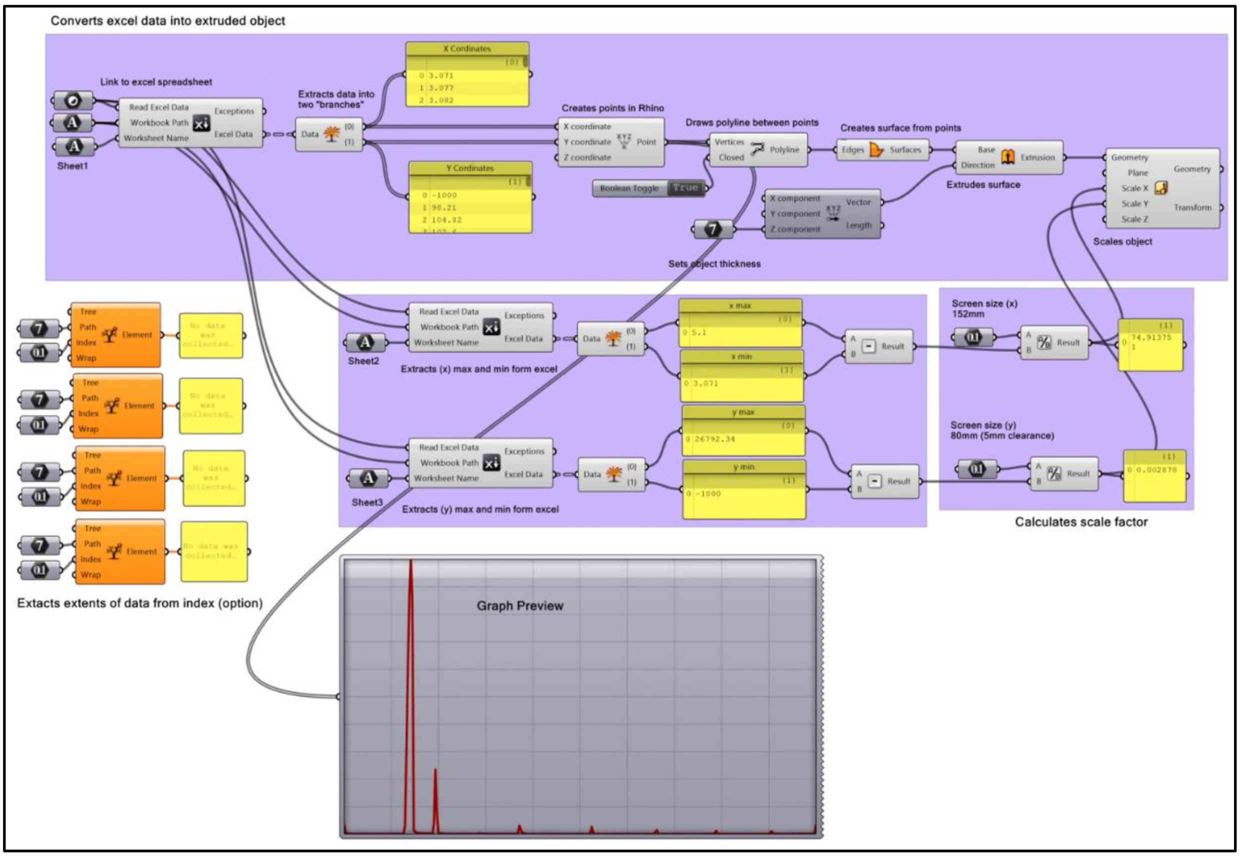


Figure 33 complete Grasshopper definition

Explanation of definition

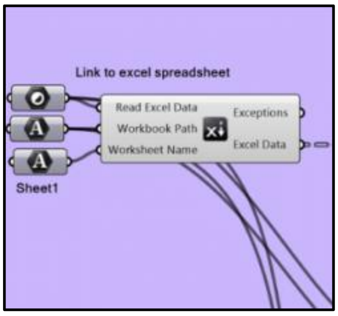


Figure 144 Grasshopper excel reader component

1. The **excel reader** component links to the spreadsheet file. Given the workbook path and the worksheet name, it extracts the data. (fig 34)

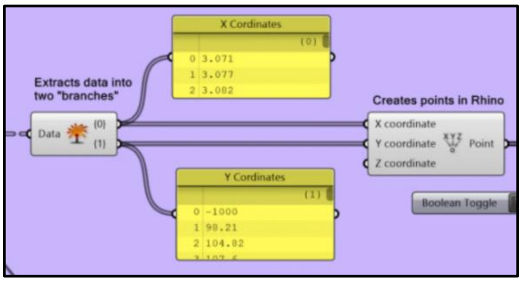


Figure 15 Grasshopper explode tree

2. The explode tree component splits the data into two branches (x and y coordinates). This data is then sent to the construct point component creating discrete points for every pair of x and y coordinates. *(fig 35)*

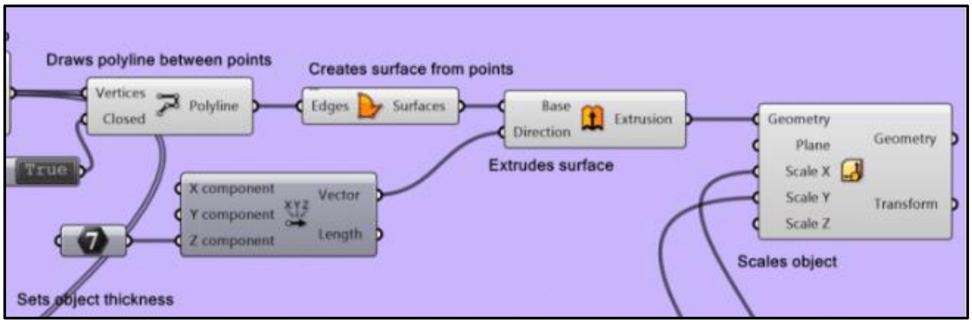


Figure 16 Grasshopper polyline and scaling

3. The polyline component constructs a line through the points. These lines are then used to construct a surface which is then extruded. The Z component input of the

vector component sets the thickness of this extrusion. In this case, set to 7 (7mm), which is fed to the geometry component. *(fig 36)*

At this point, a 3D object is created. However, this still requires scaling to a "real-world" size.

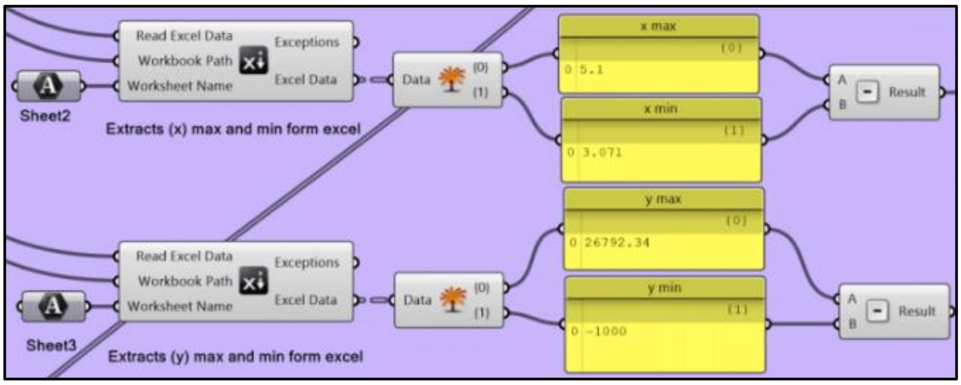


Figure 17 x and y max and min values

4. The x and y max and min data set up earlier is read from the relevant worksheet and extracted into data trees. The max and min values are then subtracted from each other. *(fig 37)*

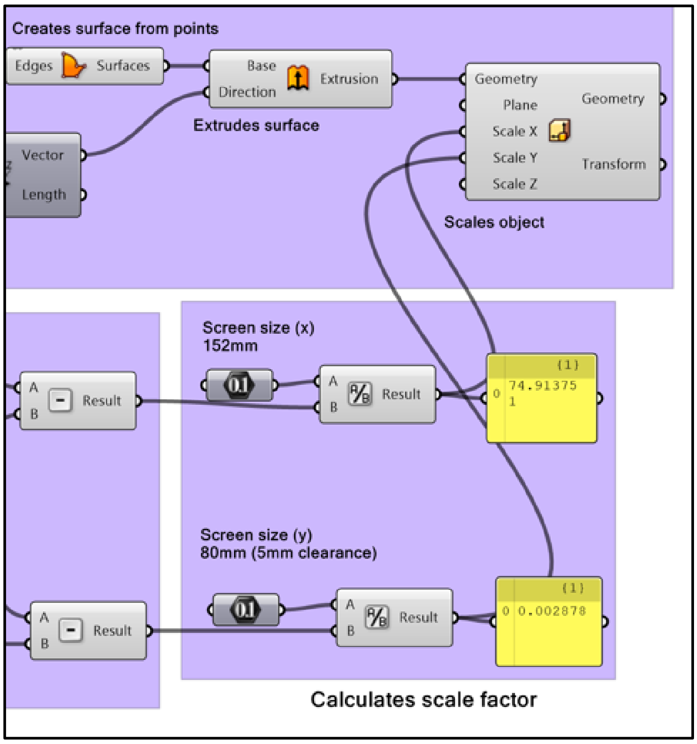


Figure 18 Scale factor calculation

Finally, a division component divides the screen size by the result of the subtraction component providing a scaling value. This value is fed to the geometry component, which scales the chromatogram. *(fig 38)*

Figure 39 below shows the Rhino preview of the completed chromatogram.

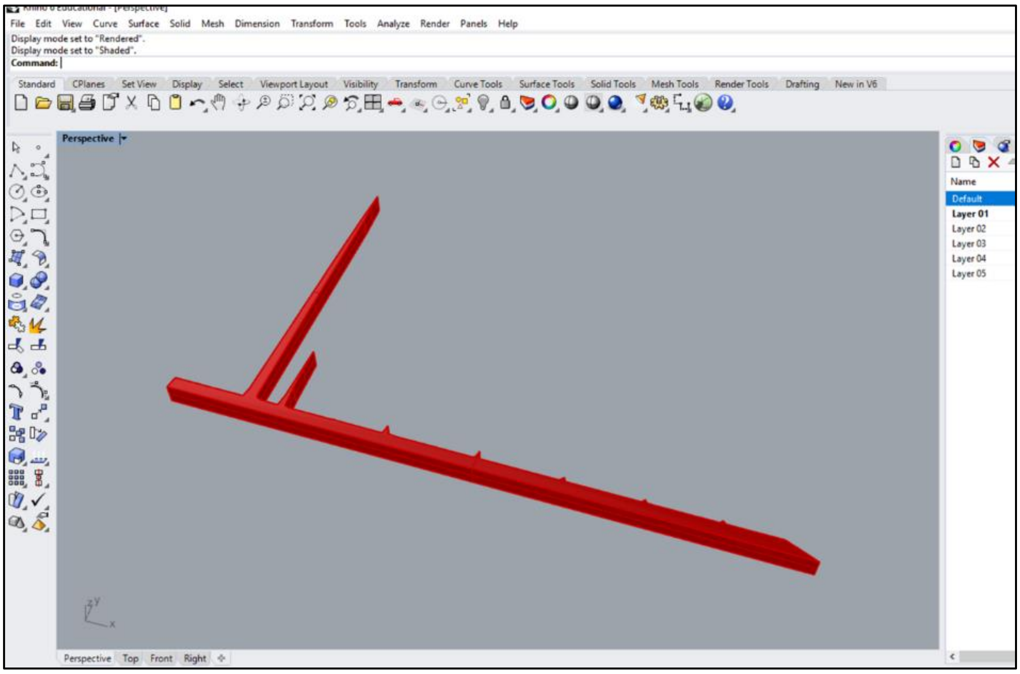


Figure 39 Rhino screenshot showing geometry ready for printing

Updated Arduino code

The Arduino code was adapted to set Graph reader to read the Grasshopper-produced models. Maximum and minimum values for x and y were set up.

```
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Set this to graph/spectra x,y ranges (data from Grasshopper max/min)
// ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
const float maxScaleX = 12.00; // max X value
const float minScaleX = 6.00; // min X value
const float maxScaleY = 3000; //max Y value
const float minScaleY = -100; // min Y value

```

Code snippet 10

These were applied when the correct x and y values were mapped to the screen size. The final piece of code then extracts the integer and fractional part of the result. These are required so that spoken output is (integer) “point” (fractional part) (units).

```
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Apply calibration to X
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
X = correctX(readX, readY);
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// maps readings to graph scale
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
mapX = mapf(X, 0, scrX, minScaleX, maxScaleX); //maps X corrected screen reading  to graph scale

int mapXi = mapX; //extracts integer
int pointX = abs((mapX - mapXi) * 100); //extracts fractional part
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
//Speech output
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
sayNumber(mapXi);
delay(250);
voice.say(sp2_POINT);
delay(250);
sayNumber(pointX);
delay(250);
voice.say(sp2_MINUTES);
//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

Code snippet 11

6.6 Workflow overview

Figure 40 & 41 show the workflow from CSV file to completed print. At this point, the time to complete the process is dominated by the time to 3D print the chromatogram. In testing, this was generally found to take between 1- 1:30 hours.

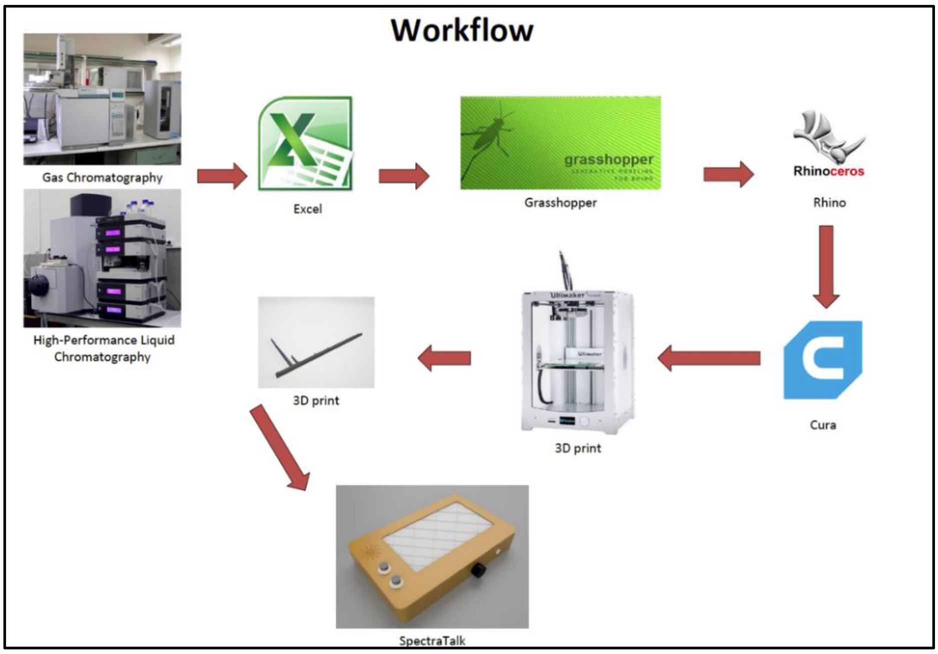


Figure 40 Workflow

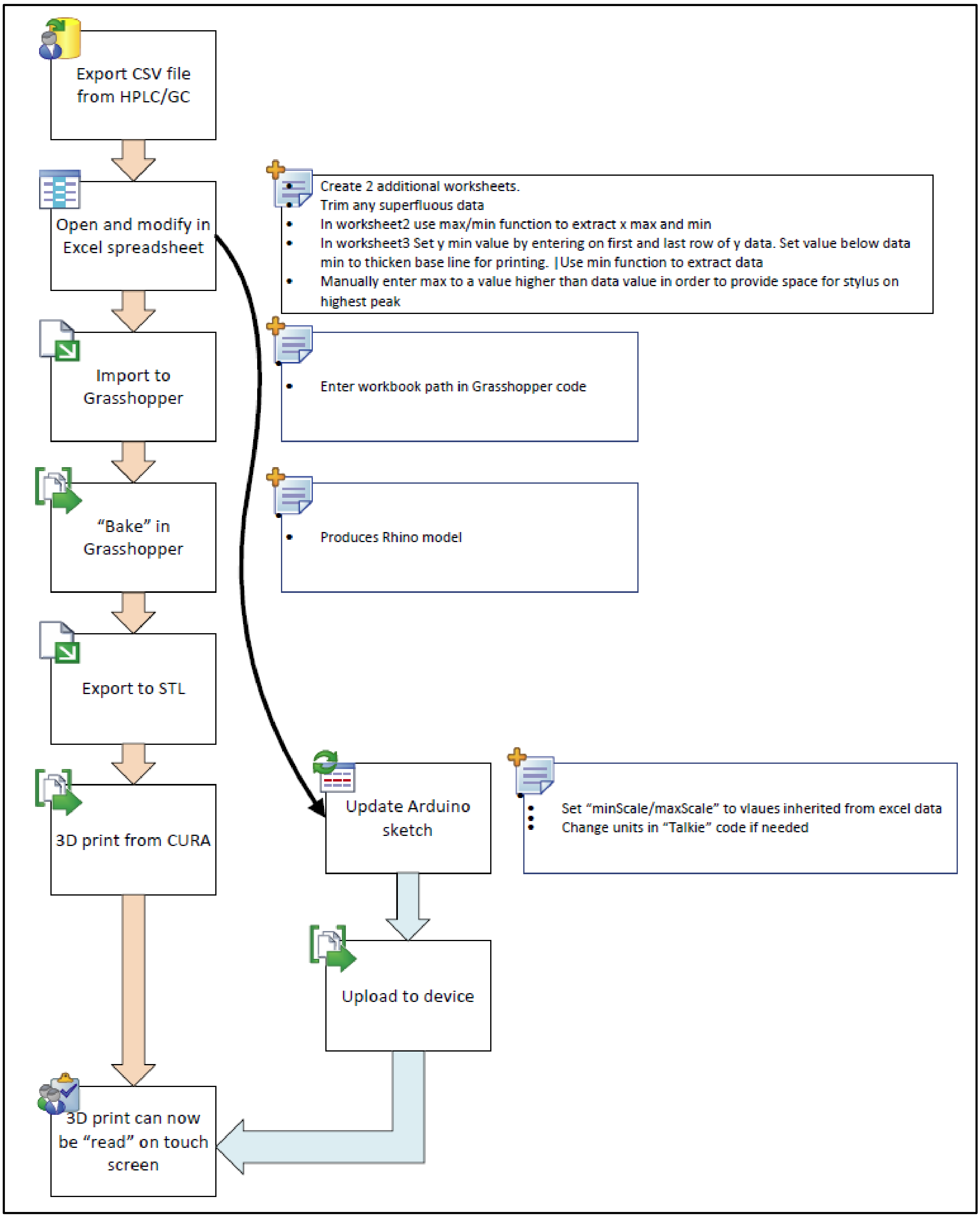


Figure 41 Flowchart showing operations

7. Evaluation

Evaluation method

Evaluation is a type of applied research where the approach is concerned with real-world problems and their possible solutions. Robson[72] states that an evaluation has a specific purpose. Typically, this is to evaluate the effectiveness of some innovation or intervention.

Evaluation research is often broken down into two types: formative and summative. Formative is intended to facilitate the development of an innovation or service, whereas summative is focused on assessing the effectiveness. However, the distinction between the two is not always clear-cut. In this project, the summative evaluation will have a formative effect on future developments. Robson[72] points out that evaluation can also be described in terms of outcome and process. Traditionally, evaluation measured how far an innovation or service met its objectives. Although this is still a central tenet of evaluation, it is now considered important to measure "how?" and "why?". Without studying the process, outcome evaluation can be considered a "black box" approach that only studies what goes in and what comes out. Robson[72] provides valuable checklists for carrying out evaluations. He lists four criteria, utility, feasibility, propriety and technical adequacy, that should be satisfied before embarking on an evaluation. Utility is at the heart of an evaluation; its raison d'être is not to prove but improve. It should be feasible both in practical and cost-effective terms. It should be able to be conducted fairly and ethically and finally carried out with technical skills.

There are threats to the validity of the research. Maxwell[73] presents a typology of three types of understanding in qualitative research, description, interpretation and theory. Robson[7] suggests that each of these types has associated threats to validity. The threat to valid descriptions can lie with incomplete or inaccurate data. The imposition of frameworks or meanings on what is happening rather than looking at what is actually occurring can threaten a valid interpretation. Not considering alternatives can affect the validity of the theory.

With these points in mind, a methodical triangulation strategy identified by Denzin[74] was used. This followed Creswells[75] guidelines by employing a mixed method using quantitative and qualitative approaches to improve the rigour of the research. This method further enhanced the interpretation of the quantitative data by providing a qualitative narrative account.

In this project, the quantitative data was collected via questionnaires and qualitative data was acquired using structured observation of participants.

Observation

Observation is a basic method of data collection. By being present in the situation, a record of what takes place is recorded for later analysis. The advantage of observation is its directness, watching what participants do and listening to what they say. Observation eliminates the common discrepancy in surveys where people report what they do compared to what they "actually" do.

There are several different observation methods. Jones and Somek[76] suggest that the methodological framework for the research will be determined by what is "seen". This is ontologically determined and depends on the observer's conceptualisation of the world. In this case, a positivistic approach is taken that holds that the world is external to the observer and facts about people and events can be recorded in a straightforward manner. With this approach, the methodological issues involve performing accurate observations and reducing observer bias.

Because the researcher is present during observation, threats to validity involving people must be considered. Lincoln and Guba[77] list reactivity, respondent biases and researcher biases as possible threats. Reactivity refers to the impact the researcher's presence has on a participant's behaviour. Respondent bias can arise if the researcher is seen as a threat and can materialise in obtrusiveness. Alternatively, participants give answers they perceive the researcher wants. Researcher bias refers to assumptions and preconceptions affecting the questions, interviewee selection and data selection.

Structured observation and coding scheme

A structured observation approach was used to evaluate how users interacted with the device. With this method, the observation is structured around pre-determined categories recording what is observed systematically and within a controlled environment.

The code development started with a system derived from Weick[78] that is widely used and adaptable to various research questions. Two bases were used in the development of the code: non-verbal behaviours and linguistic behaviours. The non-verbal behaviours were how the participant interacted with the device and the linguistic content of talking.

The areas of interest for the observation categories were what the users were doing, as opposed to what was expected they might do, and to identify any problems that they encountered. The classification of observed behaviours was kept to a minimum to avoid overwhelming the observer.

Videoing the interaction between the users and the device would have been valuable. However, unless used minimally, the data protection issues this brings about would have required participants to waive all moral rights to the recording[79]. Therefore, video filming was not used.

According to Jakob Nielsen [80], up to 85% of usability problems can be identified by observation of just five users. This figure was based on earlier research by Nielson and Lindauer[81] that looked at eleven empirical user testing case studies. They found that testing with one user finds almost a third of the issues. A second user will overlap the findings of the first but add a little more insight. As you add more users, you see the same problems occurring multiple times and learn little new.

As this project aimed to produce a working prototype, the initial number of participants in the usability study was seven. This gave rapid feedback on issues with the design. Problems were then fixed in a redesign and tested again.

Simulating blindness

There were difficulties in finding enough BVI participants to evaluate the device. Therefore, sighted participants wearing blindfolds to simulate blindness were recruited in addition to a single BVI participant.

However, Silverman[82] suggests caution is required as simulations can cause misunderstandings about the realities of blindness. Although it can create empathy, this can come at the price of reinforcing stereotypes. Silverman, Gwinn, and Van Boven[83] found that an unintended consequence of performing a task whilst simulating a disability lead to underestimating the abilities of a disabled person.

In the evaluations, participants operated under simulated blindness. This experience is short-term and only used for the duration of the evaluation. In effect, what the participants are experiencing is the feeling of initially becoming blind rather than having lived with the disability for a length of time.

Silverman[82] suggests that an instructor should guide the participants and give them time for practice and repetition during a simulation.

Observation Procedure

Ethics consideration

Prior to the initiation of the project, careful consideration was given to the risks and ethical considerations involved. As a result, an ethics review checklist was prepared and submitted to the University Research Ethics Advisory Group, which subsequently approved it.

The design of the procedure aimed to minimise any discomfort or stress experienced during the observation sessions. Blindfolding participants was a potential risk area; however, this was mitigated by ensuring that they remain seated and could freely voice their opinions end the session at any point. Personal details were not gathered from the participants, and their identities were anonymised using letters in the observation findings. The only distinction made was to acknowledge whether a participant had a visual impairment.

Observations

The participants were randomly approached from a cohort of undergraduate and postgraduate chemistry and physics students. These students were chosen for convenience;

they were available in the department throughout the testing period. Being science students, they were also familiar with data presented in graphical form and therefore understood the nomenclature of graphs.

The participants were given an introductory letter outlining the project and their role in it. During the session, the instructor went through a predetermined exercise guided by a script. The researcher undertook the observation.

Each observation session initially followed the same format. The researcher read through the introductory script.

Observer script

1. *You've been invited to help us understand the effectiveness of a device. that reads out graphical data.*
2. *To do this you will be blindfolded.*
3. *You are not being tested but the device is.*
4. *You cannot do anything wrong.*
5. *If things do not work, it is not your fault.*
6. *Nobody's feelings will be hurt if you say anything critical about the device.*
7. *It's important that you speak your thoughts aloud.*
8. *Think of it as an item-by-item description of what you're doing and why you're doing it.*

You can ask the instructor questions and clarify instructions.

The participant was then blindfolded if required. The instructor then introduced the device and the data that would be "visualised". The instructor read from a pre-prepared script.

After each instruction, observations were made of the participant's interaction with the device, and reactions were noted. The instructor was free to offer further advice and instruction at the participants' request. These requests were also noted. The participants were asked to provide some data points form the peaks so that accuracy could be tested.

Finally, the participants were presented with and asked to complete a short paper-based questionnaire.

Observation results

Participants were asked to orientate the 3D print (Item 5 from instructor's script)

"Place the chromatogram on the desk. To orientate it correctly you will feel a small, raised mark. This is placed at the bottom left of the spectra. If you can't feel this you may need to turn it over."

Four of the seven participants quickly orientated the 3D print correctly. Two participants struggled to find the raised mark. Of these, a single participant initially had the print orientated vertically (y-axis perpendicular to desk), requiring verbal input from the instructor to re-orientate. The other had to be reminded to place the print flat on the desk.

The BVI participant had difficulties finding the marker. Initially, they tried to see the 3D print by placing it close to the eye. (The participant had minimal partial vision) This appeared to hamper their ability to manipulate the 3D print. Only when not trying to see print were they able to identify the marker.

Participants were asked to describe what they felt and if they could make some deductions (Item 6 from the instructor's script)

"Can you describe what you feel?"

Four of the seven participants quickly and easily identified the peaks. Two participants were able to describe the peaks in detail. Two participants initially misidentified the most prominent peak as the y-axis. Once the instructor corrected the mistake, they could correctly identify the peaks. The BVI participant continued to try to visualise the peaks by placing them close to the eye. Their progress was slower than the non-BVI participants; however, they could identify the peaks using limited vision and touch.

Participants were asked to place print onto the screen (Item 10 on the instructor's script)

"You must first place the 3D model in the device. The raised dot will be to the bottom left. It should fit snuggly at the bottom of the indent."

All participants could quickly and easily place the print into the screen recess. Once fitted participants continued to touch and feel the print ensuring it was fitted correctly.

Participants were asked to read x and y values (item 11/12 on the instructor's script)

"You can now touch the screen with the stylus and press the buttons to read the x and y values."

"Try to keep the stylus at 90 degrees/perpendicular to the screen to maintain accuracy. Starting from the left can you find the retention times and the counts for the most prominent peaks?"

There was a range of observed actions when asked to read the x/y values. All participants were able to take x and y readings and repeat back to the instructor. The researcher took the initial x/y reading by making a fine mark at the highest point of the most prominent peak. The participant's results were compared to this. The percentage error in the readings ranged from -4% to 13 % for the x-axis and -9% to 56% for the y-axis. The average percentage error was 3% for the x axis and -15% for the y axis.

The two left-handed participants struggled to take readings due to the positioning of the x and y buttons. Both operated the stylus with the left hand forcing them to cross their hands to activate the buttons. Participants generally used two hands to locate the peaks with the stylus initially and then transferred to one hand so they could press the buttons. The change from two to one hand sometimes resulted in the stylus moving before the reading was taken. It was noted that they got better as they worked through the peaks and appeared more confident taking readings.

The angle of the stylus was another issue with some of the participants. Although asked by the instructor to keep the stylus perpendicular to the screen, four participants held the stylus at around 45 degrees to the screen, which along with the taper of the stylus, resulted in incorrect readings of up to 5mm off target. *(fig 42)*

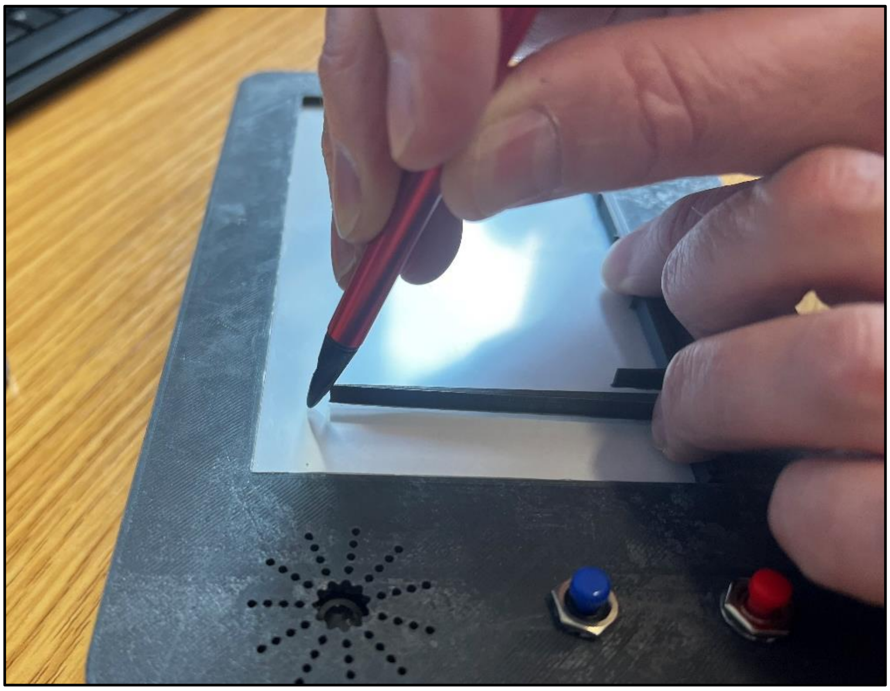


Figure 42 Stylus shown at an angle of 45 degrees

Another problem encountered by two participants was that whilst taking readings, the model could rotate upwards away from the screen. The rotation was caused by pressing down on the model's baseline, causing it to pivot on the bottom edge. *(fig 43)*

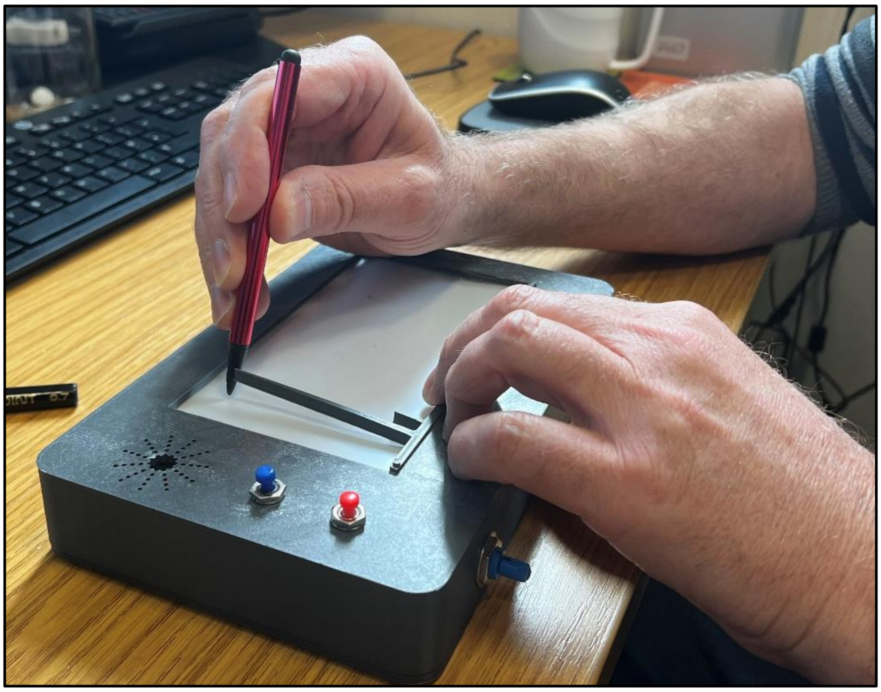


Figure 43 Print rotating upwards when pressure applied to base

Two participants had problems due to the flexibility of the material. As they tried to take readings, the peak would flex to the right or left, introducing an error to the readings. They also had issues stopping the stylus on top of the peak from slipping off.

Two participants were observed moving the stylus before the reading was taken.

A single participant got erroneous results due to resting their hand on the touchscreen whilst taking a reading.

The BVI participant encountered several of the issues described above and again used a combination of close visual inspection and touch to take readings.

Participants comments

During the observation, participants were encouraged to verbalise their actions. Comments included;

Comments on the 3D print

"Peak wobbles around; it needs more thickness."
"Peak is flimsy – it flexes."
"I think thicker peaks are needed."
"Voice was difficult to understand."
"Awkward to hold still."

Comments on the stylus

"Tricky to hold the stylus on top of peak without it wobbling or bending."
"The Stylus slips off the peaks."
"Stylus was slippery to hold."
"Awkward to hold still."

Comments on x y buttons

"Buttons were inconvenient" (LH user)
"x and y buttons need moving" (LH user)

General comments

"I think I would be easier with practice."
"It's a good idea."
"It would be good for schools."

Questionnaire feedback

6 of the 7 participants, labelled A- F on figure 44, answered the questionnaire. Questions were rated 1-5 with 5 being easy and 1 not easy.

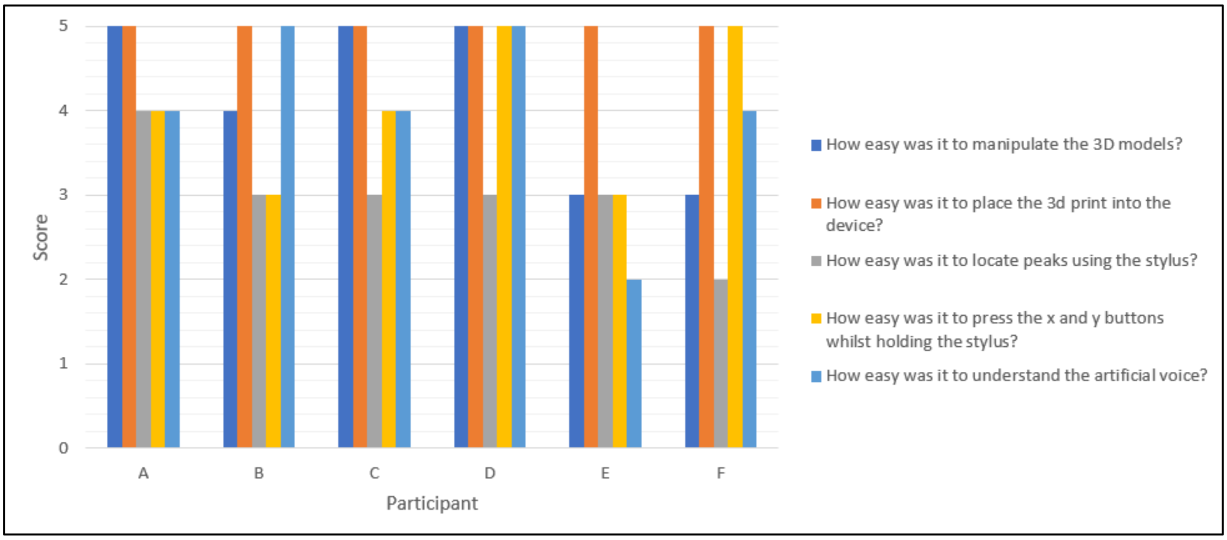


Figure 19 results from questionnaire

7.1 Discussion

Initially, after being blindfolded, participants were hesitant and clumsy in their exploration of the 3D print. This initial hesitancy improved as the evaluation progressed. This behaviour resonates with simulating blindness research[83]. The initial blindfolding throws the participant instantly from seeing to being blind. It then takes time to adjust. For some participants, orienting the object took a little time; it appeared that this was not so much feeling the object but understanding what they were meant to be feeling based on the instructions. So, for instance, the instructions for finding the raised mark confused participants. Not knowing the base of the print, they found it difficult to understand how to place it horizontally and flat on the table.

Another issue was around locating the stylus on the peaks. The highest peak gave the most problems. As seen in the image below *(fig 45)*, it was thin with a sharp peak. Participants noted that the peak would bend when touched by the stylus.

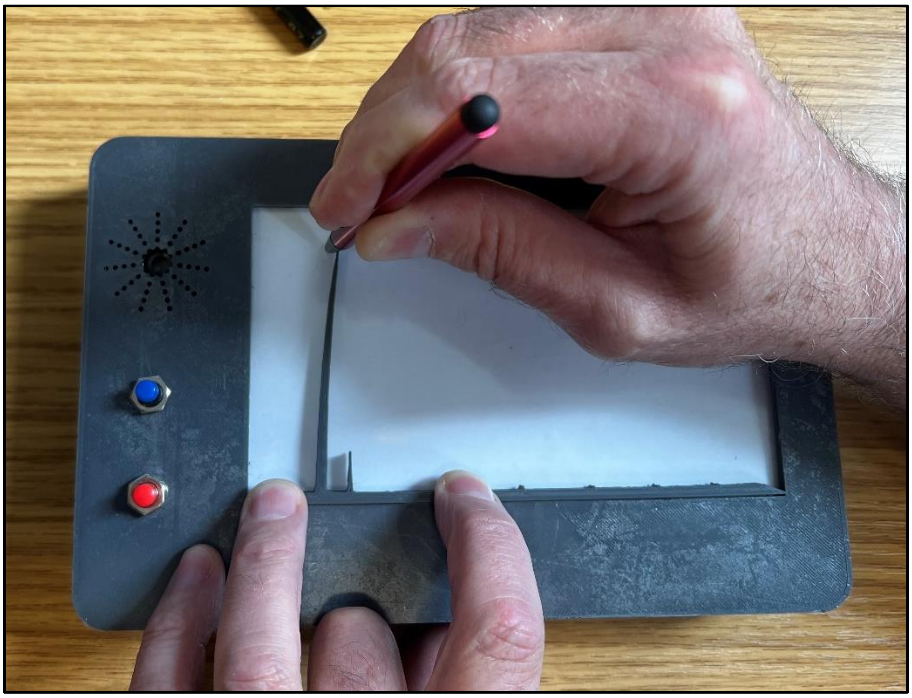


Figure 45 Peak bending

However, they knew this was occurring and were observed to take more care while making measurements. A problem in measuring that participants were unaware of was the angle of the stylus. The instructor asked them to maintain the stylus perpendicular to the screen. However, not all achieved this, resulting in errors introduced to the measurements. It was noted that the taper on the stylus prevented the tip from touching the edge of the 3D print.

It was immediately apparent that the x and y buttons were not ideally situated, resulting in the crossing of hands for the left-handed participants.

Although it was not the best quality, all the participants understood the speech synthesis. One participant remarked it was difficult to understand, however, all were able to repeat the data points when asked. The questionnaire response was positive with most participant scoring 4 and 5.

The observation of the BVI participant was interesting. Having some partial sight meant that they used the graph reader and 3D print differently than the blindfolded students. Most noticeably, they raised the apparatus and prints close to the eyes to visualise rather than relying on touch alone.

Observation suggested that the BVI participant had more issues using the instrument than the blindfolded student. Although not much can be gleaned from a single participant, it was a surprise as evidence from the literature suggested that BVI people have enhanced haptic skills.[83] [84]

The workflow to produce the print requires little intervention and the time to produce the print is dominated by the actual print time.

Several areas were identified in the evaluation where further development was required. These are listed below.

1. The x and y buttons required relocation to be usable regardless of handiness.
2. A solution was required to stop the 3D print from rotating when readings were being taken.
3. Redesign of the stylus to reduce errors caused by taper and angle.
4. Experimentation to make peaks less flexible.
5. Considering the observations of the BVI user there is a need to improve the contrast between the screen and the 3D print.
6. Clearer guidance on what was the base of the 3D print.

So taking each of these areas in turn;

1. Relocating the buttons was a simple modification; see the CAD image below.

Figure 20 Button relocation

2. The Grasshopper sketch was adapted to make a frame around the print to avoid rotation. The frame has a 2.5 mm width and the same depth as the graph print. It is constructed by creating a rectangle the same size as the graph reader screen and subtracting a rectangle 5mm smaller in width and height. The frame fits securely into the graph reader screen recess, preventing rotation. The frame should also prevent the misidentification of peaks for the y-axis. *(fig 47 & 48)*

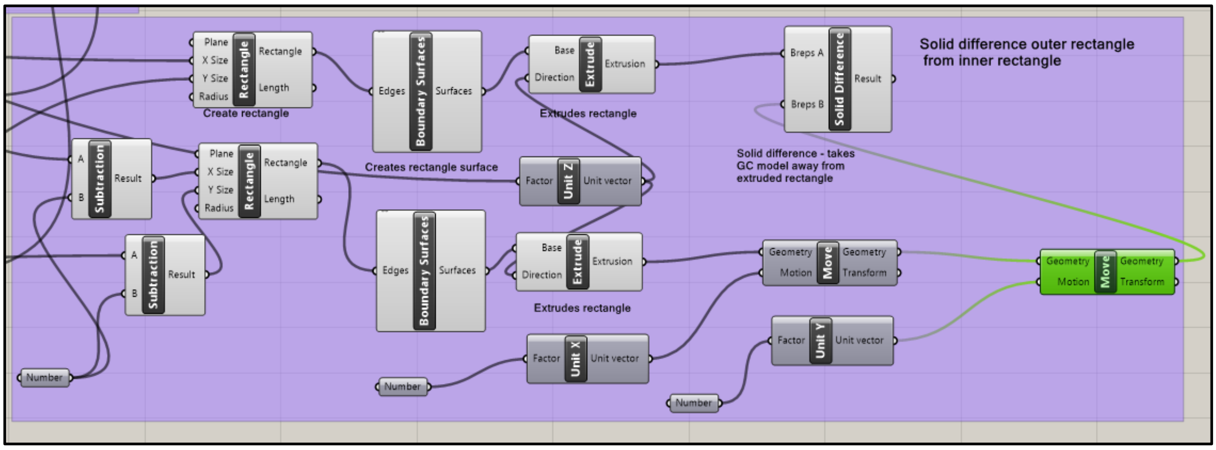


Figure 21 Grasshopper definition for rectangle creation

Figure 22 3D printed chromatogram with a frame

3. The stylus was redesigned by using a stylus from a graphics pad and extending the nib. *(fig 49)*

Figure 49 Stylus with extension

4. Negative 3D prints were trialled. A grasshopper definition was created that subtracted the chromatogram from a solid rectangle. Turning the peaks into grooves removed the flexing problems. However, fitting the redesigned stylus to the narrow tip of the peak was difficult therefore this solution was discounted. *(figs 50 & 51)*

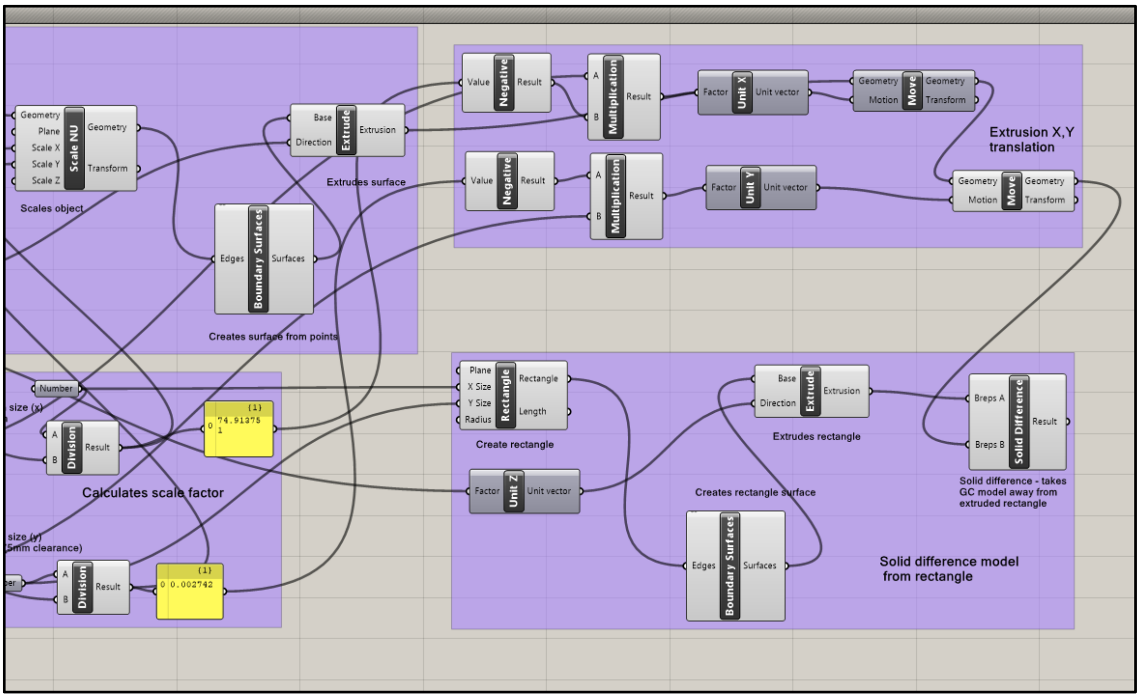


Figure 50 Grasshopper definition for negative print.

Figure 51 Negative 3D print

5. A 3D chromatogram was printed using carbon-impregnated PLA. A force of 10 Newtons was applied to the peak using a spring balance, and the distance deflected from the vertical position was measured. The deflection was compared to the distance the standard PLA printed peak moved. The results showed that the carbon-impregnated PLA increased stiffness exhibiting around 60% less flexing than standard PLA. *(fig 52)*

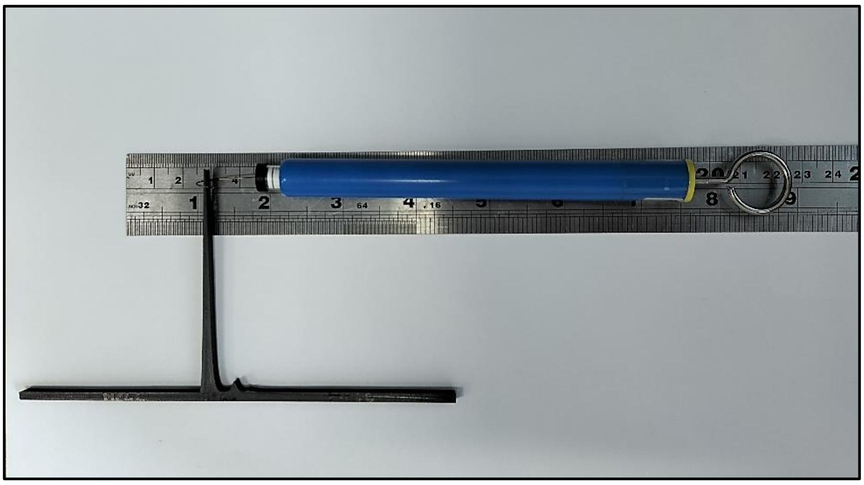


Figure 52 Spring balance used to measure flexing.

6. The installation of a white LED made little difference between the 3D print and the touchscreen. The white card on the back of the resistive touchscreen was too thick to let much light through. However, different types of diffusers could be trialled in future developments of the device.

8. User evaluation with improved design

A second round of user evaluations was undertaken that incorporated the changes made above.

8.1 Blindness simulation

In order to more accurately simulate blindness a decision was made to move away from blind folds, which as described previously, has some unintended consequences. Although there are many degrees of vision impairment, in this user evaluation a set of laboratory safety spectacles were lightly sanded using emery cloth to give approximately 3/60 (20/200) vison. *(fig 53)* 3/60 vision was achieved by repeated sanding and testing using a standard eye chart at 10 feet until the top line E was no longer resolved.

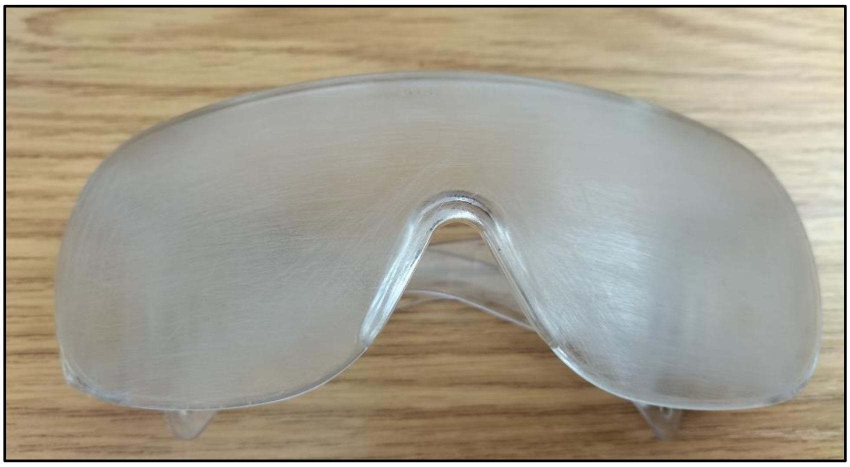


Figure 53 "Foggles"

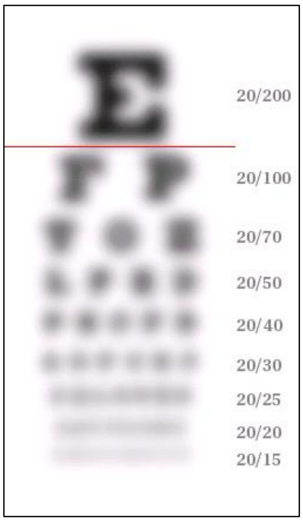


Figure 54 Simulation of 20/200 vision at 10 feet

8.2 Observation results 2

Three participants took part in the second evaluation. The second evaluation followed the same procedure as the first, apart from substituting the blindfolds with the "foggles".

Participants were asked to orientate the 3D print (Item 5 from instructor script)

"Place the chromatogram on the desk. To orientate it correctly you will feel a small, raised mark. This is placed at the bottom left of the spectra. If you can't feel this you may need to turn it over."

Two of the three orientated the 3D print correctly, quickly identifying the raised mark. The third identified the raised mark however had misunderstood what they were looking for and, having the instruction, were able to orientate correctly. All placed the frame flat on the desk.

Participants were asked to describe what they felt and if they could make some deductions (Item 6 from instructor script)

"Can you describe what you feel?"

Two of the participants quickly and easily identified the seven peaks. Two participants could describe the peaks in detail; the third missed a peak and was less able to describe them in detail. Unlike the first evaluation, there was no misidentification of the axis.

Participants were asked to place print onto the screen (Item 10 on instructors script)

"You must first place the 3D model in the device. The raised dot will be to the bottom left. It should fit snuggly at the bottom of the indent."

All participants were able to place the print onto the reader correctly. One participant intuitively fitted the print before receiving the instruction. Once the print was fitted on the reader, participants did not continue to touch the print, unlike the first evaluation.

Participants were asked to read x and y values (item 11/12 on instructors script)

"You can now touch the screen with the stylus and press the buttons to read the x and y values."

"Try to keep the stylus at 90 degrees/perpendicular to the screen to maintain accuracy. Starting from the left can you find the retention times and the counts for the most prominent peaks?"

When asked to read the x and y values, there was a range of observed actions. All participants were able to take x and y readings.

Surprisingly, all participants were observed struggling with the new positions of the x and y buttons to take readings due to the positioning of the x and y buttons. The new position of the x and y buttons required them to pass one hand over the other regardless of handiness. Two participants initially used two hands to locate the peaks with the stylus and then transferred to one hand so they could press the buttons. The change from two to one hand again resulted in the stylus moving before the reading was taken. As found in the first evaluation, they improved as they worked through the peaks and appeared more confident taking readings.

All participants could hold the stylus at 90 degrees to the screen. There was visibly less flex when measuring the most significant peak, and no flexing was noted when the measurement was being taken.

A single participant got erroneous results due to resting their hand on the touchscreen whilst taking a reading. However, they recognised that this might be an issue and, on clarifying with the instructor, were able to correct it for a second attempt.

Participants comments

One participant commented that even using the goggles they were able to see the correct orientation of the stylus. The same participant asked if their fingers resting on the screen would affect the readings.

Discussion

Similar to the first evaluation, participants were initially hesitant and clumsy in their exploration of the 3D print after being given the goggles to wear. However, this was observed to be less so than with the participants with blindfolds. It was evident that although unable to resolve detail, the fact that they could see larger shapes helped them locate where objects were and, in some instances, such as using the stylus, assisted with orientation.

Unlike the first evaluation, the object's orientation was quicker and presented fewer issues. Where a problem occurred, it was more a case of the spoken instructions requiring clarification rather than a fundamental issue with the equipment. Once the print was placed in the reader, it was secure, and the rotation experienced in the first version did not occur.

Locating the stylus on the peaks was less problematic than on the first evaluation because of less flexing due to the increased stiffness of the carbon-impregnated PLA.

The redesign of the stylus introduced fewer errors than the tapered version in the first evolution. The stylus was able to get closer to the peaks. Keeping the stylus perpendicular did not present any problems once instructed. This may have been partly due to perceiving larger shapes using the goggles. One participant said that this was the case.

Using the new stylus, the participant's results were again compared to the researchers. The percentage error in the readings ranged from -4% to -3% for the x-axis and -15% to 5% for the y-axis. The average percentage error was -3% for the x-axis and -4% for the y-axis, which was an improvement on the first evaluation, especially in the y-axis.

Unfortunately, the x and y buttons were still not ideally situated, resulting in the crossing of hands for all participants.

8.3 Conclusion

It was evident in the observations that, overall, the participants could acquire meaningful results using the 3D print and graph reader. Generally, using touch, the participants could recognise and describe the most salient features of the GC chromatogram. They could extract peak values using the reader. This improved with practice. The participants were generally positive in their comments and in answering the questionnaire.

As set out in the project aims, the costs for the Graph reader were kept low. The reader costs were approximately £30, and the 3D prints were £0.15. Further development of the reader optimising for design for manufacturing and assembly (DFAM) would reduce the costs if volume production were a reality. Although a GC chromatogram was used in the evaluation, using a csv file, it is expected that most single-line and bar graphs could be printed and read using the graph reader.

Future developments

The results of the evaluation prompted further development ideas.

- Further coding to streamline the data export to remove manual manipulation. This could be achieved using Python coding within Grasshopper; with further development in the programming, a system could be envisaged where a csv file goes through the workflow directly to the 3D printer. The user would only open a csv file and press print.
- Relocate buttons to the side of the unit and use an auto-rotation function for the screen to allow left-hand and right-hand use.
- Improved speech synthesis using a commercially available module.
- Speech recognition to remove the need to press buttons.

9. Bibliography

(1) Schnepp, Z.; Watson, R. Making Chemistry Accessible for Learners with Vision Impairment. *Commun. Chem.* **2023**, *6* (1), 1–3. https://doi.org/10.1038/s42004-023-01033-x.

(2) Rindermann, H.; Ackermann, A. L.; te Nijenhuis, J. Does Blindness Boost Working Memory? A Natural Experiment and Cross-Cultural Study. *Front. Psychol.* **2020**, *11*, 1–9. https://doi.org/10.3389/fpsyg.2020.01571.

(3) Nicole Johnson, E. D.; Anne Brawand, P. D. Increasing Problem-Solving Ability for Students with Visual Impairments and Intellectual Disabilities. *J. Blind. Innov. Res.* **2021**, *11* (1).

(4) Jones, M. G.; Minogue, J.; Opepewal, T.; Cook, M. P.; Broadwell, B. Visualizing Without Vision at the Microscale: Students With Visual Impairments Explore Cells With Touch. *J. Sci. Educ. Technol.* **2006**, *15* (5–6), 345–351. https://doi.org/DOI:10.1007/S10956-006-9022-6.

(5) D'Agostino, A. T. Accessible Teaching and Learning in the Undergraduate Chemistry Course and Laboratory for Blind and Low-Vision Students. *J. Chem. Educ.* **2021**. https://doi.org/10.1021/acs.jchemed.1c00285.

(6) *Vision impairment and blindness*. https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment (accessed 2022-04-26).

(7) Pezzullo, L.; Streatfeild, J.; Simkiss, P.; Shickle, D. The Economic Impact of Sight Loss and Blindness in the UK Adult Population. *BMC Health Serv. Res.* **2018**, *18* (1), 63. https://doi.org/10.1186/s12913-018-2836-0.

(8) Key Statistics about Sight Loss. www.media.rnib.org.uk/documents/Key_stats_about_sight_loss_2021.pdf (accessed 2023-03-05).

(9) Admin, V. *Key issues for VI education in England*. VIEW. https://viewweb.org.uk/view-statement-on-the-key-issues-for-vi-education-in-england/ (accessed 2023-03-07).

(10) O'Day, B. Employment Barriers for People with Visual Impairments. *J. Vis. Impair. Blind.* **1999**, *93* (10), 627–642. https://doi.org/10.1177/0145482X9909301002.

(11) Secondary Analysis of the Labour Force Survey 2020: Comparison of People with Sight Loss to the Rest of the Population, 2021. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fmedia.rnib.org.uk%2Fdocuments%2FLabour_Force_Survey_2020.docx&wdOrigin=BROWSELINK (accessed 2023-04-17).

(12) Roberts, S.; Heaver, C.; Hill, K.; Rennison, J.; Stafford, B.; Howat, N.; Kelly, G.; Krishnan, S.; Tapp, P.; Thomas, A. *Disability in the workplace: Employers' and service providers' responses to the Disability Discrimination Act in 2003 and preparation for 2004 changes*. https://webarchive.nationalarchives.gov.uk/ukgwa/20080305184620/http://www.dwp.gov.uk/asd/asd5/rports2003-2004/rrep202.asp (accessed 2023-04-18).

(13) Employment Facts and Stats 2020. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fmedia.rnib.org.uk%2Fdocuments%2FEmployment_facts_and_stats_2020_-_External_version.docx&wdOrigin=BROWSELINK (accessed 2023-04-17).

(14) Saunders, A. The Jobs That Blind and Partially Sighted People Do. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fmedia.rnib.org.uk%2Fdocuments%2FJobs_that_blind_and_partially_sighted_people_do_-_Research_report.docx&wdOrigin=BROWSELINK (accessed 2023-04-17).

(15) Ferguson, E. S. *Engineering and the Mind's Eye*; MIT Press, 1994.

(16) Miller, A. I. In *Insights of Genius: Imagery and Creativity in Science and Art*; Springer Science & Business Media, 2012; p 36.

(17) Moore, E. B.; Smith, T. L.; Greenberg, J. Keyboard and Screen Reader Accessibility in Complex Interactive Science Simulations: Design Challenges and Elegant Solutions. In *Universal Access in Human-Computer Interaction. Methods, Technologies, and Users*; Antona, M., Stephanidis, C., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, 2018; pp 385–400. https://doi.org/10.1007/978-3-319-92049-8_28.

(18) Carter, J.; Fourney, D. Research Based Tactile and Haptic Interaction Guidelines. In *Gothi - 05*; USERLab, Department of Computer Science University of Saskatchewan, 2005; pp 84–92.

(19) Hix, D.; Gabbard, J. L. Usability Engineering of Virtual Environments. In *Handbook of Virtual Environments*; 2002.

(20) Sherman, B. Nathaniel I. Durlach and Anne S. Mavor (Eds),Virtual Reality: Scientific and Technological Challenges (Washington DC: National Academy Press, 1995), 542pp. ISBN 0 309 05135 5 (Hbk. *Convergence* **1996**, *2* (1), 142–144. https://doi.org/10.1177/135485659600200111.

(21) Boyd-Kimball, D. Adaptive Instructional Aids for Teaching a Blind Student in a Nonmajors College Chemistry Course. *J. Chem. Educ.* **2012**, *89* (11), 1395–1399. https://doi.org/10.1021/ed1000153.

(22) Supalo, C. A.; Kennedy, S. H. Using Commercially Available Techniques To Make Organic Chemistry Representations Tactile and More Accessible to Students with Blindness or Low Vision. *J. Chem. Educ.* **2014**, *91* (10), 1745–1747. https://doi.org/10.1021/ed4005936.

(23) Supalo, C. Techniques To Enhance Instructors' Teaching Effectiveness with Chemistry Students Who Are Blind or Visually Impaired. *J. Chem. Educ.* **2005**, *82* (10), 1513–1518. https://doi.org/10.1021/ed082p1513.

(24) McCallum, D.; Ahmed, K.; Jehoel, S.; Dinar, S.; Sheldon, D. The Design and Manufacture of Tactile Maps Using an Inkjet Process. *J. Eng. Des.* **2005**, *16* (6), 525–544. https://doi.org/10.1080/09544820500273946.

(25) *PRINT - Non-Impact Printer and Plotter for Braille/Moon and tactile Graphics*. https://www.dinf.ne.jp/doc/english/Us_Eu/conf/csun_98/csun98_038.html (accessed 2023-01-13).

(26) Supalo, C.; Mallouk, T.; Rankel, L.; Wohlers, H.; Roth, A.; Greenberg, A. Talking Tools to Assist Students Who Are Blind in Laboratory Courses. *J. Sci. Educ. Stud. Disabil.* **2007**, *12* (1), 27–32. https://doi.org/10.14448/jsesd.01.0003.

(27) Burch, D.; Pawluk, D. Using Multiple Contacts with Texture-Enhanced Graphics. In *2011 IEEE World Haptics Conference*; 2011; pp 287–292. https://doi.org/10.1109/WHC.2011.5945500.

(28) Lunney, D.; Morrison, R. C. High Technology Laboratory Aids for Visually Handicapped Chemistry Students. *J. Chem. Educ.* **1981**, *58* (3), 228–231. https://doi.org/10.1021/ed058p228.

(29) *Sci-Voice TM Talking LabQuest 2 Version 2.3 Package*. Independence Science. https://independencescience.com/product/sci-voice-talking-labquest-2/ (accessed 2021-08-13).

(30) Espinosa-Castañeda, R.; Medellín-Castillo, H. I. Virtual Haptic Perception as an Educational Assistive Technology: A Case Study in Inclusive Education. *IEEE Trans. Haptics* **2021**, *14* (1), 152–160. https://doi.org/10.1109/TOH.2020.3001586.

(31) Ramloll, R.; Yu, W.; Brewster, S.; Riedel, B.; Burton, M.; Dimigen, G. Constructing Sonified Haptic Line Graphs for the Blind Student: First Steps. **2000**. https://doi.org/10.1145/354324.354330.

(32) Kobayashi, M.; Watanabe, T. A Tactile Display System Equipped with a Pointing Device — MIMIZU. In *Computers Helping People with Special Needs*; Miesenberger, K., Klaus, J., Zagler, W., Eds.; Lecture Notes in Computer Science; Springer: Berlin, Heidelberg, 2002; pp 527–534. https://doi.org/10.1007/3-540-45491-8_100.

(33) Gay, S. L.; Pissaloux, E.; Romeo, K.; Truong, N.-T. F2T: A Novel Force-Feedback Haptic Architecture Delivering 2D Data to Visually Impaired People. *IEEE Access* **2021**, *9*, 94901–94911. https://doi.org/10.1109/ACCESS.2021.3091441.

(34) Teshima, Y.; Hosoya, Y.; Sakai, K.; Nakano, T.; Tanaka, A.; Aomatsu, T.; Yamazawa, K.; Ikegami, Y.; Watanabe, Y. Development of Tactile Globe by Additive Manufacturing. In *Computers Helping People with Special Needs*; Miesenberger, K., Manduchi, R., Covarrubias Rodriguez, M., Peňáz, P., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, 2020; pp 419–426. https://doi.org/10.1007/978-3-030-58796-3_49.

(35) *3D Printing Tactile Graphics For The Blind: Application To Histology*. https://www.resna.org/sites/default/files/conference/2014/Other/Williams.html (accessed 2021-12-06).

(36) Davis, J. U.; Wu, T.-Y.; Shi, B.; Lu, H.; Panotopoulou, A.; Whiting, E.; Yang, X.-D. TangibleCircuits: An Interactive 3D Printed Circuit Education Tool for People with Visual Impairments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*; ACM: Honolulu HI USA, 2020; pp 1–13. https://doi.org/10.1145/3313831.3376513.

(37) Goncu, C.; Marriott, K. GraVVITAS: Generic Multi-Touch Presentation of Accessible Graphics. In *Human-Computer Interaction – INTERACT 2011*; Campos, P., Graham, N.,

Jorge, J., Nunes, N., Palanque, P., Winckler, M., Eds.; Hutchison, D., Kanade, T., Kittler, J., Kleinberg, J. M., Mattern, F., Mitchell, J. C., Naor, M., Nierstrasz, O., Pandu Rangan, C., Steffen, B., Sudan, M., Terzopoulos, D., Tygar, D., Vardi, M. Y., Weikum, G., Series Eds.; Lecture Notes in Computer Science; Springer Berlin Heidelberg: Berlin, Heidelberg, 2011; Vol. 6946, pp 30–48. https://doi.org/10.1007/978-3-642-23774-4_5.

(38) Midway, S. R. Principles of Effective Data Visualization. *Patterns* **2020**, *1* (9), 1–7. https://doi.org/10.1016/j.patter.2020.100141.

(39) Wilke, C. O. *Fundamentals of Data Visualization: A Primer on Making Informative and Compelling Figures*; O'Reilly Media, Inc., 2019.

(40) *Making data visualization more accessible for blind and low-vision individuals*. MIT News | Massachusetts Institute of Technology. https://news.mit.edu/2022/data-visualization-accessible-blind-0602 (accessed 2023-01-06).

(41) Butler, M.; Holloway, L.; Marriott, K.; Goncu, C. Understanding the Graphical Challenges Faced by Vision-Impaired Students in Australian Universities. *High. Educ. Res. Dev.* **2017**, *36* (1), 59–72. https://doi.org/10.1080/07294360.2016.1177001.

(42) Marriott, K.; Lee, B.; Butler, M.; Cutrell, E.; Ellis, K.; Goncu, C.; Hearst, M.; McCoy, K.; Szafir, D. A. Inclusive Data Visualization for People with Disabilities: A Call to Action. *Interactions* **2021**, *28* (3), 47–51.

(43) Sharif, A.; Zhang, A. M.; Shih, A.; Wobbrock, J. O.; Reinecke, K. Understanding and Improving Information Extraction From Online Geospatial Data Visualizations for Screen-Reader Users. In *The 24th International ACM SIGACCESS Conference on Computers and Accessibility*; ACM: Athens Greece, 2022; pp 1–5. https://doi.org/10.1145/3517428.3550363.

(44) Watanabe, T.; Mizukami, H. Effectiveness of Tactile Scatter Plots: Comparison of Non-Visual Data Representations. In *Computers Helping People with Special Needs: 16th International Conference, ICCHP 2018, Linz, Austria, July 11-13, 2018, Proceedings, Part I*; Lecture Notes in Computer Science; Springer International Publishing: Cham, 2018; Vol. 10896, pp 628–635. https://doi.org/10.1007/978-3-319-94277-3.

(45) *Teaching Math to Students Who are Blind or Visually Impaired*. Perkins School for the Blind. https://www.perkins.org/resource/teaching-math-students-who-are-blind-or-visually-impaired/ (accessed 2023-01-13).

(46) *APH Graph Board, Part 3, Graphing a Straight Line*; 2010. https://www.youtube.com/watch?v=YtRxp7O3biY (accessed 2024-05-22).

(47) Zy Chem ltd. *Swell Touch Paper for Tactile Graphics*. Zychem Tactile Graphics. https://zychemltd.com/swell-touch-paper-for-tactile-graphics/ (accessed 2023-01-13).

(48) *Swell Form Graphics Machine - high quality tactile graphics from Braillo*. Braillo Braille Printers and Braille Embossers. https://braillo.com/swell-form-graphics-machine/ (accessed 2023-01-16).

(49) Yu, W.; Ramloll, R.; Brewster, S. Haptic Graphs for Blind Computer Users.; 2000; Vol. 2058, pp 41–51. https://doi.org/10.1007/3-540-44589-7_5.

(50) Grabowski, N. A.; Barner, K. E. Data Visualization Methods for the Blind Using Force Feedback and Sonification. In *Telemanipulator and Telepresence Technologies V*; SPIE, 1998; Vol. 3524, pp 131–139. https://doi.org/10.1117/12.333677.

(51) Wall, S.; Brewster, S. Feeling What You Hear: Tactile Feedback for Navigation of Audio Graphs. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*; CHI '06; Association for Computing Machinery: New York, NY, USA, 2006; pp 1123–1132. https://doi.org/10.1145/1124772.1124941.

(52) Sharif, A.; Wang, O. H.; Muongchan, A. T.; Reinecke, K.; Wobbrock, J. O. VoxLens: Making Online Data Visualizations Accessible with an Interactive JavaScript Plug-In. In *CHI Conference on Human Factors in Computing Systems*; ACM: New Orleans LA USA, 2022; pp 1–19. https://doi.org/10.1145/3491102.3517431.

(53) Pereira, F.; Ponte-e-Sousa, J. C.; Fartaria, R. P. S.; Bonifácio, V. D. B.; Mata, P.; Aires-de-Sousa, J.; Lobo, A. M. Sonified Infrared Spectra and Their Interpretation by Blind and Visually Impaired Students. *J. Chem. Educ.* **2013**, *90* (8), 1028–1031. https://doi.org/10.1021/ed4000124.

(54) *Touch Graphics*. Touch Graphics. https://www.touchgraphics.com (accessed 2023-01-13).

(55) Gates, P. The Importance of Diagrams, Graphics and Other Visual Representations in STEM Teaching. In *STEM Education in the Junior Secondary: The State of Play*; 2018; pp 169–196. https://doi.org/10.1007/978-981-10-5448-8_9.

(56) Ferry, B.; Hedberg, J.; Harper, B. Designing Computer-Based Cognitive Tools to Assist Learners to Interpret Graphs and Tables. *Australas. J. Educ. Technol.* **1999**, *15* (1), 1–19. https://doi.org/10.14742/ajet.1844.

(57) Roth, W.-M.; Bowen, G. M. Complexities of Graphical Representations during Ecology Lectures: An Analysis Rooted in Semiotics and Hermeneutic Phenomenology. *Learn. Instr.* **1999**, *9* (3), 235–255. https://doi.org/10.1016/S0959-4752(98)00029-2.

(58) Cahill, H.; Others, A. Blind and Partially Sighted Students' Access to Mathematics and Computer Technology in Ireland and Belgium. *J. Vis. Impair. Blind.* **1996**, *90* (2), 105–114. https://doi.org/10.1177/0145482X9609000206.

(59) Cryer, H. Teaching STEM Subjects to Blind and Partially Sighted Students: Literature Review and Resources., 2013. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fmedia.rnib.org.uk%2Fdocuments%2F2013_05_Teaching_STEM.docx&wdOrigin=BROWSELINK (accessed 2023-04-17).

(60) Offnfopt. *English: Diagram of a Gas Chromatograph Apparatus*; 2015. https://commons.wikimedia.org/wiki/File:Gas_chromatograph-vector.svg (accessed 2022-11-27).

(61) *What is Arduino? | Arduino Documentation*. https://docs.arduino.cc/learn/starting-guide/whats-arduino (accessed 2023-04-18).

(62) Knight, P. Talkie, 2022. https://github.com/ArminJo/Talkie (accessed 2022-11-12).

(63) FozzTexx. *English: Original Speak & Spell with Chiclet Keys.*; 2017. https://commons.wikimedia.org/wiki/File:Speak_%26_Spell_(original_style).jpg (accessed 2022-11-27).

(64) LM386 Low Voltage Audio Power Amplifier Data Sheet, 2017. https://www.ti.com/lit/ds/symlink/lm386.pdf?HQS=dis-mous-null-mousermode-dsf-pf-null-wwe&ts=1681807603416&ref_url=https%253A%252F%252Fwww.mouser.com%252F.

(65) Subedi, B. *LM386 Audio Amplifier IC Pins, Working & Applications*. How To Electronics. https://how2electronics.com/lm386-audio-amplifier-ic-pins-working-circuit-applications/ (accessed 2023-04-18).

(66) Wu_tech_review_v3_no1.Pdf. http://www.samhallas.co.uk/repository/telegraph/wu_tech_review_v3_no1.pdf (accessed 2022-11-27).

(67) Szente. *Resistive Touchscreen*; 2012. https://commons.wikimedia.org/wiki/File:Resistive_touchscreen2.jpg (accessed 2022-11-27).

(68) Mercury13. *English: Schema of Capacitive Touchscreen*; 2008. https://commons.wikimedia.org/wiki/File:TouchScreen_capacitive.svg (accessed 2022-11-27).

(69) *4 Touch Panel Types - Explained*. ViewSonic Library. https://www.viewsonic.com/library/business/touch-panel-types-explained/ (accessed 2022-11-20).

(70) *Touch Screen Basics*. TRU-Vu Monitors. https://tru-vumonitors.com/touch-screen-basics/ (accessed 2022-11-20).

(71) JayWeeks. *Resistive Touch Screen on the DP32*. Instructables. https://www.instructables.com/Resistive-Touch-Screen-on-the-DP32/ (accessed 2022-11-25).

(72) Robson, C. *Real World Research*; Blackwell: Oxford, 2002.

(73) Maxwell, J. Understanding and Validity in Qualitative Research. *Harv. Educ. Rev.* **1992**, *62*, 279–300.

(74) Denzin, N. *The Research Act: A Theoretical Introduction to Sociological Methods*, 3rd ed.; Prentice Hall: N.J., 1988.

(75) Creswell, J. *Research Design: Qualitative, Quantitative and Mixed Methods Approaches*, 4th ed.; Sage, 2014.

(76) Joines, L.; Somekh, B. Observation. In *Research Methods in the Social Sciences*; Sage: London, 2005.

(77) Lincoln, Y. S.; Guba, E. G. *Naturalistic Inquiry*; SAGE, 1985.

(78) Weick, K. E. Systematic Observational Methods. In *Handbook of social psychology vol3*; Addison-Wesley: Reading, MA, 1968; pp 357–368.

(79) University of Kent. Photographic and Audio-Visual Release/Consent Form, 2017.

(80) Experience, W. L. in R.-B. U. *Why You Only Need to Test with 5 Users*. Nielsen Norman Group. https://www.nngroup.com/articles/why-you-only-need-to-test-with-5-users/ (accessed 2022-10-14).

(81) Nielsen, J.; Landauer, T. K. A Mathematical Model of the Finding of Usability Problems. In *Proceedings of the INTERACT ’93 and CHI ’93 Conference on Human Factors in*

Computing Systems; CHI ’93; Association for Computing Machinery: New York, NY, USA, 1993; pp 206–213. https://doi.org/10.1145/169059.169166.

(82) Silverman, A. M. The Perils of Playing Blind: Problems with Blindness Simulation and a Better Way to Teach about Blindness. **2015**.

(83) Silverman, A. M.; Gwinn, J. D.; Van Boven, L. Stumbling in Their Shoes: Disability Simulations Reduce Judged Capabilities of Disabled People. *Soc. Psychol. Personal. Sci.* **2015**, *6* (4), 464–471. https://doi.org/10.1177/1948550614559650.

(84) Bhirud, B. G.; Chandan, L. M.; Chawla, A. Do Congenitally Blind Individuals Have Better Haptic Object Perception Compared to Blindfolded Sighted Individuals? *Indian J. Physiol. Pharmacol.* **2016**, *60* (3), 230–234.

10. Appendix

a) *Observer script*

1. You've been invited to help us understand the effectiveness of a device. that reads out graphical data.
2. To do this you will be blindfolded.
3. You are not being tested but the device is.
4. You cannot do anything wrong.
5. If things do not work, it is not your fault.
6. Nobody's feelings will be hurt if you say anything critical about the device.
7. It's important that you speak your thoughts aloud.
8. Think of it as an item-by-item description of what you're doing and why you're doing it.
9. You can ask the instructor questions and clarify instructions.

b) *Instructor Script*

1. Please put on the blindfold
2. The purpose of this experiment is to extract information and data from a chromatogram.
3. I am going to hand you a 3d printed model of a gas chromatogram
4. You can feel it has a thickness and some peaks.
5. Place the chromatogram on the desk. To orientate it correctly you will feel a small, raised mark. This is placed at the bottom left of the spectra. If you can't feel this you may need to turn it over.
6. Can you describe what you feel?
7. Can you make any deductions at this point?
8. In front of you is device that will read out the values of the graph. You can touch this as I explain the device.
9. It has an indented area on top where the printed model can be placed. It has raised buttons on the left that will read out the x and y values. You also have been given a stylus to trace around the graph.

10. You must first place the 3D model in the device. The raised dot will be to the bottom left. It should fit snuggly at the bottom of the indent.
11. You can now touch the screen with the stylus and press the buttons to read the x and y values.
12. Try to keep the stylus at 90 degrees/perpendicular to the screen to maintain accuracy. Starting from the left can you find the retention times and the counts for the most prominent peaks?

c) *Information for participants*

Dear participant

I am conducting research into assistive technology for visually impaired students. I would be grateful for your participation in this project, user feedback is crucial to the success of this study.

To participate, you will undertake a series of tasks using a simple piece of equipment. For the duration of these tasks, you will wear a blindfold to simulate blindness. You will be guided through the tasks and able to ask questions throughout.

In addition, you will need to complete a short questionnaire. Your responses are anonymous and kept confidential. However, if you later want to withdraw, it will not be possible as there will be no way of identifying your questionnaire.

At the completion of this project, the results will be made available to all participants. The outcome of this project may contribute to further projects, and as such, the findings may be published. All information will be kept completely anonymous.

Should you have any questions, concerns or issues relating to this study, contact me on 01227 823459. If you have concerns about the implementation of this project, please discuss, in the first instance, with the school ethics representative Dr Donna Arnold.

Many thanks

Phil Marsh

d) Questionnaire

"SpectraTalk" questionnaire

Dear student, we are conducting a small survey on assistive technology. The outcome of this project may guide further development within the chemistry modules. Your feedback is crucial to the success of this study. Therefore, we would be grateful for your participation. To participate, you will need to complete this questionnaire. This is voluntary; there will be no consequences if you decline. Any responses are kept confidential and anonymous. This means that if you later wish to withdraw, it will not be possible as there will be no way of identifying your questionnaire.

		Very easy				Not easy
1	**How easy was it to manipulate the 3D models?**	5	4	3	2	1
2	**How easy was it to place the 3d print into the device?**	5	4	3	2	1
3	**How easy was it to locate peaks using the stylus?**	5	4	3	2	1
4..	**How easy was it to press the x and y buttons whilst holding the stylus?**	5	4	3	2	1
5	**How easy was it to understand the artificial voice?**	5	4	3	2	1

5 **Please use the box below any feedback you'd like to make.**