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Coursework Title: Group Report Wireless Voice Recognition Interface to Assist People with Tetraplegia to Control their Environment
Submission Deadline: 11/12/2019 4:00 pm
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Wireless Voice Recognition Interface to Assist People with Tetraplegia to Control their Environment

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***Abstract*— Around 50% of patients suffering from tetraplegia prefer to stay at home relying on family members or carers to help them complete their daily activities. Despite the efforts to develop control interfaces to simplify their life, it is still hard to find effective products capable to access more than one device at the same time. In this project, we suggest the use of a customizable voice recognition module (VRM) combined with a Bluetooth board to access the computer and potentially a wheelchair. The VRM can store up to 15 commands, which combined, significantly increases the number of devices that can be controlled. In this work, the VRM was characterized to understand how to train the device and find the limitations of the product. The tests showed that the VRM is user-dependent, reducing the likelihood of false positives, due to the noise from the environment or words said by someone else. It was also possible to connect to different computers (iOS, Windows) and perform daily tasks such as browsing the internet, opening an email and files, scroll pages up and down, etc. This device shows some interesting potential to aid people suffering from tetraplegia to complete multiple tasks, such as driving a wheelchair, controlling the environment or interface with computers and smartphones.**

I. INTRODUCTION

Spinal cord injuries (SCI) affect around 40'000 people in the UK, and for the year 2013-2014, 51% of them are considered to be tetraplegics [1]. Tetraplegia occurs when the the upper cervical level of the spine (C1 to C5) gets damaged, resulting on impairment or complete loss of motor and sensory function below the neck. Due their condition, most of the patients opt to stay at home relying on family members or caregivers to assist them complete their daily activities [2].

Assistive technology is an emerging research area focusing on the development of devices to aid people with any kind of impairments and improve their quality of life. The muscles above the neck of patients suffering from tetraplegia are usually (fully) functional. Therefore, they use them to access computers or smartphones, drive wheelchairs or controlling the environment [3]. A series of switches to serve this purpose have reached the market [4], such as sip and puff switches [5], electromyography sensors [6] and mechanical switches. Moreover, methods like, eye tracking [7], tongue motion [8][9], head tracking [10], sniffing [11] and brain signals [12] have been studied by different research groups. The main problem lies in the management of a significant number of actions, for instance a wheelchair needs at least five commands to be operated (forward, backwards, left and right, stop) [13]. Unfortunately, the aforementioned methods can saturate when more tasks are combined, thus the interest in more dynamic and efficient methods for hands-free completion of tasks.

[1] All students are MSc candidates in Rehabilitation Engineering and Assistive Technologies at University College London (UCL). This project is part of the coursework for SURG0092 Assistive Technology Devices and Rehabilitation Robotics.

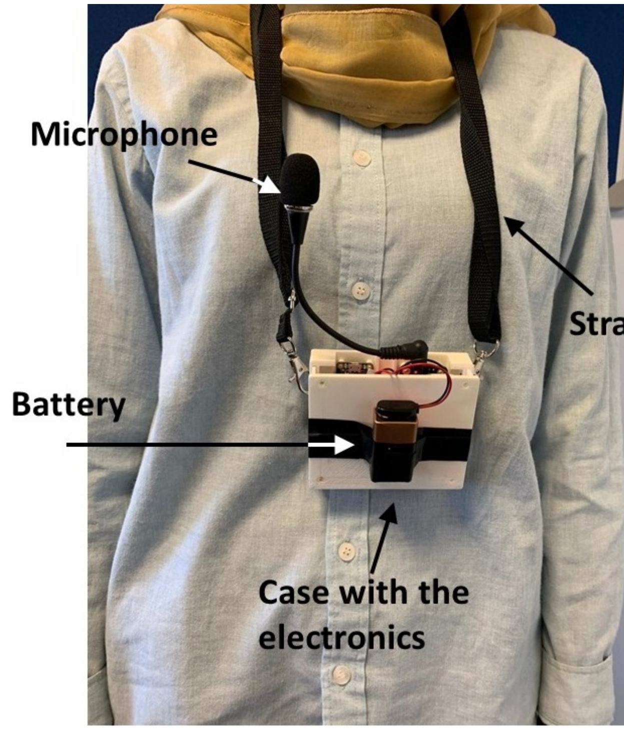

Fig. 1. User wearing the final prototype. The VRM and the Feather 32u4 are inside the 3D printed box.

An interface that has improved over the years if speech recognition, today it is possible to control (almost) every handheld or computer using speech recognition. However, the most recent devices controlled by voice require access to internet limiting the capabilities of the devices [13]. Nonetheless, voice represents a viable solution to provide patients suffering of tetraplegia with a control interface. Speech has already been used to control wheelchairs [14][15] and more effective algorithms have been develop [13] to enhance their performance. Thus, for this group project we propose the use of a commercial voice recognition module (VRM) capable of recording 15 different commands. The contributions of his work is the characterization of such module and the development of a wireless standalone device capable of aid people with upper limps paralysis to control a computer or a smart phone device. The device design will be described in section II, the methodology and results will be presented in sections III and IV, and the project will be discussed and concluded in sections V and VI respectively.

II. DEVICE DESIGN

A. User Requirements and Product Specifications

The intention was to design a user-oriented prototype, hence, potential end-users were interviewed about their ideas and preferences of the device. This indicated a need to obtain ethical approval before the start of the consultation. Main ethical considerations relate to users' false expectations of the prototype and confidentiality of the collected data. Since the developed design is a prototype only, a user will not be able to take it home or start using it independently. The number of ethics application is 6860/001 and it was approved by University College London (UCL) Research Ethics Committee. To ensure confidentiality of the obtained data, it was used anonymously in the report. The user requirements were acquired by questionnaire method. There were two questionnaires, one for user and one for family, caregiver and clinician (Appendix **??**, and were distributed by email. Due to time constraint, the questionnaires were filled by an assistive technology specialist. The user requirements are presented (Table I).

Parameter	Requirement
Cost	Below 100£
Performance	Reliable in different environments
Battery Life	2 to 3 days
Physical Design	Inconspicuous
Compatibility	iOS, Windows, Android
Type of communication	Wireless
Minimum Actions	Trigger 1 action

TABLE I
USER REQUIREMENTS

A set of device specifications listed below were derived from the user requirements:

- Arduino based hardware
- Capable to trigger multiple actions
- Customizable
- Capable to interface with different devices (computer, cellphone, wheelchair, home automation, etc.)
- HID Bluetooth communication protocol

B. Voice Recognition Module

1) Hardware: we purchased an Arduino compatible VRM(Geeetech Voice Recognition, Shenzhen Getech Technology Co.) for this prototype. An image can be seen in Fig. 2, the module can store up to 15 commands in three groups of 5 commands per group. The needed commands have to be recorded on the module first. The module has 4 pins (VCC, GND, Tx, and Rx) to be powered (5V) and to communicate (5V logic) with the environment.

2) Training the voice recognition device: the module is capable to record any kind of commands, as long as it is less than 1.3s long, can be a word or a sentence and it is not language specific. When recording the commands, the entire group has to be recorded at the same time (5 commands), to do so the module has to be accessed through a serial port, we used a UART to USB bridge (CP2102, Silicon Labs). Once the device is accesessed the commands can be recorded. The person recording the commands has to say each command twice to ensure repeatability. If the voice recognition device considers that both pronunciations were identical (or almost the same) the command will be stored, otherwise he will ask to repeat that specific command. The process is repeated for each command until the 5 of them are recorded. After a group is completed it is possible to record the other groups (it is not necessary to record all the commands).

Listing 1. Command examples

```
// Mouse right click
ble.sendCommandCheckOK
(F("AT+BleHidMouseButton=R, click"));

// Mouse left click
ble.sendCommandCheckOK
(F("AT+BleHidMouseButton=L, click"));

// Double click
ble.sendCommandCheckOK
(F("AT+BleHidMouseButton=L, doubleclick"));

// Drag and Drop
ble.sendCommandCheckOK
(F("AT+BleHidMouseButton=L, hold ,500"));

// Read email
 ble.sendCommandCheckOK
 (F("AT+BLEHIDCONTROLKEY=EMAILREADER"));
```

C. Electronic Circuit

1) Interface: The entire control interface is composed of different components as depicted in Fig 2. The voice recognition and the Feather have different power requirements, 5V and 3.3V respectively. Two batteries are used to power this prototype, a 9V alkaline battery and a 3.7 LiPo Battery. Therefore, they were not compatible, we solved this problem by adding a logic converter module (Sparkfun Electronics) that converts the 5V logic of the voice recognition to 3.3V logic of the feather, making the data processing possible. A buck converter (Sparkfun Electronics) was used to convert the 9V of the battery to 5V.

2) Software: the software was written in Arduino. When the VRM, detects a command it sends a value between 1-5 (one for each command). The Feather is constantly reading from the serial port, if a value comes in it is passed to a switch statement and the respective command is triggered.

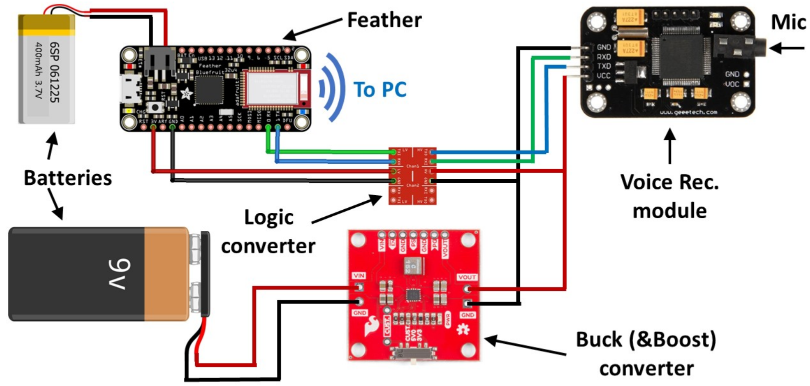

Fig. 2. Electric diagram of the device. An Feather 32u4 is connected to a VRMthrough a logic converter. The Feather is capable to connect to any Bluetooth device and control it using HID commands. This prototype uses two sources of power.

The used commands were chosen after the characterization, and are presented in Listing 1:

D. Case Design

To protect the electronics a case comprising a base and a cover, was designed using Autodesk Inventor. On the base, there were two spaces for Feather and the voice recognition module, with adequate space for cables and battery (Fig. 3). The case and its cover was coupled by protruding the cover and extruding the case. There were also screw holes to hold them together. Two supports were made on the left and right sides of the base to attach a strap. Case was printed in Ultimaker 2+ Extended 3D Printer, using acrylonitrile butadiene styrene (ABS). The final product weighed 65 g.

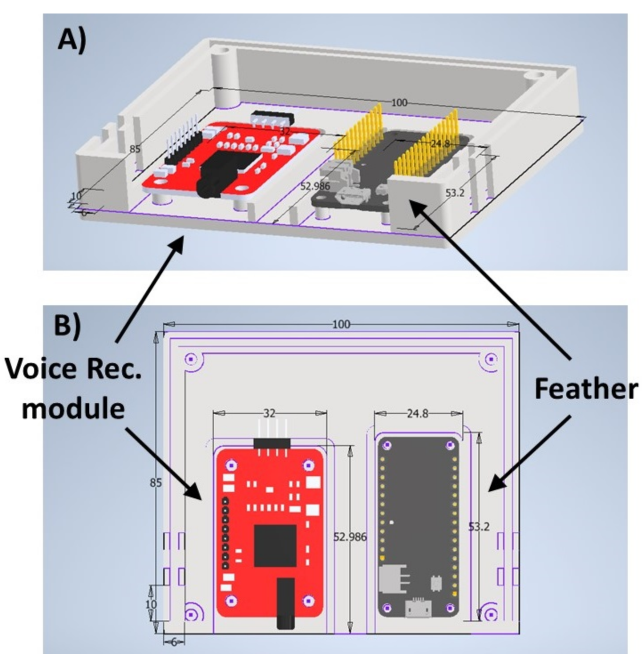

Fig. 3. CAD assembly of the device with dimensions (the cover is not depicted on this diagram). A) Isometric view. B) Top view.

III. EXPERIMENTS AND PROCEDURES

A. Characterization of the Voice Recognition Module

We performed a characterization of the voice recognition module, to understand its behavior and to be able to optimize the commands that will be implemented in the final prototype. We were interested in measuring the response of the device to different voices. Three subjects (S1, S2 and S3) participated in this experiment. First, the commands were recorded by S1, secondly, the response of the device to all the subjects was measured (including S1). Then the same commands were recorded by S2 and tested by all subjects and same for S3. A total of 15 measurements were taken for each experiment. The VRMwas connected to the computer through an Arduino, the response was displayed on the serial port and the result was recorded manually in Excel. The following experiments were performed:

1) Functional testing: the commands recorded for this experiment were the following:

- "Turn yellow"
- "Turn red"
- "Turn green"
- "Right"
- "Left"

Each command was given 5 times by each subject.

2) Commands length: the experiment was carried as described in the previous test, longer commands were recorded:

- "Turn yellow light on"
- "Turn red light on"
- "Turn green light on"
- "Make a right click"
- "Make a left click"

Each command was given 5 times by each subject.

B. Device Performance

The characterization served to optimize the commands of the final prototype. One subject recorded the commands and all the experiments were carried by that subject. The five commands chosen are sufficient to fully control a computer wirelessly using the device. Each command was given to the VRMand sent to the computer via Bluetooth (through the Feather). As a result an action was triggered on the computer. Same commands were used for the following experiments:

- ”Left mouse”
- ”Right click”
- ”Open file”
- ”Drag and drop”
- ”Email reader”

For all the test each command was given 5 times.

1) Noisy environments: the user repeated each command five times in the following environments:

- **Classroom:** the device was placed in a classroom with other people and the commands were tested while other people were speaking.
- **Street:** the device was tested outside the building in a street with cars and people.
- **Coffee shop** the switch was tested in a coffee shop with music playing and other people speaking.
- **Bus stop:** the device was taken to a bus stop and was tested with other cars and passengers passing.
- **Bar:** the device was tested in a relatively noisy environment with the music and other people speaking/screaming.

2) False Positives: the aim of this experiment was to try triggering false positives by giving commands similar to the ones above, two tests were carried:

- **Similarity:** following commands were given 5 times each:
  - ”Left house”
  - ”Right blick”
  - ”Open smile”
  - ”Dark and drop”
  - ”Email speeder”
- **Only one word of the command:** following commands were given 5 times each:
  - ”Mouse”
  - ”Click”
  - ”File”
  - ”Drag”
  - ”Email”

3) Distance between interface and controlled device: The final prototype was first tested at a distance of 1m and then at a distance of 2m from the computer to observe the strength of a bluetooth connection. Each command was given 5 times.

IV. RESULTS

A. Characterization

1) Functional Testing: the results of the experiment are presented in Fig. 4. Accuracy, sensitivity, precision, prevalence and false positive rate were calculated. For the group testing their own voice (blue column) all values were above 98%. Meanwhile, the result from testing the other’s voice had lower results for all the parameters, and a decrease in respect to increasing distance was visible.

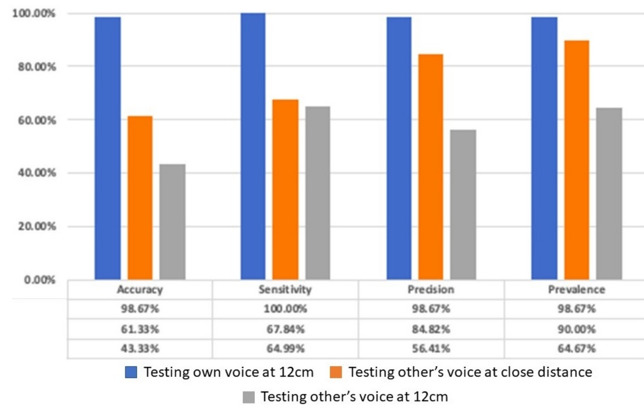

Fig. 4. Experiment to assess the functionality of the voice recognition module.

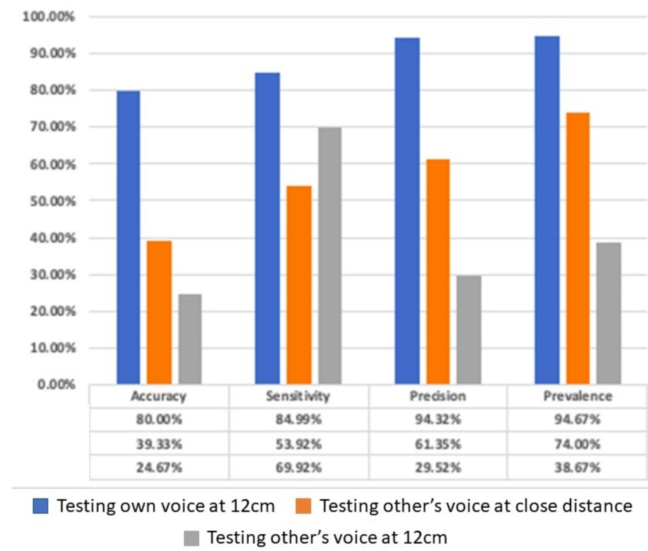

Fig. 5. Response of the VRMto longer commands.

2) Length of the commands: the results for longest commands are depicted in Fig. 5. The trends are similar to the ones shown in the previous experiment. However, there was a decrease in all parameters for all subjects. The highest value for testing own’s voice was 94.67%. The positives rates dropped significantly for the other’s voice results. Longer commands are more difficult to recognize.

B. Performance

The characterization experiments helped to define the commands for the final prototype. The following experiments were only performed by the subject that recorded the commands.

1) Noisy Environments: the environment experiment was performed and 6 non-controlled environments (street, coffee shop, bus stop, bar). The results of the silent room were compared to the average value from 6 non-controlled environments (Fig. 6). Classroom is slightly higher than that of the non-controlled group in term of accuracy and sensitivity (76% and 70.4% respectively) meanwhile there is no differ-

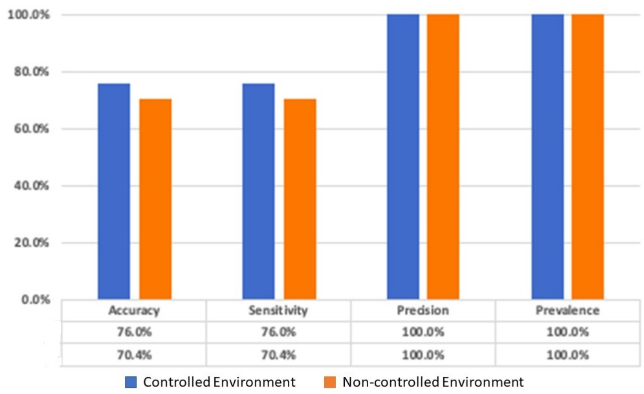

Fig. 6. Final prototype tested in 6 non controlled environments including street, coffee shop, bus stop, bar.

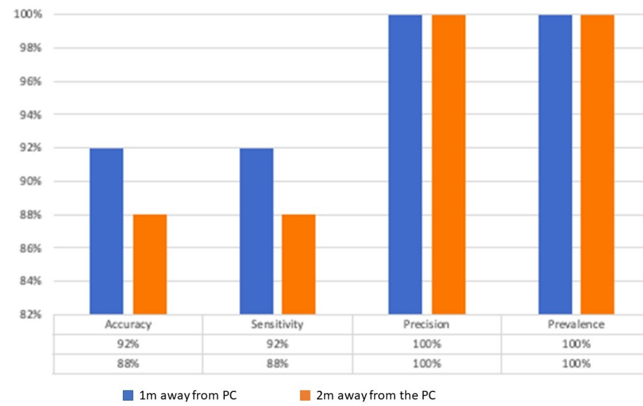

Fig. 8. User testing the device at different distances from the PC

ence of the precision and prevalence (100% in both group). Trial done at bus stop has highest accuracy and sensitivity (80%) while lowest in the bar (48%). Environments with moderate noise do not affect the performance of the device. Whereas high noise results in an accurate behavior.

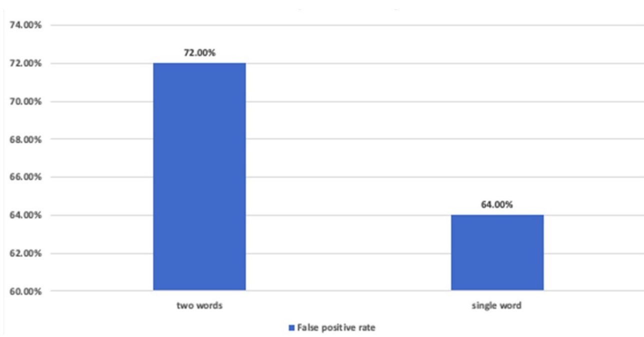

Fig. 7. After the commands were established. Similar words were given to the edvice to test the sensibility to other or simmilar commands.

2) False Positives: The results of the experiment are depicted in Fig. 7. Two words using similar ending (except drag and drop) showed a higher error rate (72%) than the one of the single similar word (64%). The device is highly sensitive to words similar to the commands, even if only one word of the command is said, the VRMis likely to react.

3) Connection performance: The trial done in 1 metre distance has greater value of accuracy and sensitivity (92%) than the 2 metre trial (88%), whereas, the precision and prevalence reach 100% in both trials as shown in Fig. 8. The experiments show that distance influences the performance of the interface.

V. DISCUSSION

A. Electronic Circuit

A VRMavailable in the market was chosen for this project. Combined with an Arduino based board (Feather 32u4) with Bluetooth capabilities it was possible to develop a wireless interface to control the environment. A series of difficulties arose due the different power requirements of the boards. A logic converter had to be included and the prototype is currently powered by 2 batteries making the entire device bigger and inefficient. The electronics can be reduced to one printed circuit board (PCB) containing the logic converter and boost converter to power the entire device with one power source. Additionally the PCB would act as link between the Feather and the VRM.

B. Wireless Voice Recognition Interface

A series of tests were carried to study and understand the behavior of the VRM. The characterization experiments showed that shorter commands are more likely to be interpreted correctly by the VRM. Moreover, the device is significantly more responsive if the commands are recorded by the user itself. We also found out that commands need to differ from each other to increase the reliability.

Commands to interface with and control a computer were chosen after the characterization. The reliability of the device was shown in the environment experiment, where the device performed similar in environments with moderate noise. However, we also found out that the use of similar words (or commands) are likely to trigger the device. Reasons for this can be the quality of the microphone. In addition, the voice commands could be filtered to enhance the quality of the command received by the VRM.

The last experiment, indicated that an effective behavior is achieved if the user is close to the device that needs to be controlled. During the experiments we observed that the 3D printed case weakens the signal of the Feather. Therefore, the placement of the board is quite relevant. This can be solved by redesigning the case.

VI. CONCLUSION

Spinal cord injuries affect a significant number of people in the UK (and worldwide), and 51% of them suffer from tetraplegia. Thus, the need to create innovative devices for them to regain their independence and improve the quality of life. Plenty of mechanical switches and interfaces have reached the market, moreover research in this area is beeing supported and progress has been made. Nonetheless, the needs vary from patient to patient and is difficult to find a device suitable for every patient.

For this project we proposed the use of a commercially available VRM, capable to be trained with 15 different commands according to the individual's requirements. Combined with a Bluetooth device (Feather) it was possible to create an interface to control electronic devices such as the computer hands-free. The experiments showed a high personalized device, likely to respond only to the user regardless of the environment capable to control the computer using 5 simple commands (right and left mouse click, drag and drop, double click and open email). In addition, the device is compatible with iOS and Windows without having to configure it.

In future work we will focus on the improvement of the electronic design, integrating everything into one PCB. This will allow the use of only one rechargeable LiPo battery making the device smaller. The software can also be improved, while it is possible to control the computer, more devices could be included such as wheelchair or the environment (lamps, TV etc.). To achieve this, we need to make use of the 15 commands valaible and be able to jump from one group to an other.

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APPENDIX I
SURVEY OF ASSISTIVE TECHNOLOGY FOR USER

1. What is your age?
   - ☐ 20 and below
   - ☐ 21 - 30
   - ☐ 31 - 40
   - ☐ 41 - 50
   - ☐ 51 - 60
   - ☐ above

2. Do you live alone or with other people?
   - ☐ Living alone
   - ☐ Living with people who provide assistance

3. Please indicate if you have difficulty in the following functions.
   - ☐ Head movement e.g. nodding
   - ☐ Eye twitching or blinking
   - ☐ Mouth gripping
   - ☐ Speaking

4. What is your current method to trigger a switch action (e.g. turning on computer)?
   ____
   ____

5. Why did you decide to use the current method?
   ____
   ____

6. What are your main factors in choosing an assistive technology to trigger a switch action?
   ____
   ____

7. What kind of actions do you want to trigger by assistive technology? (e.g. texting, calling, sending commands to wheelchair)
   ____
   ____

8. What do you think about using touch sensor to trigger a switch action?
   ____
   ____

9. How often do you think the assistive device should be charged?

   ____hours/days

10. How much do you expect a touch sensor to cost?
    ____

11. What do you think of other assistive technology to trigger a switch action, e.g. voice recognition device?
    ____
    ____

SURVEY OF ASSISTIVE TECHNOLOGY FOR RELATIVES AND CLINICIANS

1. Please indicate who is completing this survey

    - ☐ Patient's family
    - ☐ Caregiver
    - ☐ Doctor
    - ☐ Other health professional, please specify: __________

2. Does tetraplegic patient require any assistance from you?
    - ☐ Yes
      If yes, please indicate the activities that require your assistance.
      ____

    - ☐ No
      If no, is there any other form of assistance for the patient?
      ____

3. Based on your experience, what is the best assistive technology to trigger a switch action?
   ____
   ____

4. What do you consider in choosing an assistive technology to trigger a switch action for your patient/relative?
   ____
   ____

5. What do you think about using touch sensor to trigger a switch action?
   ____
   ____

6. How often do you think the assistive device should be charged?

   ____hours/days

7. How much do you expect a touch sensor to cost?
   ____

8. What do you think of other assistive technology to trigger a switch action, e.g. voice recognition device?
   ____
   ____

APPENDIX II

SURVEY OF ASSISTIVE TECHNOLOGY FOR USER - FILLED

1. What is your age?

    - 20 and below
    - 21 - 30
    - 31 - 40
    - 41 - 50
    - 51 - 60
    - above

2. Do you live alone or with other people?
    - Living alone
    - Living with people who provide assistance YES

3. Please indicate if you have difficulty in the following functions.
    - Head movement e.g. nodding
    - Eye twitching or blinking
    - Mouth gripping
    - Speaking

4. What is your current method to trigger a switch action (e.g. turning on computer)?
    None____

5. Why did you decide to use the current method?
    n/a

6. What are your main factors in choosing an assistive technology to trigger a switch action?
    Reliability and consistency. Inconspicuous.

7. What kind of actions do you want to trigger by assistive technology? (e.g. texting, calling, sending commands to wheelchair)
    Could be a number of possible uses. If it is easy to operate then I think it would have a wide application

8. What do you think about using touch sensor to trigger a switch action?
    Depends on the way I would need to touch the device.

9. How often do you think the assistive device should be charged?
    Every 2-3 days
    ____hours/days

10. How much do you expect a touch sensor to cost?
    <£100

11. What do you think of other assistive technology to trigger a switch action, e.g. voice recognition device?
    OK providing it meets other criteria._

SURVEY OF ASSISTIVE TECHNOLOGY FOR RELATIVES AND CLINICIANS - FILLED

1. Please indicate who is completing this survey

    - Patient’s family
    - Caregiver
    - Doctor
    - Other health professional, please specify: Assistive Technology Specialist

1. Does tetraplegic patient require any assistance from you?
    - Yes
      If yes, please indicate the activities that require your assistance.
      Help with selection of Assistive devices for computer access_

    - No
      If no, is there any other form of assistance for the patient?
      ____

3. Based on your experience, what is the best assistive technology to trigger a switch action?
   It depends in what context the switch is being used and what movement is available to the user. With a high level injury there are limited options available.

4. What do you consider in choosing an assistive technology to trigger a switch action for your patient/relative?
   Reliability and consistency oil operation. Inconspicuous.

5. What do you think about using touch sensor to trigger a switch action?
   I am unable to touch with my hands - it would depend on how I am able to ac5vate it.

6. How often do you think the assistive device should be charged?
   Once every 2-3 days would be best.
   ____hours/days

7. How much do you expect a touch sensor to cost?
   If it does the job well than it will be worth a premium price. Typically switches should be

<£100

8. What do you think of other assistive technology to trigger a switch action, e.g. voice recognition device?
   Voice is fine, providing it is reliable and consistent and I can use independently.

APPENDIX III
RESULTS OF EXPERIMENT 1 TESTING SHORT COMMANDS BY DIFFERENT SUBJECTS: FUNCTIONAL TESTING

Test №	Voice owner	Tester	Testing distance	Trial	Commands				
					Turn yellow	Turn red	Turn green	Right	Left
1	S1	S1	12 cm	1	+	+	+	+	+
				2	+	+	+	+	-
				3	+	+	+	+	+
				4	+	+	+	+	+
				5	+	+	+	+	+
2	S1	S3	12 cm	1	-(red)	+	+	+	-
				2	-	+	-	+	-
				3	-(red)	+	-	-	-
				4	-(red)	+	+	+	-
				5	-(red)	+	-	+	-
3	S1	S2	12 cm	1	-	-	-	-	+
				2	-	-	-	-(left)	+
				3	-	-	-	-(greeen)	-(right)
				4	-	-	-	-(yellow)	-(right)
				5	-	-	-	-(left)	-(right)
4	S1	S3	As close as possible	1	+	+	+	-(red)	+
				2	+	+	-(noice)	+	+
				3	-(red)	+	+	+	+
				4	-	+	+	+	-(right)
				5	+	+	-	+	-(right)
5	S1	S2	As close as possible	1	-(right)	-(left)	+	-(left)	-(right)
				2	-	-(left)	+	-(yellow)	+
				3	-	-(left)	-(left)	-(left)	+
				4	-(left)	-(right)	-(left)	-(left)	+
				5	-	-(right)	-(right)	+	+
6	S2	S2	12 cm	1	+	+	+	+	+
				2	+	+	+	+	+
				3	+	+	+	+	+
				4	+	+	+	+	+
				5	+	+	+	+	+
7	S2	S3	12 cm	1	+	-	-(red)	+	-
				2	-	-	+	-	-
				3	-	-	+	+	-
				4	-	-	+	-	-
				5	-	-	+	+	-
8	S2	S1	12 cm	1	+	-	+	-(left)	+
				2	-	-	+	-(left)	+

				3	-	-	+	-(left)	+
				4	-	-	+	-(left)	+
				5	-	-(green)	+	-(left)	+
9	S2	S3	As close as possible	1	-(red)	+	+	+	+
				2	+	+	-(red)	+	+
				3	+	+	+	+	+
				4	+	+	-(red)	+	+
				5	+	+	+	+	+
10	S2	S1	As close as possible	1	-(green)	+	+	-(left)	+
				2	+	+	+	-(left)	+
				3	+	+	+	+	+
				4	+	+	+	-(left)	+
				5	+	+	+	+	+
11	S3	S3	12 cm	1	+	+	+	+	+
				2	+	+	+	+	+
				3	+	+	+	+	+
				4	+	+	+	+	+
				5	+	+	+	+	+
12	S3	S2	12 cm	1	+	+	-	+	+
				2	-(red)	+	-(left)	+	+
				3	-(red)	-right	+	+	+
				4	-(red)	-(left)	-(left)	+	+
				5	-(red)	-(left)	+	+	+
13	S3	S1	12 cm	1	-(red)	+	-(red)	+	+
				2	+	+	+	+	-(right)
				3	+	-	-	+	-(right)
				4	+	+	+	+	+
				5	+	-(green)	+	+	+
14	S3	S2	As close as possible	1	-	+	+	+	+
				2	-	-(right)	+	-(left)	+
				3	-(red)	-(left)	-(left)	-(left)	+
				4	-(left)	-(left)	+	+	+
				5	-	-(left)	-(red)	-(left)	+
15	S3	S1	As close as possible	1	-(left)	+	-(red)	+	+
				2	+	-	-(red)	+	+
				3	+	-	-(red)	+	+
				4	+	-(yellow)	+	-(left)	-(right)
				5	+	+	-	-(left)	+

APPENDIX IV
RESULTS OF EXPERIMENT 2 TESTING LONG COMMANDS BY DIFFERENT SUBJECTS: COMMAND LENGTHS

Test №	Voice owner	Tester	Testing distance	Trial	Commands				
					Turn the yellow light on	Turn the red light on	Turn the green light on	Make a right click	Make a left click
1	S1	S1	12 cm	1	-(red)	+	+	- (make a left click)	+
				2	-(red)	+	+	- (make a left click)	+
				3	-(red)	+	+	- (make a left click)	+
				4	+	+	+	- (make a left click)	+
				5	+	+	+	- (make a left click)	+
2	S1	S4	12 cm	1	-	+	-	- (make a left click)	+
				2	-	-	-	-	-
				3	-	-	-	- (make a left click)	-
				4	+	-	+	- (make a left click)	+
				5	-	-	-	- (make a left click)	+
3	S1	S2	12 cm	1	-	-	-	-	+
				2	-	+	-	-	-
				3	-	-	+	-	-
				4	-	-	-	-	-
				5	-	-	+	-	-
4	S1	S4	As close as possible	1	-	-	-(make a right click)	- (make a left click)	+
				2	-	-(make a left click)	-(make a left click)	- (make a left click)	+
				3	+	-(green)	-	- (make a left click)	-
				4	-	-(make a left click)	-	- (make a left click)	+
				5	+	-	-	- (make a left click)	+
5	S1	S2	As close as possible	1	-(make a left click)	-(green)	-	- (make a left click)	+
				2	-	-	+	- (make a left click)	+
				3	-	-	+	-	+
				4	-	-	-(make a left click)	- (make a left click)	+

				5	-	-	+	- (make a left click)	+
6	S2	S2	12 cm	1	-(red)	+	+	+	+
				2	+	+	+	+	+
				3	+	+	+	+	+
				4	-	-(green)	+	+	+
				5	-	+	+	+	+
7	S2	S4	12 cm	1	-(green)	-	+	+	-(make a right click)
				2	-	-(make a right click)	+	+	-(make a right click)
				3	-	-	-	+	-(make a right click)
				4	-	-	+	+	-
				5	-	-	+	+	-
8	S2	S1	12 cm	1	-(red)	+	-	-	+
				2	-(green)	+	-	-	+
				3	-	+	-	-	+
				4	-	-	-	-	-
				5	-(red)	-	-	-	-
9	S2	S4	As close as possible	1	-(red)	+	-	+	-(make a right click)
				2	-(red)	-(make a right click)	-(make a right click)	+	-(make a right click)
				3	-	+	-(make a right click)	+	-(make a right click)
				4	-	+	-(make a right click)	+	-(make a right click)
				5	-	+	+	+	+
10	S2	S1	As close as possible	1	-	+	-(red)	+	-
				2	-	+	-(red)	+	-(make a right click)
				3	-(red)	+	+	+	-(make a right click)
				4	-	+	-(red)	+	+
				5	-	-	-(red)	+	+
11	S4	S4	12 cm	1	+	-(green)	+	-	+
				2	+	+	+	+	+
				3	+	+	+	+	+
				4	+	+	+	+	+
				5	+	-	+	+	+
12	S4	S2	12 cm	1	-	+	-	-	-
				2	-	+	-	+	+

				3	-	-	-	-	-
				4	-	+	-	-	-
				5	-	+	-	-	-(make a right click)
13	S4	S1	12 cm	1	+	-(yellow)	-(yellow)	-	-
				2	-	-(yellow)	-(yellow)	-	-
				3	+	-	-(yellow)	- (make a left click)	-
				4	+	-	-(yellow)	-	+
				5	+	-(yellow)	-	-	+
14	S4	S2	As close as possible	1	-	+	+	-	+
				2	-	+	-(yellow)	+	+
				3	-	+	-	+	+
				4	-	+	-	- (make a left click)	-(make a right click)
				5	+	+	-	+	+
15	S4	S1	As close as possible	1	+	-(yellow)	-(yellow)	-	+
				2	+	-	-(yellow)	- (make a left click)	-(make a right click)
				3	+	-(yellow)	-(yellow)	- (make a left click)	+
				4	+	-(yellow)	-(yellow)	- (make a left click)	-(make a right click)
				5	+	-(yellow)	-(yellow)	- (make a left click)	+

APPENDIX V
RESULTS OF EXPERIMENT 3: ENVIRONMENTAL TESTING

Quiet environment

№ trial	Left mouse	Right click	Open file	Drag n drop	Email reader
1	+	+	+	+	+
2	-	-	-	-	+
3	+	-	+	+	+
4	+	+	+	+	+
5	+	-	+	+	+

Street

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	+	+	-	+	+
2	+	+	-	+	+
3	+	+	+	+	+
4	-	-	+	+	+
5	+	-	-	+	+

Coffee shop

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	+	+	-	+	+
2	+	-	+	-	+
3	+	-	+	-	+
4	+	+	+	+	+
5	+	-	+	+	+

Bus stop

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	+	+	+	+	+
2	+	+	+	+	+
3	-	-	+	+	+
4	-	-	+	+	-

5	+	+	+	+	+

Bar

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	-	+	-	-	-
2	+	+	-	+	-
3	+	-	-	+	+
4	+	-	+	+	+
5	-	+	-	-	-

Classroom

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	+	+	+	+	+
2	+	-	+	-	+
3	+	-	-	+	+
4	+	-	+	+	+
5	+	+	-	-	+

APPENDIX VI
RESULTS OF EXPERIMENT 4: FALSE POSITIVE TESTING

№ trial	Left house	Right blick	Open smile	Dark and drop	Email speeder
1	-	-	+	+	+
2	-	+	+	+	+
3	+	-	+	+	+
4	+	-	-	+	+
5	+	+	+	-	+

№ trial	Mouse	Click	File	Drag	Email
1	+	+	-	-(right click)	+
2	+	+	-	-(right click)	-
3	+	+	+	-(right click)	-
4	+	+	-	-	-
5	+	+	-	-(right click)	-

APPENDIX VII
RESULTS OF EXPERIMENT 5: DISTANCE TESTING

Distance - bluetooth 1m

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	+	-	+	+	+
2	+	+	+	+	+
3	+	+	+	-	+
4	+	+	+	+	+
5	+	+	+	+	+

Distance – bluetooth 2m

№ trial	Left mouse	Right click	Open file	Drag and drop	Email reader
1	+	-	-	+	+
2	+	+	+	+	+
3	+	+	+	+	+
4	+	+	-	+	+
5	+	+	+	+	+

APPENDIX VIII
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 1: FUNCTIONAL TESTING

Data collection											
Test	Recorder	Tester	Distance	TN	FN	PN	FP	TP	PY	AN	AY
1	S1	S1	12 cm	0	0	0	1	24	25	1	24
2	S1	S3	12 cm	0	4	4	10	11	21	10	15
3	S1	S2	12 cm	0	7	7	16	2	18	16	9
4	S1	S3	Closest	0	5	5	2	18	20	2	23
5	S1	S2	Closest	0	15	15	3	7	10	3	22
6	S2	S2	12 cm	0	0	0	0	25	25	0	25
7	S2	S3	12 cm	0	1	1	16	8	24	16	9
8	S2	S1	12 cm	0	6	6	8	11	19	8	17
9	S2	S1	Closest	0	4	4	0	20	20	0	24
10	S2	S3	Closest	0	0	0	3	22	25	3	22
11	S3	S3	12 cm	0	0	0	0	25	25	0	25
12	S3	S2	12 cm	0	9	9	1	15	16	1	24
13	S3	S1	12 cm	0	5	5	2	18	20	2	23
14	S3	S2	Closest	0	11	11	3	11	14	3	22
15	S3	S1	Closest	0	8	8	3	14	17	3	22

Data analysis							
Test	Recorder	Tester	Distance	Accuracy	Sensitivity	Precision	Prevalence
1	S1	S1	12 cm	96.00%	100.00%	96.00%	96.00%
2	S1	S3	12 cm	44.00%	73.33%	52.38%	60.00%
3	S1	S2	12 cm	8.00%	22.22%	11.11%	36.00%
4	S1	S3	Closest	72.00%	78.26%	90.00%	92.00%
5	S1	S2	Closest	28.00%	31.82%	70.00%	88.00%
6	S2	S2	12 cm	100.00%	100.00%	100.00%	100.00%
7	S2	S3	12 cm	32.00%	88.89%	33.33%	36.00%
8	S2	S1	12 cm	44.00%	64.71%	57.89%	68.00%
9	S2	S1	Closest	80.00%	83.33%	100.00%	96.00%
10	S2	S3	Closest	88.00%	100.00%	88.00%	88.00%
11	S3	S3	12 cm	100.00%	100.00%	100.00%	100.00%
12	S3	S2	12 cm	60.00%	62.50%	93.75%	96.00%
13	S3	S1	12 cm	72.00%	78.26%	90.00%	92.00%
14	S3	S2	Closest	44.00%	50.00%	78.57%	88.00%
15	S3	S1	Closest	56.00%	63.64%	82.35%	88.00%
Testing their own voice in 12 cm distance			Average	98.67%	100.00%	98.67%	98.67%
			S.D.	2.31%	0.00%	2.31%	2.31%
Testing other's voice in closest distance			Average	61.33%	67.84%	84.82%	90.00%
			S.D.	22.86%	24.56%	10.32%	3.35%
Testing other's voice in 12 cm distance			Average	43.33%	64.99%	56.41%	64.67%
			S.D.	22.26%	23.03%	32.02%	26.10%

APPENDIX IX
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 2: COMMAND LENGTHS

Data collection											
Test	Recorder	Tester	Distance	TN	FN	PN	FP	TP	PY	AN	AY
1	S1	S1	12 cm	0	8	8	0	17	17	0	25
2	S1	S4	12 cm	0	4	4	15	6	21	15	10
3	S1	S2	12 cm	0	0	0	21	4	25	21	4
4	S1	S4	Closest	0	10	10	9	6	15	9	16
5	S1	S2	Closest	0	7	7	10	8	18	10	15
6	S2	S2	12 cm	0	2	2	2	21	23	2	23
7	S2	S4	12 cm	0	5	5	11	9	20	11	14
8	S2	S1	12 cm	0	3	3	16	6	22	16	9
9	S2	S4	Closest	0	10	10	4	11	15	4	21
10	S2	S1	Closest	0	7	7	6	12	18	6	19

Data analysis							
Test	Recorder	Tester	Distance	Accuracy	Sensitivity	Precision	Prevalence
1	S1	S1	12 cm	68.00%	68.00%	100.00%	100.00%
2	S1	S4	12 cm	24.00%	60.00%	28.57%	40.00%
3	S1	S2	12 cm	16.00%	100.00%	16.00%	16.00%
4	S1	S4	Closest	24.00%	37.50%	40.00%	64.00%
5	S1	S2	Closest	32.00%	53.33%	44.44%	60.00%
6	S2	S2	12 cm	84.00%	91.30%	91.30%	92.00%
7	S2	S4	12 cm	36.00%	64.29%	45.00%	56.00%
8	S2	S1	12 cm	24.00%	66.67%	27.27%	36.00%
9	S2	S4	Closest	44.00%	52.38%	73.33%	84.00%
10	S2	S1	Closest	48.00%	63.16%	66.67%	76.00%
11	S4	S4	12 cm	88.00%	95.65%	91.67%	92.00%
12	S4	S2	12 cm	24.00%	85.71%	25.00%	28.00%
13	S4	S1	12 cm	24.00%	42.86%	35.29%	56.00%
14	S4	S2	Closest	56.00%	82.35%	63.64%	68.00%
15	S4	S1	Closest	32.00%	34.78%	80.00%	92.00%
Testing their own voice in 12 cm distance			Average	80.00%	84.99%	94.32%	94.67%
			S.D.	10.58%	14.87%	4.92%	4.62%
Testing other's voice in closest distance			Average	39.33%	53.92%	61.35%	74.00%
			S.D.	11.98%	17.51%	15.92%	12.33%
Testing other's voice in 12 cm distance			Average	24.67%	69.92%	29.52%	38.67%
			S.D.	6.41%	20.14%	9.82%	15.73%

APPENDIX X
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 3: ENVIRONMENTAL TESTING

Data collection								
Environment	TN	FN	PN	FP	TP	PY	AN	AY
Quiet	0	6	6	0	19	19	0	25
Street	0	6	6	0	19	19	0	25
Coffee shop	0	6	6	0	19	19	0	25
Bus stop	0	5	5	0	20	20	0	25
Bar	0	13	13	0	12	12	0	25
Classroom	0	7	7	0	18	18	0	25

Data analysis					
Environment		Accuracy	Sensitivity	Precision	Prevalence
Controlled	Quiet	76.00%	76.00%	100.00%	100.00%
Non-controlled	Street	76.00%	76.00%	100.00%	100.00%
	Coffee shop	76.00%	76.00%	100.00%	100.00%
	Bus stop	80.00%	80.00%	100.00%	100.00%
	Bar	48.00%	48.00%	100.00%	100.00%
	Classroom	72.00%	72.00%	100.00%	100.00%
	Average	70.40%	70.40%	100.00%	100.00%
	S.D.	12.84%	12.84%	0.00%	0.00%

APPENDIX XI
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 4: FALSE POSITIVE TESTING

Trial	Left house	Right blick	Open smile	Dark and drop	Email speeder
1	-	-	+	+	+
2	-	+	+	+	+
3	+	-	+	+	+
4	+	-	-	+	+
5	+	+	+	-	+

N=25	Predicted: NO	Predicted: YES	
Actual: NO	TN = 7	FP = 0	7
Actual: YES	FN = 18	TP = 0	18
	25	0	

Trial	Mouse	Click	File	Drag	Email
1	+	+	-	-(right click)	+
2	+	+	-	-(right click)	-
3	+	+	+	-(right click)	-
4	+	+	-	-	-
5	+	+	-	-(right click)	-

N=25	Predicted: NO	Predicted: YES	
Actual: NO	TN = 9	FP = 0	9
Actual: YES	FN = 16	TP = 0	16
	25	0	

APPENDIX XII
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 5: DISTANCE TESTING

Data collection								
Distance	TN	FN	PN	FP	TP	PY	AN	AY
1 metre	0	2	2	0	23	23	0	25
2 metre	0	3	3	0	22	22	0	25

Data analysis				
Distance	Accuracy	Sensitivity	Precision	Prevalence
1 metre	92.00%	92.00%	100.00%	100.00%
2 metre	88.00%	88.00%	100.00%	100.00%

APPENDIX XI
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 4: FALSE POSITIVE TESTING

Trial	Left house	Right blick	Open smile	Dark and drop	Email speeder
1	-	-	+	+	+
2	-	+	+	+	+
3	+	-	+	+	+
4	+	-	-	+	+
5	+	+	+	-	+

N=25	Predicted: NO	Predicted: YES	
Actual: NO	TN = 7	FP = 0	7
Actual: YES	FN = 18	TP = 0	18
	25	0	

Trial	Mouse	Click	File	Drag	Email
1	+	+	-	-(right click)	+
2	+	+	-	-(right click)	-
3	+	+	+	-(right click)	-
4	+	+	-	-	-
5	+	+	-	-(right click)	-

N=25	Predicted: NO	Predicted: YES	
Actual: NO	TN = 9	FP = 0	9
Actual: YES	FN = 16	TP = 0	16
	25	0	

APPENDIX XII
DATA COLLECTION AND DATA ANALYSIS OF EXPERIMENT 5: DISTANCE TESTING

Data collection								
Distance	TN	FN	PN	FP	TP	PY	AN	AY
1 metre	0	2	2	0	23	23	0	25
2 metre	0	3	3	0	22	22	0	25

Data analysis				
Distance	Accuracy	Sensitivity	Precision	Prevalence
1 metre	92.00%	92.00%	100.00%	100.00%
2 metre	88.00%	88.00%	100.00%	100.00%