Tongue-To-Speech (TTS): Wearable Wireless Assistive Device for Augmented Speech

BY

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THESIS

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LIST OF ABBREVIATIONS

A	Ampere
AD	Assistive Device
ADC	Analog to Digital Converter
atm	Atmosphere
ATTT	Average Typing Test Time
BLE	Bluetooth Low Energy
C	Celsius
ccpm	Correct Characters per Minute
CNS	Central Nervous System
DC	Direct Current
DIY	Do It Yourself
e.g.	exempli gratia
g	Grams
GND	GrouND
Hz	Hertz
I^2C	Inter Integrated Circuit
IEEE	Institute of Electrical and Electronic Engineers

LIST OF ABBREVIATIONS (continued)

IoT	Internet of Things
ITC	Inductive Tongue Control
iTDS	intraoral Tongue Drive System
LED	Light Emitting Diode
MIT	Massachusetts Institute of Technology
mm	Millimeters
ms	Millisecond
PC	Personal Computer
pF	Pico Farad
PWM	Pulse Width Modulation
RPM	Round Per Minute
SCL	Serial CLock
SCI	Spinal Cord Injury
SDA	Serial DAta
SGD	Speech Generating Devices
SoC	System–on–a–Chip
TC	Typed Characters
TCI	Tongue–Computer Interface

LIST OF ABBREVIATIONS (continued)

TDS	Tongue Drive System
TDS–UI	Tongue Drive System Universal Interface
TTS	TongueToSpeech
UART	Universal Asynchronous Receiver Transmitter
ULD	Upper Limb Disability
UIC	University of Illinois at Chicago
USB	Universal Serial Bus
V	Volts
VMD	Vibrating Motor Disc

SUMMARY

Communication is an essential aspect in human life, in every environment or social aspect of people's life, private or public. In modern society, the word communication does not only refer to speech or vocal communication, but also to silent communication (communication via typed words) since typing devices such as smartphones, tablets and personal computers are extensively used nowadays. There are many different reasons that can cause on individual to have difficulty or inability to communicate. The most common and important disabilities are upper limb disabilities (e.g. spinal cord injury), speech impairments or disorders (e.g. mutism and aphasia), or medical conditions such as fractures or carpal tunnel. We have developed the TongueToSpeech (TTS) device with the goal of augmenting communication for individuals that are affected by these conditions. TTS is a wearable, wireless, non–invasive and discreet assistive device that incorporates a capacitive touch keyboard inside a retainer positioned in the oral cavity. The device is connected via Bluetooth to an Android smartphone application. The developed TTS app, receives the text typed by the tongue on the retainer and displays it on the screen. Using TextToSpeech technology, the app is also able to convert the text into audible speech. Our studies have shown that using a 7 contact points keyboard configuration provides the best results in terms of accuracy, precision and typing speed performances. Tests have shown that it takes 3 days for the user to remember correctly the position of the keys inside the mouth and to obtain steady results at typing the same sentence, while it needs 5 days to remember the position of the letter in the keyboard. On average using TTS inside the oral cavity takes around 2.5–3 times longer than using the T9 configuration on smartphone to type the same phrase. This gap is consistent over time. Our studies have shown that TTS delivers better results in terms of typing performances compared to the assistive device available on the market. In conclusion, we have developed a discreet, non–invasive, wearable and wireless device, that provides a quality solution that helps people with communication problems.

CHAPTER 1

INTRODUCTION

Communication is essential in modern society, in every environment or social aspect of people's life, private or public. In the United States in 2015 the total number of people with disabilities was 13 million (more than twice compared to 2012) [1] and it has been estimated that 1 every 6 American has or will have a communication disorder during his or her lifetime [2]. In modern society, the word communication does not only refer to speech or vocal communication, but also to silent communication (communication via typed words) since typing devices such as smartphones, tablets and personal computers are extensively used nowadays.

There is a wide range of different conditions that can lead to a person's inability, difficulty or discomfort to communicate: upper limb disabilities (e.g. spinal cord injury), physical injuries (temporary or permanent), speech/language disorders (e.g. aphasia) or mutism [3].

Damages to the Central Nervous System (CNS) are often cause of upper limb disability (ULD). ULD is a condition that prevent an individual from partially or completely using his arms and hands. ULDs are often caused by spinal cord injury (SCI) [4].

SCIs are permanent injuries caused by damage of vertebrae, ligaments or disks of the spinal column [4]. The spinal cord is made of group of nerves that diffuse around the body in different directions and areas and it extends from the base of the brain to the area above the waist [4]. Common causes of SCI are motor vehicle accidents, falls, act of violence, sport injuries, alcohol abuse and diseases (e.g. cancer, inflammations) [4]. Depending on the position and the severity of the spinal cord injury, the ability to control limbs are different, as shown in Figure 1. The red areas highlighted in Figure 1 are the body parts affected by the injury.

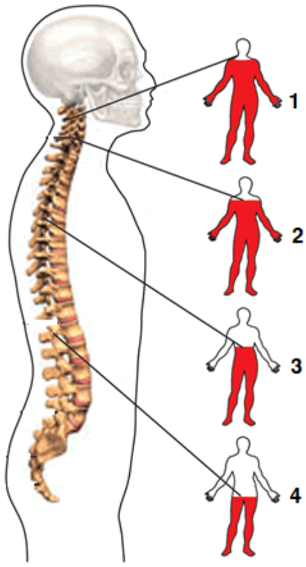


Figure 1: Spinal Cord Injury [5]

The injuries of the cervical and thoracic upper vertebrae shown in Figure 1 (1-2) can cause Tetraplegia (or Quadriplegia), while the injuries of the lumbar and thoracic lower vertebrae shown in Figure 1 (3-4) can cause Paraplegia. Tetraplegia is a condition that does not allow the individual to use his hands, arms, trunk, legs and pelvic area, while Paraplegia only affect the pelvic area, the legs and part of the trunk [4].

Other injuries that can affect the ability to properly use hands and arms are the carpal tunnel, arm or wrist fractures, or epicondylitis. These injuries are temporary and usually not severe. The duration of them is based on their severity.

The most common physical injuries, not involving upper limbs, related to the inability to communicate are injuries of the body parts involved in human speech, such as vocal cords, larynx and lungs. At the anatomical level, what happens during speech is that the vocal cords regroup over the trachea and vibrate to the airflows coming from the lungs (Figure 2 (a)). The vibration is what makes the sound and allows different tones. Any injury that prevents this process to happen, can cause in the subject an obstacle to speak [3].

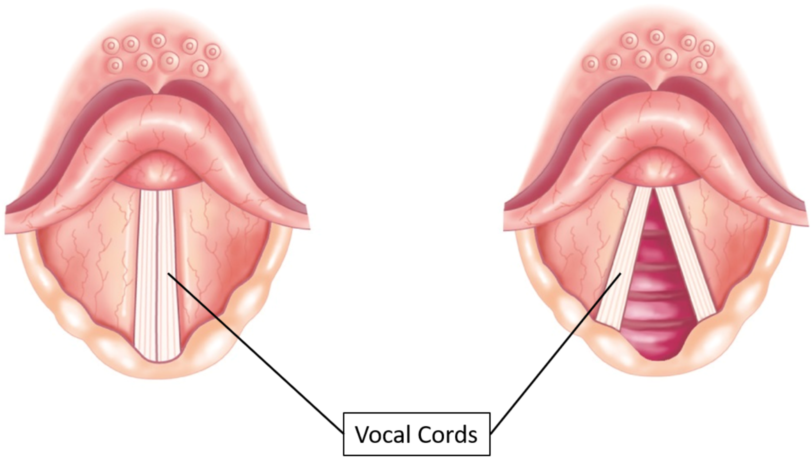


Figure 2: Vocal cords close (a) and open (b) [6]

Other diseases as laryngitis, or more severe (larynx tumor), can also likely cause inability or discomfort during speech.

Emotional trauma, fear or anxiety are also reason of a permanent (rare) or temporary status of inability to communicate, especially in children. This phenomenon is called elective mutism, which is a total lack of speech, that comes from a personal choice of the patient. This can happen as a reaction to traumatic events that could trigger a mental change in the person [7].

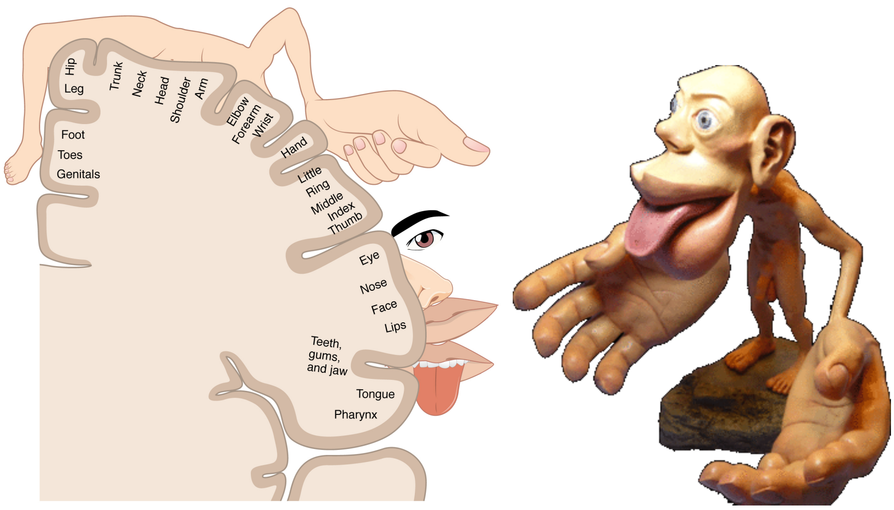
Speech and language disorders such as aphasia also are an important cause of communication related problems. Aphasia is a condition that leads to inability to formulate or understand language and is caused by damage to specific brain regions [8] [9]. The most common cause of brain damage is stroke or head trauma.

A medical condition that can prevent people from communicating is the brain aneurysm [10] [11]. An aneurysm is a sac formed by the weakening of the blood vessels wall of an artery or a vein [12]. While it increases in size, the risk of rupture also increases. If an aneurysm pops, it causes internal bleeding and if it is localized in the brain it can cause severe damages to the patient [12].

1.1 Tongue as Input

When designing an assistive device, one of the most important aspect to consider is its discreetness, since the final user does not want to attract unwanted attentions while using the device [13]. One of the best location to position an assistive device is the oral cavity, using the tongue as input to control it. The tongue is a muscle that has various tasks: it helps during food mastication, it helps during the swallowing process, it is the most important organ of taste in the gustatory system and most important, plays a crucial role in enabling human speech [14]. Using the tongue as input methods for assistive devices, not only allows the device to be discreet, but has also other important advantages:

- The tongue is one of the most used muscles and it is almost never subject to fatigue.
- The tongue has the ability to perform complex, accurate and fast movements inside the mouth [15]. In the Homunculus Primary Motor Cortex representation (Figure 3), it is visible that the fingers and the tongue cover almost the same area, which means that the tongue is capable of having similar motor skills to the fingers, in terms of precision and complexity [15] [16].



(a) (b)

Figure 3: Primary motor cortex in homunculus 2D (a), 3D (b) [16]

- The tongue is not easily affected by involuntary neurological activities such as muscular spams, it is not affected by the position or posture of the body [15].
- The tongue is directly connected to the brain, it is not affected in presence of disabilities like spinal cord injuries.

1.2 Assistive Devices

Assistive Devices (AD) that are used to help individuals that suffers from severe speech impairments or general communication problems to restore their ability to communicate are part of a category of devices named Speech Generating Devices (SGD) [17].

SGDs utilize digitized or synthesized speech. Digitized devices deliver words or sentences using prerecorded messages, and have the final user playing it back on demand. On the contrary, synthesized devices take the users input and convert it into speech using algorithms. Users are not limited to prerecorded messages but can create their customized real–time messages by themselves according to their needs [17] [18].

The most important assistive devices and interfaces currently available on the market are:

- Mouthstick Device

  Mouthstick (shown in Figure 4 (a)) is a low tech system that provides access to personal computers for people with disabilities. It consists of a stick held with the mouth that is used to type on external keyboards or touchscreens. It is a cheap and easy to learn device [19] [20]. One of the limitations of the Mouthstick system is that it is not portable because it requires an external keyboard, also this device is not discreet and requires extensive use of the head and the neck for typing, which over time can cause fatigue.

(a) (b)

Figure 4: Mouthstick Device and Sip and Puff Device [19] [21]

- Sip and Puff

  Sip and Puff (shown in Figure 4 (b)) is a device that uses the user's breath to control an external device. These devices are currently commercially available. The Sip and Puff can also be used to control the computer mouse using lip movements and breathe to manage the clicking action [19]. One of the limitations of the Sip and Puff system is that an extensive use can cause fatigue because it requires to constantly breathe in the device.

- Gaze Tracker Device

  Eye gaze (shown in Figure 5) is a device that uses a camera to convert eye movements to an input that controls a personal computer. There are various commercial versions of Gaze Tracker available on the market; the price range varies from couple of hundreds of dollars to free ones using a personal computer webcam [22] [23]. Gaze tracker is sufficient at controlling the personal computer cursor and can also be used as a typing device using an on-screen keyboard [24]. Other limitations of the device are the fact that it is not portable due to the use of an external camera.

Figure 5: Eye Tracker Device [19]

- Head Tracker Device

  Head Tracker (shown in Figure 6) is a device that uses an infrared camera to control reflective markers positioned on the subject head [23]. The camera analyzes the position and the movements of the marker over time and, based on the trajectory, scrolls the letters on a on–screen keyboard. Head Tracker's limitation is the facts that it is not a portable device because it uses an infrared camera and wide external screen keyboard.

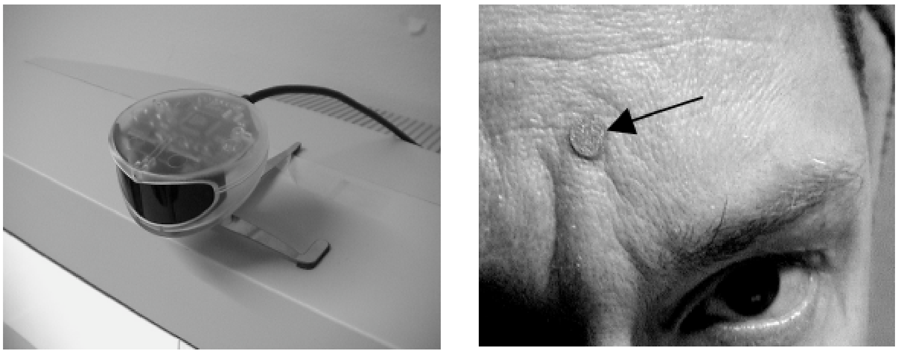


Figure 6: Head Tracker Camera and Marker [19]

- Dasher Interface

  Dasher is an interface that uses an user–controlled pointer and word prediction system [19] [25]. Dasher can also be combined with other commercially available assistive devices. A possible solution is combining the Eye Gaze tracker and Dasher. This combination can increase the efficiency and the typing speed of 3 times [19]. Dasher is not portable because it used an external screen.

- EZ Keys

  Ez Keys is a popular commercially available word prediction software and speech output program. It can be used with different inputs: single mouse click, external button, EMG switch signal, or any other device that is able to provide a switch signal [19]. Stephen Hawking, diagnosed with ALS, has used EZ Keys in his computer-based communication system to write email, surf on the internet and write [19] [26]. EZ Keys is an expensive not portable device, due to its wide external screen.

All the assistive devices listed above, offer very different input methods and solutions for typing and communicating (head, eyes, breath or hands), but none of these uses the tongue. As already described in 1.1, using the tongue as input methods presents multiple advantages over other methods such as the fact that it is resistant to fatigue, its accuracy, speed and ability to properly function even in presence of upper limb disabilities (e.g. spinal cord injury) or speech impediments. All the devices that uses the tongue as input methods to control a personal computer (PC) or smartphone are also named Tongue–Computer Interfaces (TCI).

1.3 Tongue–Computer Interface (TCI)

TCI devices are technological systems that allows the users to send data to control an external device such as smartphones or personal computers using the tongue as an interface. Usually, TCI devices are used to help people that suffers severe disabilities (e.g. spinal cord injury, tetraplegia, etc.), have difficulties to communicate or cannot use their arms or hand as input method. TCI devices allows them to control their wheelchair with the tongue, control the mouse on a personal computer and type words on external devices [15] [27] [28] [29] [30] [31]. There is a wide variety of different TCI devices on the market or research that allows users to type and communicate using external devices such as smartphones and PC.

- Inductive Tongue Control (ITC)

  ITC (shown in Figure 7 (a)) is a device that uses inductive sensors (coils) that change their inductances if a ferromagnetic material is placed nearby. The user attaches a ferromagnetic material to the tip of his tongue and based on the distance from the coils, the system recognize a gesture and type a letter [19] [29]. The problems linked to the ITC device are the fact that it is not wireless and has wires coming out of the mouth, it is partially invasive, since a ferromagnetic material has to be attached to the tip of the tongue and it has a limited selection of letters.

- Intraoral Tongue Drive System (iTDS)

  iTDS-2 is a device that uses a system-on-a-chip to amplify and digitalize the raw magnetic sensor data and to send it to an outside interface using a planar inverted-F antenna [27]. The TDS-UI receives the magnetic sensor data, it uses a sensor signal processing algorithm on a smartphone to recognize the user commands and sends the intended commands to an external device, such as a PC [27]. In order to function, a small magnetic tracer has to be attached to the tip of the tongue. Based on the tracer position, the external device process one of the seven programmed command to control the movement of a personal computer cursor or a wheelchair [27]. iTDS-2 device may allow only to type on on–screen keyboards using the PC cursor. It is also a partially invasive device, since it need a tracer to be attached to the tongue.

- MouthPad

  MouthPad is a TCI that displays the tongue position and movements on a computer

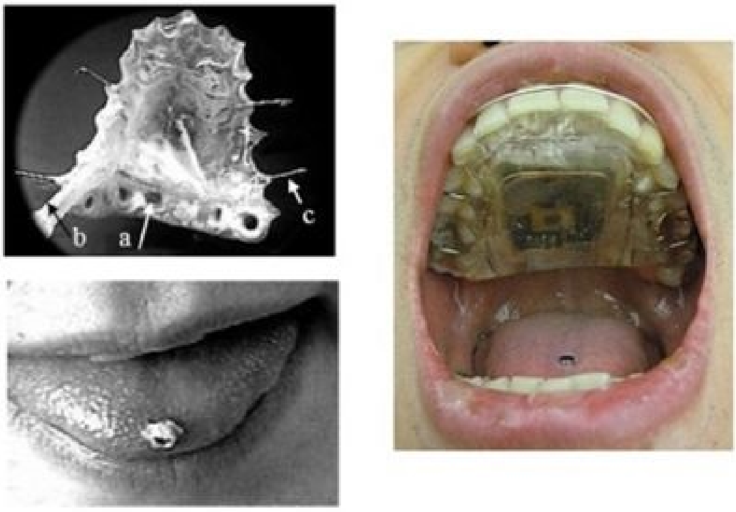


Figure 7: ITC (a), TDS (b) [19]

screen, allowing to control the cursor movements on a PC [28]. The system uses an electrode array, and an embedded controller that communicates with a target computer via Bluetooth with a custom communication protocol. The tongue movement is detected by analyzing the measurement the impedance between the tip of the tongue and the electrode array. The electrode array consists of a 49 gold plated electrodes arranged in 7 rows and 7 columns to form a square [28]. MouthPad may allow to type on on–screen keyboards that can be controlled only by using a cursor.

- Tongue Drive System (TDS)

  The Tongue Drive System (shown in Figure 7 (b)) can wirelessly detect the position of the tongue inside the mouth and converts the tongue motions into specific pre–set commands. These commands can give access to a computer cursor or drive a wheelchair

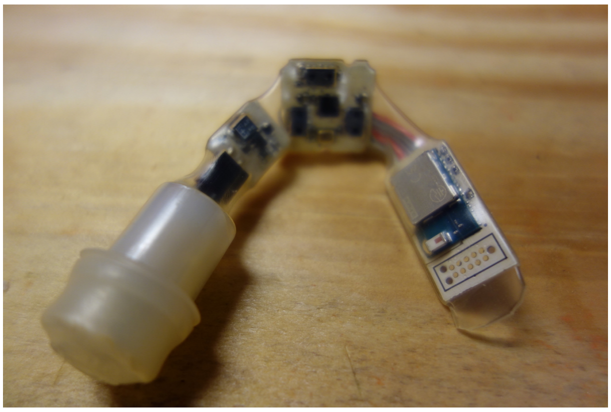


Figure 8: Pallette device [32]

[15]. TDS consists of an array of magnetic sensors placed inside the mouth, that measures the magnetic field of a magnet attached to the tongue. The data received from the array (motion and orientation of the tongue) are processed to allow the user to control the mouse cursor on a computer screen [15]. Other version of the Tongue Drive System have been developed during the years, both intraoral [31] and extra–oral [30] and the new versions are able to interact also with Android and Apple smartphones [31]. TDS may allow to type on on–screen keyboards, only controllable with a PC cursor. TDS is also not a discreet device due to the set of headphones used [30].

- Pallette

  Pallette (shown in Figure 8) is a intraoral device that allows the user to control technologies using the tongue. Pallette uses infrared sensors localized behind the upper incisors to triangulate the position of the tongue to track its motion. Pallette also used a micro-phone to detect tongue taps [32]. It currently provides the users with the ability to control computers, Android tablets and Android phones. Pallette is fully open source (hardware and software), with available guides for creating and using it [32]. Pallette allows users to type word only on on–screen keyboards that are only controllable using a cursor.

All the problems and limitations related to the devices described in section 1.2 and 1.3 are summarized in Table I.

TABLE I: ASSISTIVE DEVICES LIMITATIONS

Not Portable	Mouthstick, Sip and Puff, Gaze Tracker, Head Tracker, Dasher, EZ Keys, ITC
Not Discreet	Mouthstick, Sip and Puff, Gaze Tracker, Head Tracker, Dasher, EZ Keys, ITC
Not Designed for Typing	iTDS–2, TDS, Pallette, MouthPad
Fatigue	Mouthstick, Sip and Puff, Head Tracker
Invasive	ITC, iTDS–2, TDS

In this thesis, we propose the TongueToSpeech device (TTS). TTS has the goal of providing a solution to communication related problems, that avoids the limitations of the mentioned devices, and of improving the quality of life of people affected by these problems.

1.4 Tongue To Speech (TTS)

TTS is a retainer contained in the oral cavity with an embedded keyboard using T9 configuration that can be controlled using the tongue. The text typed by the user is sent via Bluetooth connection to a smartphone application with Text to Speech technology, that displays the text and is able to convert it into audible speech (Figure 9).

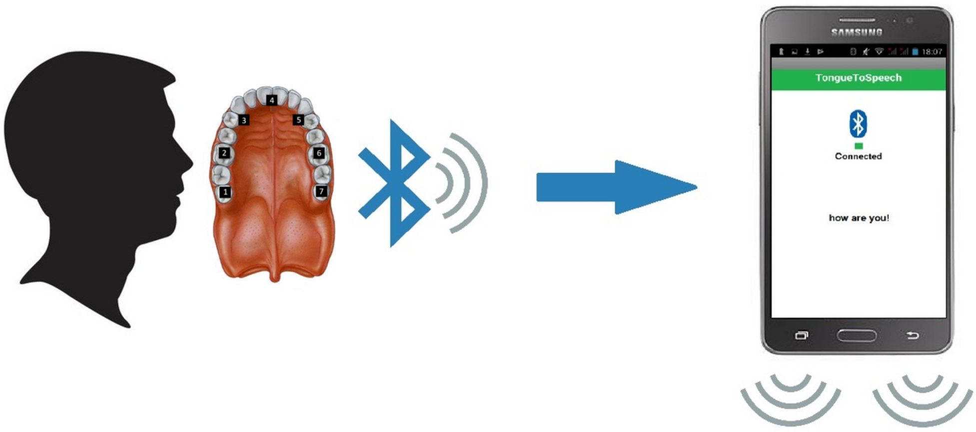


Figure 9: TTS overview

1.4.1 TTS Design

TTS composes of three building blocks: housing layers, electronic and keyboard:

Housing Layers: the electronics and the keyboard are embedded between two insulating layers. The bottom layer is made of a thermoplastic sheet that is shaped around the subject's palate and teeth impression. The top layer is made using a solidified polymeric paste that covers the electronic and the keyboard and insulate the device. On the top layer, small holes are embedded in the proximity of the keys to give the user feedback about the position of the electrodes and to guide the tongue towards the key. The shape and the depth of the holes allows the tip of the tongue to perfectly fit inside the holes.

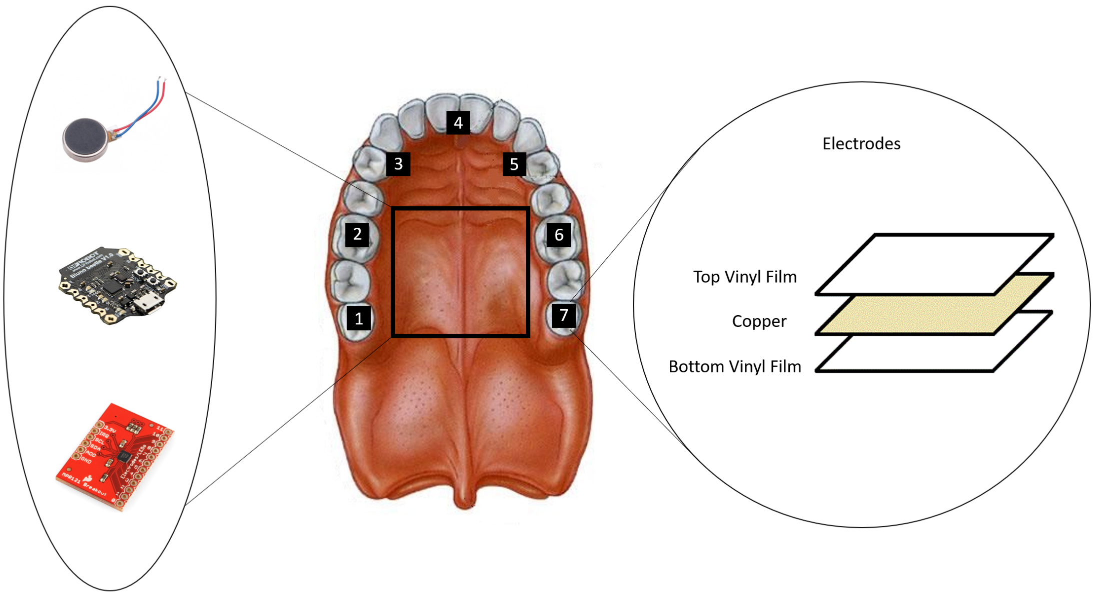


Figure 10: TTS general layout

Electronic: The electronic consists of an Arduino-based microcontroller (Beetle BLE) with integrated Bluetooth, a capacitive touch controller (MPR121) and a vibrating motor disc that provides haptic feedback to the user, to let him know when ”special character” (space, send, delete) are pressed. All the components are powered using two 3V coin batteries in series.

Keyboard: The keyboard is designed based on the T9 keyboard configuration on phones. Every electrode is made using a layer of copper insulated between two layer of vinyl film. The keyboard is composed of an array of 7 electrodes positioned on the upper dental arch as shown in Figure 10.

CHAPTER 2

METHODS AND MATERIALS

In this chapter are described the manufacturing processes and characteristics of TTS's three building blocks, the tests and software used to analyze its performances.

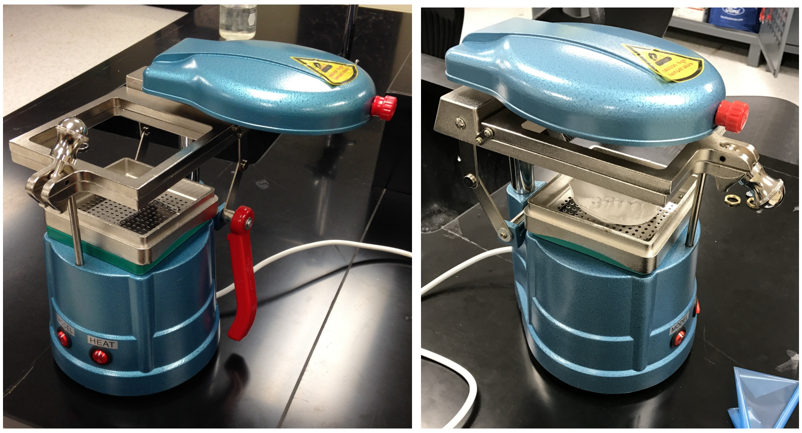
2.1 Housing Layers

The retainer has been made by taking the impression of the upper palate using a solution of alginate powder (Alginate Plus, Dentonics, Inc.) and water. The solution is poured in a blue open plastic tray. The tray is then pressed on the palate and teeth for 30–60 seconds in order to obtain the impression (Figure 11). The impression is covered with a solution of water and model stone (Trial Pack Orthostone, WhipMix).

(a) (b)

Figure 11: Alginate impression (a) and Model stone (b)

The model stone solution is left to dry ($\sim$ 48 hours), it is separated from the alginate and used as the model to create the palate impression. A thin clear thermoplastic sheet is positioned on the square shaped top area of the machine while the mold is placed on a grid underneath the sheet (Figure 12). The thermoplastic is then heated and when it starts to become soft, it is pushed on the impression using a lever while the air is sucked out to make it take the shape of the mold.



(a) (b)

Figure 12: Plastic retainer machine empty (a) and functioning (b)

When the plastic cools down, the mold is removed from the impression and it is ready to be used. After the electronic and the electrodes are correctly positioned inside the retainer, a polymeric paste is brushed on top of the retainer in order to cover all the parts and to insulate the circuits from the saliva. Once the paste is dry, the device is inserted in a polymerizing machine for 5 minutes at 2 atm pressure, to make the paste solid.

Figure 13: Polymeric paste covering the retainer

After this process, the thickness of the insulator is reduced in order to make it easier for the device to detect the tongue touch and, on top of the keys, small holes are drilled to provide guidance for the tongue towards the keys and give a feedback to the user on the position of the keys.

At the end of this process, the device is polished and smoothed using an electric brush Figure 14. The production of the housing layers of the retainer described have been performed

(a) (b)

Figure 14: Polymerizing machine (a) and Polishing brushes (b)

Figure 15: TTS final device

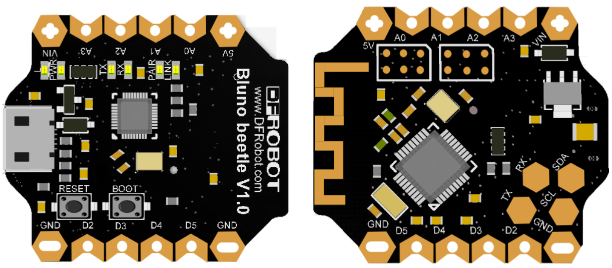
at the Dentistry Laboratory of Walter Toscano in Milan, Italy. The final product that is the results of all the previous steps is shown in Figure 15.

2.2 Electronic

The electronic part of the device consists of two boards (Beetle BLE microcontroller and MPR121 capacitive touch controller), a transistor, a vibrating motor disc and two batteries in series that power the entire device.

2.2.1 Beetle BLE

Beetle BLE is an Arduino Uno based microcontroller with a Low Energy Bluetooth 4.0 [33]. It is used to control the functionalities of the keyboard, the communication and transfer of data between the device and the app on the smartphone and the haptic feedback perceived when special characters are selected.



(a) (b)

Figure 16: Beetle BLE layout front (a) and back (b) [34]

Beetle BLE is a very compact, small and minimal board (Figure 16) and presents a very low number of output pins (Table II, Table III [34]). Beetle BLE's microcontroller is the same that is used in the Arduino Uno boards and the Bluetooth system allows connections to device that are as far as 50 meters (Table II). The I^2C channels (SDA, SCL) connected to the MPR121 do not have an output pin, but can be accessed through small hexagonal gold pads on the back of the board (Table III, Figure 16)

TABLE II: BEETLE BLE SPECIFICATIONS

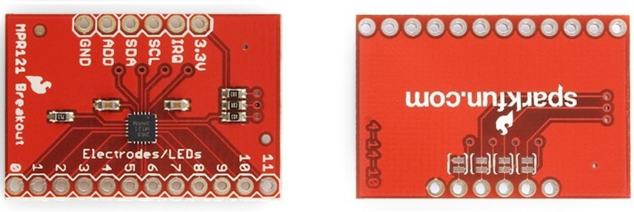
Bluetooth Chip	CC2540
Sensitivity	-93 dBm
Working Temperature	-10°C – +85°C
Maximum Distance (Open Field)	50 m
Microcontroller	ATmega328
Power Consumption	10mA
Clock Frequency	16 MHz
Operating Voltage	5V DC
Input Voltage	$\leq$ 8V
Analog Pin	4
Digital Pin	4
PWM Output	2
Power Ports	2
UART Interface	$\surd$
I^2C Interface	$\surd$
Micro USB Interface	$\surd$
Size	28.8 mm x 33.1 mm x 1 mm
Weight	10 g
Price	14.90 dollars
Producer	DFRobot

TABLE III: BEETLE BLE PIN MAPPING

Silkscreen	Digital Pin	PWM Channel	Analog Channel	UART	I^2C
RX	0			Serial1	
TX	1			Serial1	
SDA	A4				SDA
SCL	A5				SCL
D2	2				
D3	3	3			
D4	4				
D5	5	5			
A0	A0		A0		
A1	A1		A1		
A2	A2		A2		
A3	A3		A3		

2.2.2 MPR121 Breakout Board

The MPR121 is a capacitive touch sensor controller that provides integrate capacitive touch sensing. It communicates through I^2C and it works by measuring the capacitance of 12 contact sites. When an object is near to the contact site, the measured capacitance changes [35]. This change in capacitance allows the MPR121 to understand that something has touched a "button". The MPR121 works from 1.6V to 3.3V and draws only around 29 μA while sampling every 16 ms (Table IV [36]). The breakout board has a minimum of 4 pins that require to be connected to a microcontroller in order to properly function: the power lines (VDD, GND) and the I^2C lines (SCL, SDA) (Figure 17) [37]. The MPR121 Breakout Board is used to manage the press and release events related to the keys of the keyboard.



(a) (b)

Figure 17: MPR121 breakout board front (a) and back (b) [37]

TABLE IV: MPR121 BREAKOUT BOARD SPECIFICATIONS

Supply Operation	1.71V - 3.6V
Operating Temperature	-40°C - $+85$°C
Supply Current	29 μA
Sampling Interval Period	16 ms
Sensing Pins	12
Sensing Input Auto-Calibration and Auto-Configuration	$\surd$
Size	30 mm x 20 mm x 1 mm
Weight	2.2 g
Price	7.95 dollars
Producer	Sparkfun - Adafruit

2.2.2.1 Capacitance Measurement [36]

The system that measures the capacitance consists of external sensing electrodes connected to the MPR121 sensing inputs and the MPR121–host processor communication system (using I^2C) [36]. The total number of sensing channels is 13, 12 electrode inputs and one multiplexed channel. In the front end, there is a multiplexer that allows the 13 channels to be measured sequentially in time. After the capacitance is measured, it filters noise and then touch/release status is determined (Figure 18) [36].

The capacitance measured on each sensing channel, is the total capacitance to ground. The total capacitance to ground is the combination of background parasitic capacitance to ground (C_b) and the capacitance to ground induced by the tongue touching (C_x) (Figure 18) [36]. In order to calculate the capacitance, MPR121 uses a constant direct charge current: every channel is charged and completely discharged periodically (Figure 19) and all the channels are measured sequentially.

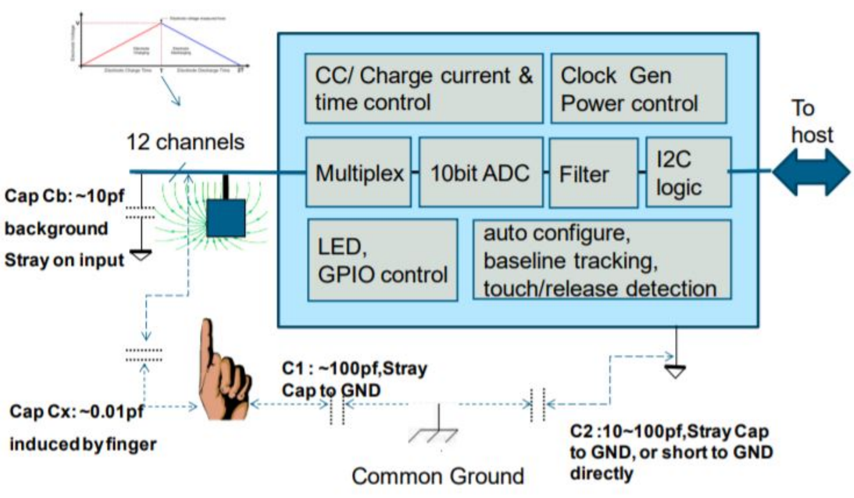


Figure 18: MPR121 internal structure [36]

During the charging, discharging and measurement period of one channel, the others are shorted to ground [36].

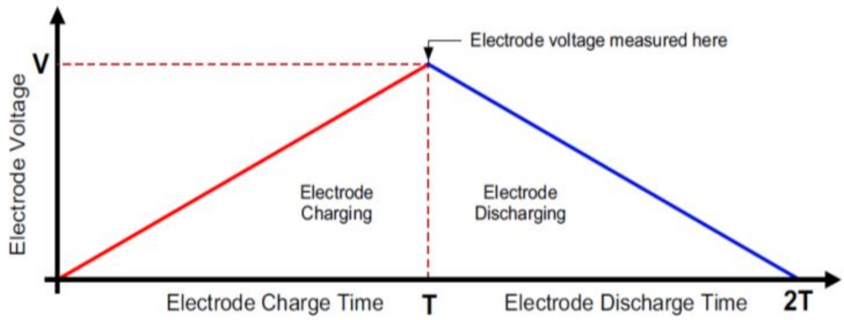


Figure 19: Single channel charging and discharging [36]

The amount of charge (Q) applied can be arranged by setting the charge current (I) and the charge time (T). At the end of the charge, the peak voltage (V) is calculated by the ADC. This voltage V is inversely proportional to the capacitance (C) as shown on Equation 2.1 [36].

$$V = \frac{Q}{C} \longrightarrow C = \frac{Q}{V} = \frac{IT}{V} \tag{2.1}$$

Since the ADC is 10 bit, the equation for ADC reading result is as below:

$$ADC_{Counts} = \frac{V}{V_{dd}} \times 2^{ADC_{bit}} = \frac{IT}{C} \times \frac{1}{V_{dd}} \times 2^{ADC_{bit}} \tag{2.2}$$

By re-arranging the equation, the capacitance C can be calculated as [36]:

$$C = \frac{IT}{ADC_{Counts}} \times \frac{1}{V_{dd}} \times 2^{ADC_{bit}} \tag{2.3}$$

2.2.3 Vibrating Motor Disc

The Vibrating Motor Disc is a very small disc that vibrates providing a haptic feedback to the user of the device. The VMD is directly powered by the Beetle BLE board at 5V (Table V [38]). The internal structure of VMD is shown in Figure 20.

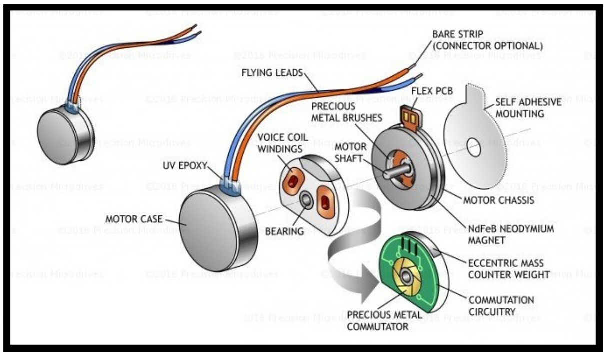


Figure 20: Vibrating motor disc [39]

Since the device requires a non–continuous vibration, the VMD has to be attached to a transistor to prevent the board from overheating and eventually be damaged.

TABLE V: VIBRATING MOTOR DISC SPECIFICATIONS

Voltage	2V – 5V
Current Draw	5V - 100mA, 4V - 80mA, 3V - 60mA, 2V - 40mA
Rounds	11000 RPM at 5V
Size	Ø 10 mm x 2.7 mm
Weight	0.9 g
Price	1.95 dollars

In application that requires constant vibration, the VMD it is attached to the poles of a battery omitting the transistor. The haptic effect is activated when the user accesses the "special characters" (space, send, delete) present on the device.

2.2.4 Batteries

The batteries used to power the electronics are two Energizer CR2032 disc batteries positioned in series in order to obtain a 6V output Figure 21. Every coin battery has a nominal voltage of 3V and it is incredibly small and light (Table VI [40]). The batteries system only directly powers the Beetle BLE microcontroller, while all the other components are powered from Beetle BLE's VDD and GND pins.

Since the MPR121 breakout board requires a lower voltage than the 5V input provided by Beetle BLE, a 42 Ω resistance has been used to lower the voltage to 3.3V.

Figure 21: 3V coin battery [41]

TABLE VI: CR2032 BATTERY SPECIFICATIONS

Classification	Lithium Coin
Chemical System	Lithium / Manganese Dioxide (Li/MnO_2)
Nominal Voltage	3 V
Typical Capacity	240 mAh
Lithium Content	0.109 g
Operating Temperature	−30°C – +60°C
Volume	1 cm^3
Weight	3 g
Price	1.5 dollars

2.3 Keyboard

2.3.1 Electrodes

The electrodes used on the device are made using one layer of copper and two layer of Clear Vinyl Film [42] (top and bottom). The copper and vinyl layers are kept together using two drops of superglue at the edges of the copper layer. That allows to strongly attach the wires used to connect the electrodes to the capacitive controller board while maintaining thin dimensions. The dimension of each electrode is 0.4 cm x 0.4 cm (sufficient to cover the upper surface of the molar tooth) in the shape of a square. The electrodes are then attached on the retainer, on top of a paper layer, used to underline the position of the electrodes on the dental arch.

The position of the electrodes has been designed to have enough space to place the electronics inside the palate, but maintaining a distance high enough to avoid conflicts between two electrodes when touched. Even if the distance is more than enough to avoid this inconvenience, it is always better to touch the electrode just with the tip of tongue to reduce the contact area of the tongue on the retainer.

2.3.2 7 Channels Keyboard

Four letters are assigned to contact sites 1–6, and two letters are assigned to contact site 7. Positions 1 to 7, cover the upper dental arch, from molar to molar (Figure 22). By pressing for 2 seconds specific keys, the user is able to access the "special characters": delete (1st contact site), space (3rd contact site), send (5th contact site), and delete all (7th contact site) [43]. If the user needs to consecutively type two letters that belongs to the same key, it has to wait 1.5 seconds after the first letter is typed in order for the system to reset the keys.

The choice of using a 7 channels keyboard has been taken by comparing results obtained with other TTS versions, using different keyboard layouts. The 7 contact points keyboard has shown that it allows good distance between the electrodes, features that increases the accuracy and the typing speed.

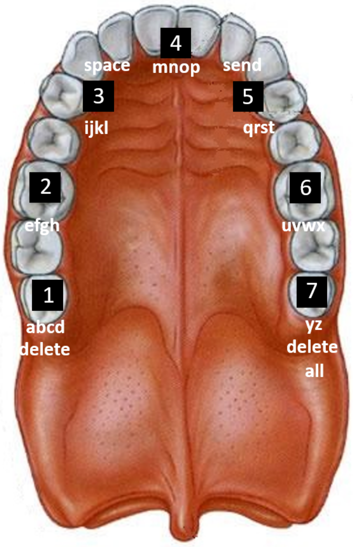
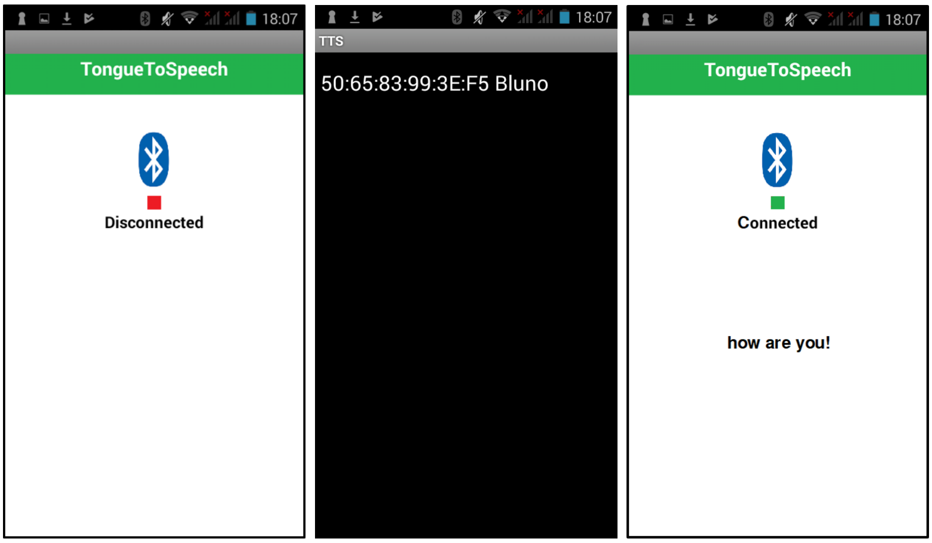


Figure 22: 7 channel electrodes layout

2.4 Smartphone Application

The TTS–app is an Android Smartphone Application that receive the data sent by the device, displays the text in real time and read the text once the user press the send command. The application is very simple: once the user opens the app, he can see a Bluetooth logo in the middle of the screen Figure 23. The subject has to press the logo and choose from the list of Bluetooth seen by the smartphone, the one named Bluno.

If the smartphone asks for a password, press 0000. The app is then connected to the device and is ready to receive data. The text written with TTS will be displayed under the Bluetooth logo, after the subject presses send on TTS.



(a) (b) (c)

Figure 23: App: Opening screen (a), Bluetooth selections (b), Connected (c)

2.5 Testing Methods

2.5.1 Liquid Ingress Test

The Liquid Ingress test is a test designed to analyzed the TTS resistance to extended usage under simulated working conditions. The device has been immersed for 12 consecutive hours, in water at 40°C to recreate the oral cavity environment. In Figure 24, it is shown the machine used to perform the test.

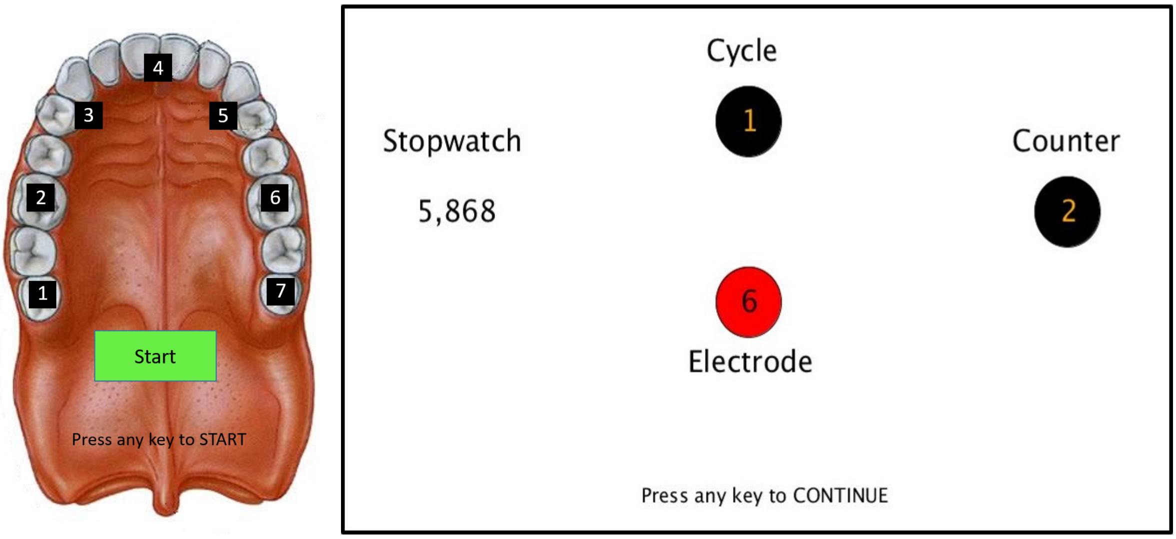
2.5.2 Position Test

The Position Test is a computer-based test specifically designed to train the user to easily find the position of the keys on the palate.

Figure 24: Soak test machine

When the program starts, it shows to the user an image (Figure 25 (a)) of the electrodes positioned on the palate. A number from 1 to 7 is associated to every electrode, starting from the left molar position to the right molar. The user is allowed to study the image for 5 minutes before starting the test, but after that time the image is permanently hidden.

At the conclusion of the 5 minutes, the test starts. The program randomly selects a number and the user has to touch the corresponding electrode; if the electrode touched is the correct one, the program randomly selects another number. If the electrode touched is not correct, the program does not proceed to the following number. This operation is repeated until the user has correctly pressed 10 electrodes. The program keeps track of the time needed to complete the task. This task is repeated 15 times, for a total of 150 electrodes touched (10 electrodes per sequence × 15 sequences). The test is performed by one user for 7 days in a row (20-25 minutes per session) in order to observe the learning process and the performance improvements over time.



(a) (b)

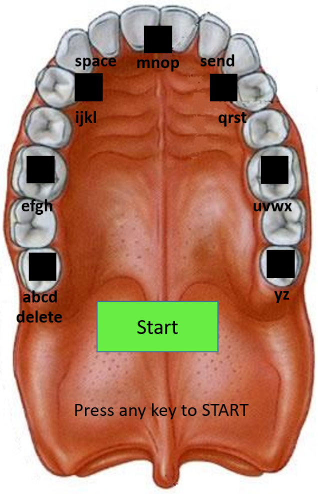
Figure 25: Training image (a), Position test design (b)

2.5.3 Memory Test

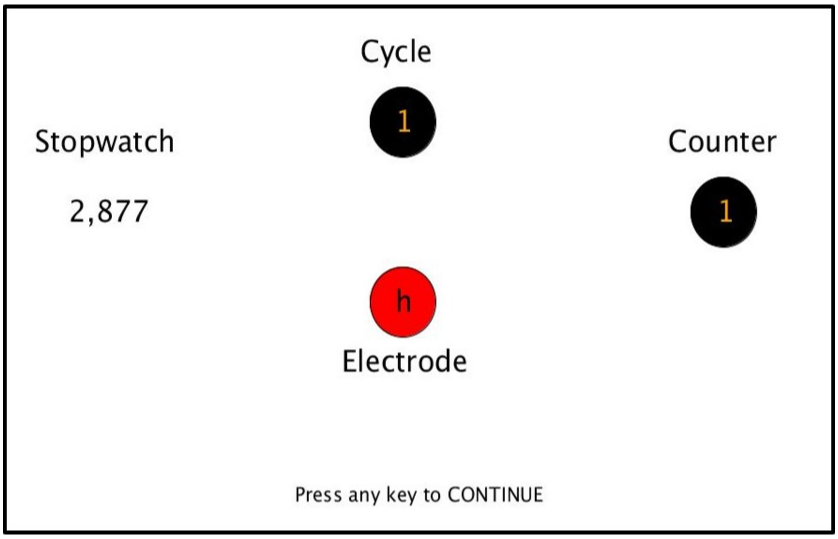
The Memory Test is a computer-based test specifically designed to train the user to remember the position of the letters on the keyboard.

When the program starts, it shows to the user an image of the electrodes positioned on the palate with the letters associated to each electrode (Figure 26 (a)). The user is allowed to study the image for 5 minutes before starting the test, but after that time the image is permanently hidden.

Once the 5 minutes are expired, the test starts. The program randomly selects a letter and the user has to touch the electrode that contains that letter; if the electrode touched is the correct one, the program randomly selects another letter. This operation is repeated until the



(a)



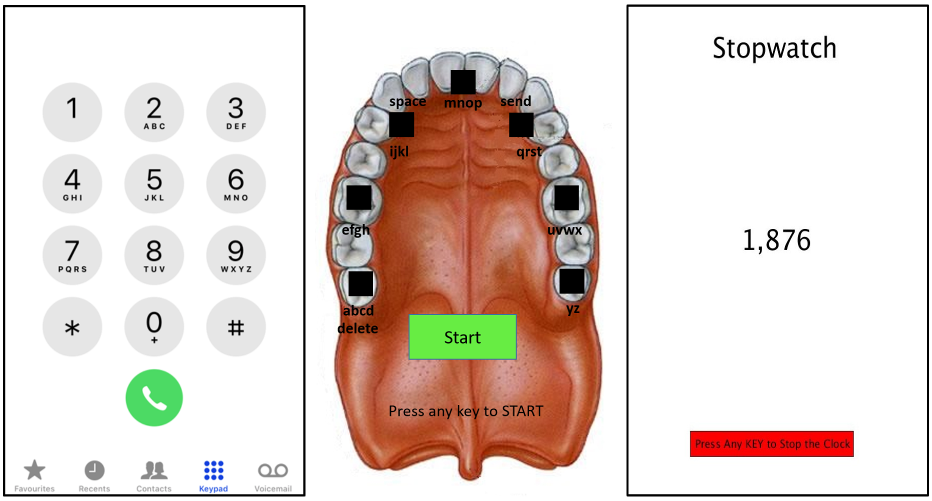
(b)

Figure 26: Training image (a), Memory test design (b)

user has correctly pressed 10 letters. The program keeps track of the time needed to complete the task. This task is performed 15 times, for a total of 150 letters touched (10 letters per sequence $\times$ 15 times). The test is performed by one user for 7 days in a row (20–25 minutes per session) in order to observe the learning process and the performance improvements over time.

2.5.4 Typing Test

The Typing Test is a computer-based test specifically designed to understand the time needed for the user to write the common phrase "How Are You" on the TTS device and on a T9 cellphone. The two results are then compared. The choice of this sentence is due to the fact that it involves the touching of every single key in the keyboard



(a) (b) (c)

Figure 27: T9 keyboard (a), Training image (b), Typing test design (c)

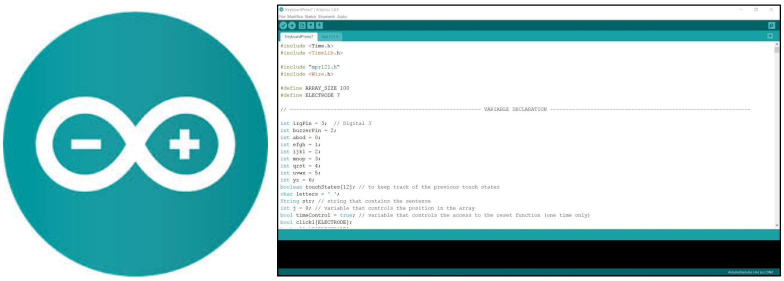
In this test, the program is used just to keep track of the time needed to complete the sentence and to send it to the application. The user has the possibility of watching an image (Figure 27 (a)) of the palate, but only for 30 seconds; the reason why the viewing time is so low, is because the subject has already completed the Memory Test.

Once the 30 seconds expires, the test starts. Until the phrase is correctly written and the send button is pressed, the clock does not stop the time. The sentence has to be written 15 times. The test is performed by one user for 7 days (35–40 minutes, considering phone and TTS tests) in a row in order to study the learning process.

2.6 Software

2.6.1 Arduino

Arduino is the worlds leading open-source hardware and software. It offers a wide range of software tools, hardware components and documentation. Arduino is a popular tool for Internet of Things (IoT) product development [44].



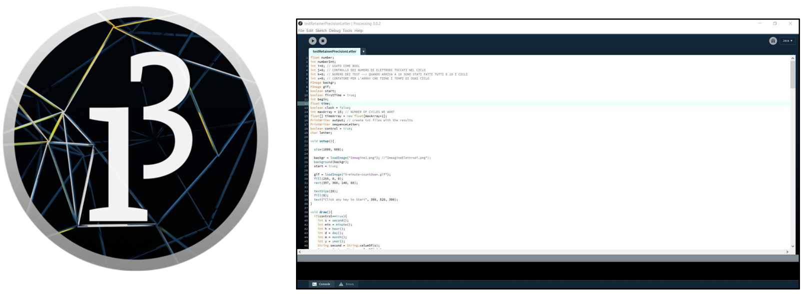
(a) (b)

Figure 28: Arduino logo (a) and environment (b)

Arduino environment (Figure 28) has been used to program the keyboard functionalities such as the 4 letters keys, the scrolling between letters in the same electrode and the long press time calculation to access the special character. The firmware has been uploaded to the Beetle BLE board and controls also the MPR121 capacitive touch controller.

2.6.2 Processing

Processing is a software sketchbook and an environment that allows to code within the context of the visual arts [45].



(a) (b)

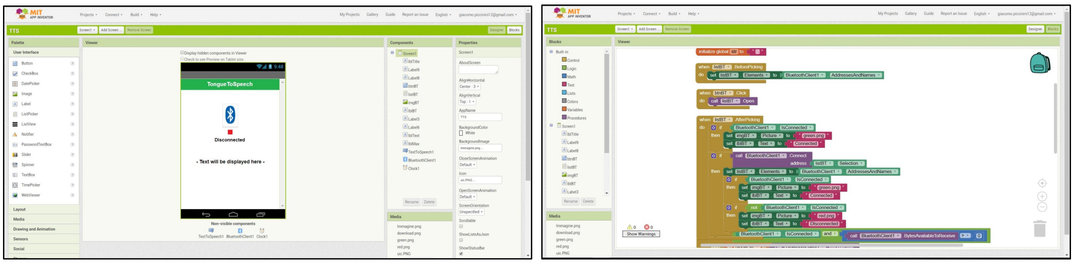
Figure 29: Processing logo (a) and environment (b)

Processing environment (Figure 29) has been used to program the Position tests, Memory test and Typing test, giving to the user the possibility to control the time needed to perform the tests. The programs are accessible only from a desktop computer or a PC.

2.6.3 MIT App Inventor

MIT App Inventor is an intuitive programming environment that allows to build fully functional Android applications for smartphones and tablets.

The blocks-based tool facilitates the creation of complex apps in significantly less time than traditional programming environments [46]. MIT App Inventor environment (Figure 30) has



(a) (b)

Figure 30: MIT App Inventor app layout (a), block scheme (b)

been used to create the graphics, the layout the blocks that control the application. In order to create the layout of the app, the user needs to drag the tools inside the screen and position them. Once every part is inside the screen, it starts the programming. The programming part is very simple, the user only needs to connect the pre-existing blocks together in order to create a running program.

CHAPTER 3

RESULTS

In this chapter, the results of testing TTS are presented, the performances of the TTS device are compared to competitor devices and various keyboard layouts. These tests were collected from one subject as a proof of concept to the performance of the device.

3.1 Liquid Ingress Test

The test has shown that, after 12 hours in 40°C water, the retainer does not present any sign of liquid penetrations and is still perfectly functioning, without any significant delay or issue. Figure 31 shows the device during the test.

Figure 31: TTS during soak test

3.2 Position Test

The Position Test is specifically designed to train the user to easily find the position of the keys inside the mouth.

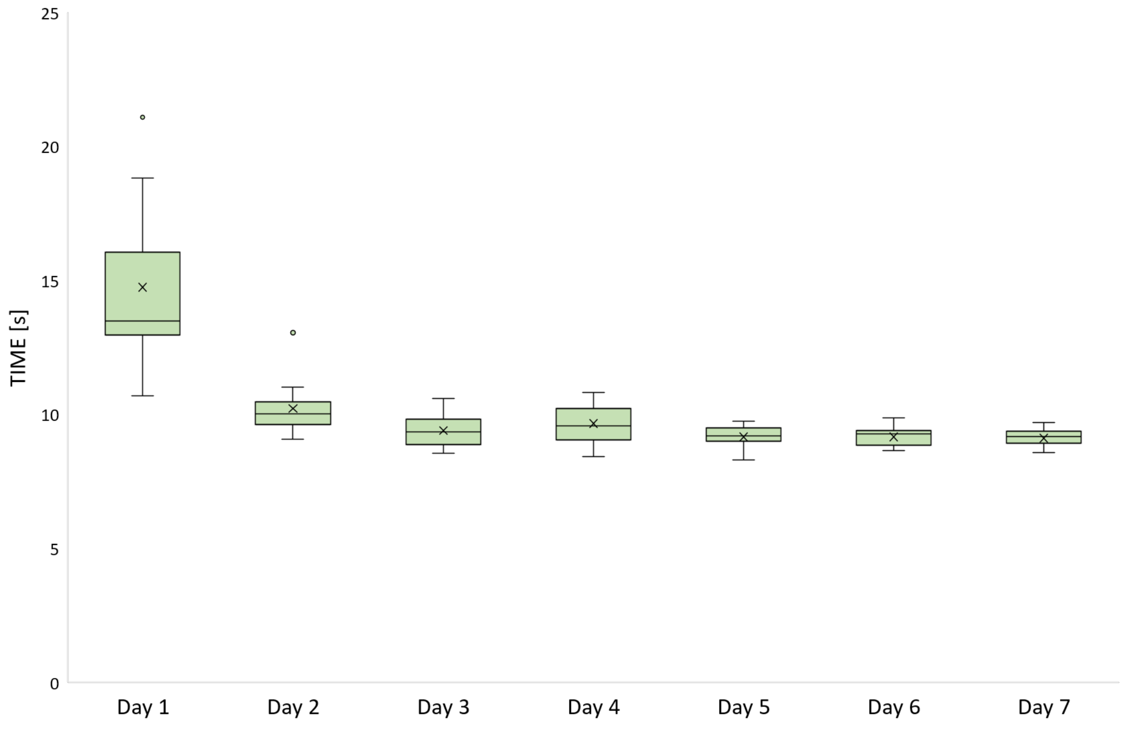


Figure 32: Box and Whiskers chart position test

In Figure 32 it is represented the Box and Whiskers plot of the user performances every day. The x in every box represents the average time that the subject needed to complete a test session. Every session consists of correctly touching a random 10–electrodes sequence for 15 times (everytime a new sequence is generated in order to create 15 different sequences). The horizontal line inside every box is the median of the performances, while the upper and lower edges of the box are respectively the third and first quartile. The error bars represent the worst and best daily performances, while the dots above the error bars are the outliers' data. The plot shows that the performances improved each day, starting from an average of 14.75 seconds in Day 1 to an average of 9.12 seconds in Day 7 (33.85% improvements in 7 days). Table VII shows that the standard deviation decreases constantly every day, which means that the performances become consistent over time, with less data disparity. This aspect is also visible in Figure 32, looking at the gap between the best and worst performance; the interval decreases consistently over the 7 days of tests.

Table VII also shows the subject's accuracy in each day. The accuracy has been calculated by counting how many of the 150 electrodes touched every day (10 electrodes $\times$ 15 daily sequences) have been correctly touched without errors and by converting the result into percentage.

$$Accuracy = \frac{CTFA}{N} \times 100 \tag{3.1}$$

where CTFA is the Correct Touch at First Attempt and N is the total number of electrodes touched.

In Figure 32, the boxes also show a trend in the performances that represents the learning curve associated with this task. It is possible to observe that starting from Day 3, the subject obtains steady results, that stay in the range of 9.66 – 9.12 seconds on average (Table VII). In fact, the average performances value reaches its plateau around the third day. These aspects

TABLE VII: POSITION TEST RESULTS

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Average [s]	14.75	10.23	9.41	9.66	9.18	9.17	9.12
Worst Performance [s]	21.09	13.061	10.603	10.829	9.761	9.882	9.707
Best Performance [s]	10.694	9.072	8.56	8.431	8.301	8.65	8.595
Variance	7.087	0.819	0.327	0.486	0.177	0.122	0.093
Standard Deviation	2.565	0.318	0.222	0.528	0.174	0.127	0.085
Accuracy [%]	86.67	89.33	91.33	92	96	96	96.67

show that it takes just 2 days (20-25 minutes per day of test) for the subject to get familiar with the position of the keys, while at the same time, obtaining good results (touching correctly 10 electrodes in 9.66 seconds means that every electrode is touched on average in 0.966 seconds, less that a second).

3.3 Memory Test

The Memory Test is specifically designed to train the user to remember the position of the letters on the keyboard.

Figure 33 shows the Box and Whiskers plot of the user performances every day. The x in the boxes represents the average time needed to complete a test session every day. Every session consists of correctly touching a random 10–letters sequence for 15 times (everytime a new sequence is generated in order to make 15 different sequences). The line inside the box is the median of the performances, while the upper and lower edges of the boxes are the third and first quartile. The error bars represent the worst and best daily performances, while the

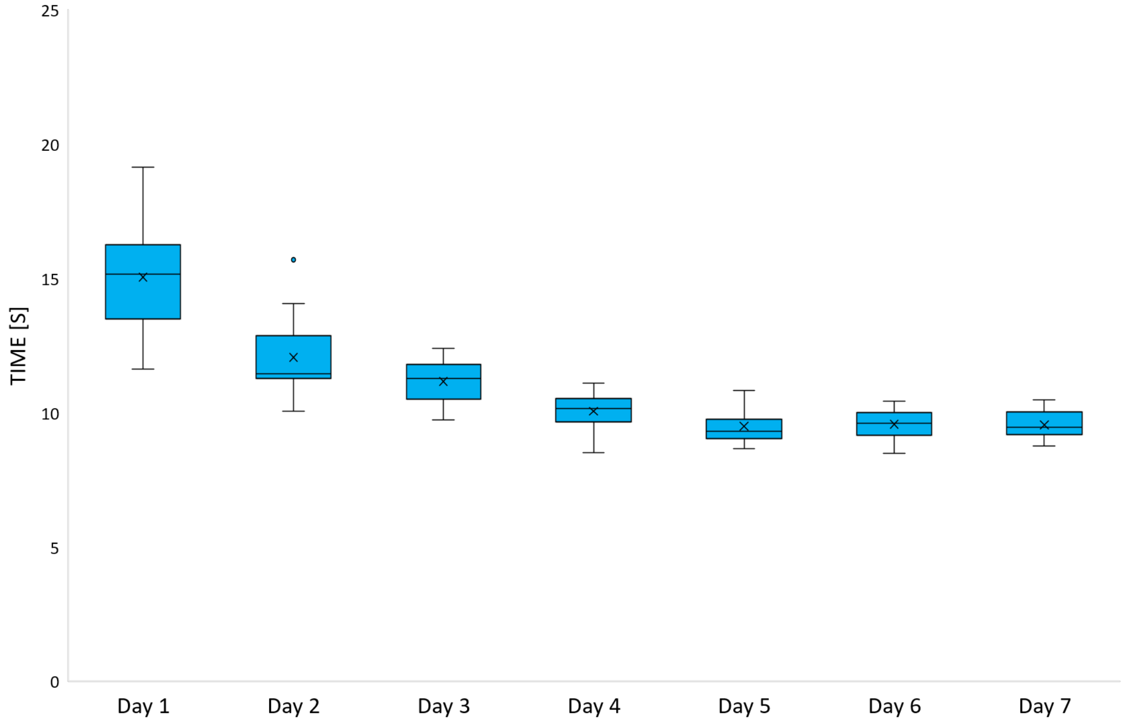


Figure 33: Box and Whiskers chart memory test

dots above the error bars are the outliers' data. In Figure 33, it is easy to notice that the average time required to complete the test decreases each day, starting from an average of 15.05 seconds on Day 1 to an average of 9.55 seconds on Day 7 (36.54% improvement over 7 days). Table VII shows that the standard deviation improves constantly every day, which means that the performances are become more consistent over time, with less data dispersion. This aspect is also visible in the Box and Whiskers plot, looking at the gap between the best and worst performance; the interval decreases consistently over the 7 days of tests. Table VII also shows the subject's accuracy in each day. The accuracy has been calculated by counting how many of the 150 letters touched every day (10 letters $\times$ 15 sequences) have been correctly touched without errors and by converting the result in percentage.

$$Accuracy = \frac{CTFA}{N} \times 100 \tag{3.2}$$

where CTFA is the Correct Touch First Attempt and N is the total number of electrodes touched.

TABLE VIII: MEMORY TEST RESULTS

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Average [s]	15.05	12.06	11.16	10.06	9.5	9.58	9.55
Best Performance [s]	11.635	10.061	9.739	8.513	8.658	8.479	8.762
Worst Performance [s]	19.15	15.695	12.407	11.099	10.84	10.424	10.48
Variance	4.104	2.025	0.593	0.449	0.37	0.299	0.274
Standard Deviation	2.03	1.42	0.77	0.67	0.61	0.55	0.52
Accuracy [%]	88	90.67	92	93.33	95.33	95.33	96

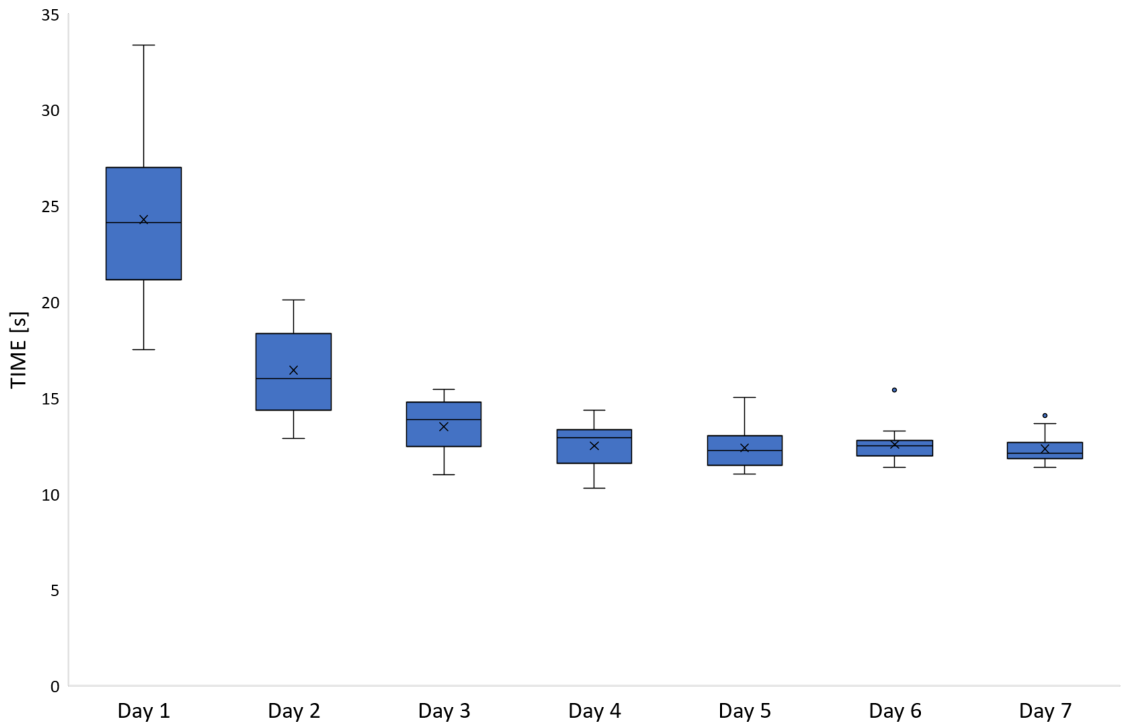
Figure 33 also shows the trend of the results that represents the learning curve for this test's specific task. It is possible to observe that starting from Day 5, the subject's performances are similar, that stay in the range of 9.58 – 9.50 seconds on average (Table VIII). In fact, the performances average time (the x in the plot) reaches its plateau around the 5th day. These aspects show that it takes 4 days for the subject to get familiar with the locations of the letters in the keyboards, while at the same time, obtaining good results (touching correctly 10 letters in 9.58 seconds means that every electrode is touched on average in 0.958 seconds, less that a second).

It is interesting to notice that while the Position Test and the Memory Test are very similar in their structure (they differ only in the given input to the subject, number vs letter), they present significantly differences in their outcomes (Table VII, Table VIII). While the average performances are comparable on a daily basis (the largest difference is 1.83 seconds in Day 2), the variance, is a considerably higher in the Memory Test (twice the value in 5 days of the 7) and also the plateau of the Learning Curve is reached 2 days earlier in the Position Test.

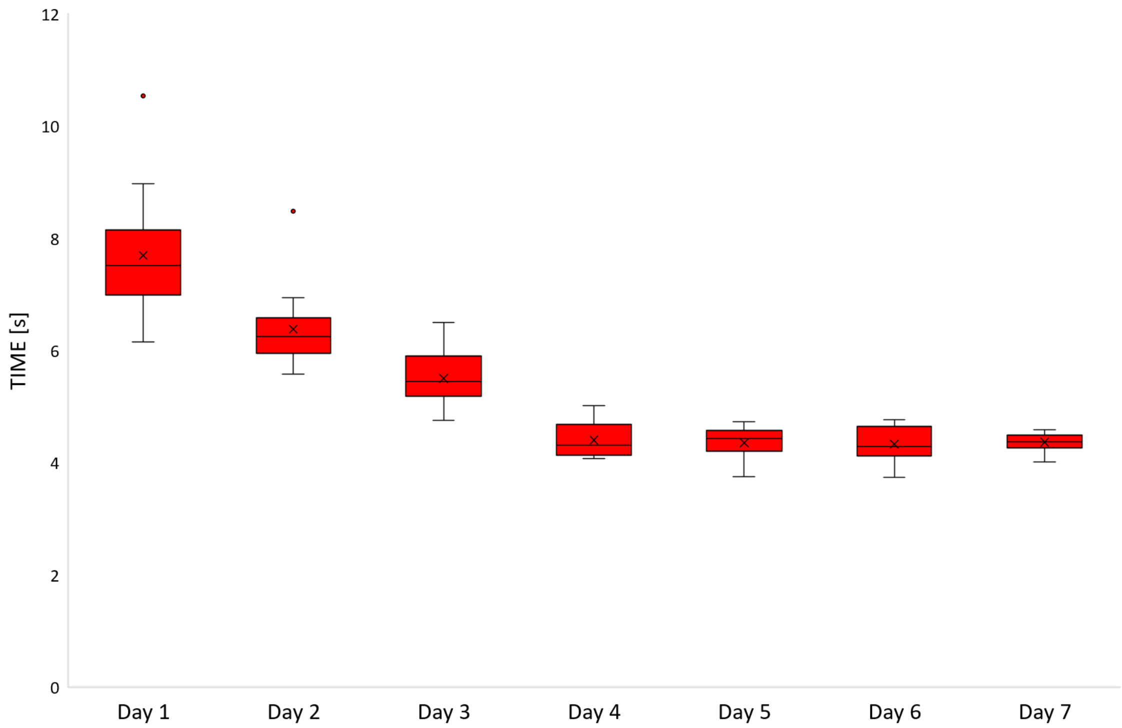
This means that it takes more time for the subject to achieve steady performances with the Memory Test. This is probably due to the different number of possible inputs that the two tests offers (26 letters vs 7 number of electrodes). From the comparison of the trend line in Figure 32 and Figure 33, it is clear that the subject needed more time to obtain good results at finding the position of the keys in the keyboard, rather than performing good at remembering the locations of the letters in the keyboard.

3.4 Typing Test

The Typing Test is specifically designed to analyze the time needed for the user to write the phrase "How Are You" on the TTS device and on a T9 cellphone. The two results are then compared. The choice of this sentence is due to the fact that it involves the touching of every single key in the keyboard.



(a)



(b)

Figure 34: Box and Whiskers chart typing test: TTS (a), T9 Phone (b)

Figure 34 (a,b) represents the Box and Whiskers plot of the user performances every day using TTS and the phone. The x in the boxes shows the average time to complete a test session each day. Every session consists of correctly typing the phrase "How are you!" for 15 times. The line inside the boxes is the median of the data, while the upper and lower edges of the boxes are the third and first quartile. The error bars represent the worst and best daily performances, while the dots above the error bars are the outliers' data. In the chart in Figure 34 (a), it can be observed that the average time decreases significantly over the 7 days of sessions, starting from an average of 24.28 seconds in Day 1 to 12.34 seconds in Day 7 for the TTS device (49.18% improvement over 7 days). The average time decreases also in the phone test, from 7.69 seconds in Day 1 to 4.36 seconds in Day 7 (Figure 34 (b)). Just like in the Position and Memory tests, the standard deviation improves consistently over the 7 days for both devices, but more so in the TTS device, since the phone variance is already very low from Day 1 (Table IX). This aspect can also be noticed in the Box and Whiskers charts by looking at the decreasing gap between the worst and best performance of each day during the 7 days.

Figure 34 (a) shows the trend line of the performances that represents the learning curve for this test's specific task. It is possible to observe that, in the TTS device, starting from Day 4, the subject's performances become similar and stay in the range of 12.56 – 12.34 seconds on average. In fact, the trend line (average performances time) reaches its plateau on the 3rd day. These aspects show that it takes 3 days for the subject to get familiar with the general use of the TTS device, while delivering good performances (typing 12 characters in 12.34 seconds leads to a projection of 58.35 characters per minute). The trend line of the phone results (Figure 34

TABLE IX: TYPING TEST TTS (T) AND PHONE (P) RESULTS

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Average [s] (T)	24.28	16.45	13.49	12.51	12.39	12.56	12.34
Average [s] (P)	7.69	6.38	5.5	4.4	4.35	4.33	4.36
Worst Performance [s] (T)	33.369	20.085	15.434	14.35	15.018	15.418	14.085
Worst Performance [s] (P)	10.534	8.481	6.499	5.016	4.732	4.766	4.584
Best Performance [s] (T)	17.518	12.885	10.984	10.282	11.034	11.368	11.384
Best Performance [s] (P)	6.15	5.582	4.751	4.068	3.751	3.738	4.017
Variance (T)	16.214	4.538	1.894	1.023	1.229	0.791	0.514
Variance (P)	1.038	0.461	0.287	0.093	0.066	0.081	0.022
Standard Deviation (T)	4.03	2.13	1.38	1.01	1.11	0.89	0.72
Standard Deviation (P)	1.02	0.68	0.54	0.30	0.26	0.28	0.15

(b)) is very similar to the TTS's one, since it reaches its plateau by Day 4, but the average time range in considerably lower compared to the TTS performances (4.4 – 4.36 vs 12.56 – 12.34 seconds).

It can be calculated that typing on TTS with the tongue takes between 2.5 – 3 longer compared to typing with a T9 keyboard on a smartphone and that the difference in seconds between the average performances of the two devices after 7 days of training is 7.98 seconds.

One reason this difference could be that TTS is brand new to the subject, while he had years of practice with the smartphone. Moreover, TTS does not allow the user to use his eyes to watch and see the keys while typing, since the keyboard in inside the oral cavity. This aspect requires the user to constantly make an extra mental effort while typing, which can cause mental fatigue and lead to mistakes. This aspect, combined with the 2 seconds of long press needed to type the space and send character, justifies the 7.98 seconds of gap.

3.5 TTS–Tongue vs TTS–Hand

In the Typing test, it has been shown the difference of performance between the use of TTS and a T9 keyboard on a smartphone. Building on this comparison, they have also been analyzed the performances of the T9 smartphone keyboard using the non–dominant hand and the performances of TTS using the fingers as input (both dominant and non–dominant hands) while typing the phrase "How are you!".

In Figure 35, are represented the different performances in terms of average time. The error bars of the histograms represent the standard deviation. The data used to make these comparisons have been taken from the Day 7 performances of the Typing test for TTS and Phone (dominant hand), while the other data (Phone with non–dominant hand, TTS with dominant hand and TTS with non–dominant hand) have been collected in a one day test, after the seven days of tests were over. Figure 35 shows that typing with the non dominant hand requires 1.04 seconds more for the TTS device and 0.66 seconds more using the T9 keyboard on the phone, compared to the results obtained using the dominant hand. By using the fingers to type on TTS, the subject obtained results similar to the performances obtained using the tongue (1.11 and 0.07 seconds better performances using hands on TTS, dominant and non–dominant respectively). These results show that the tongue can be as effective as finger when it comes to typing on the same device.

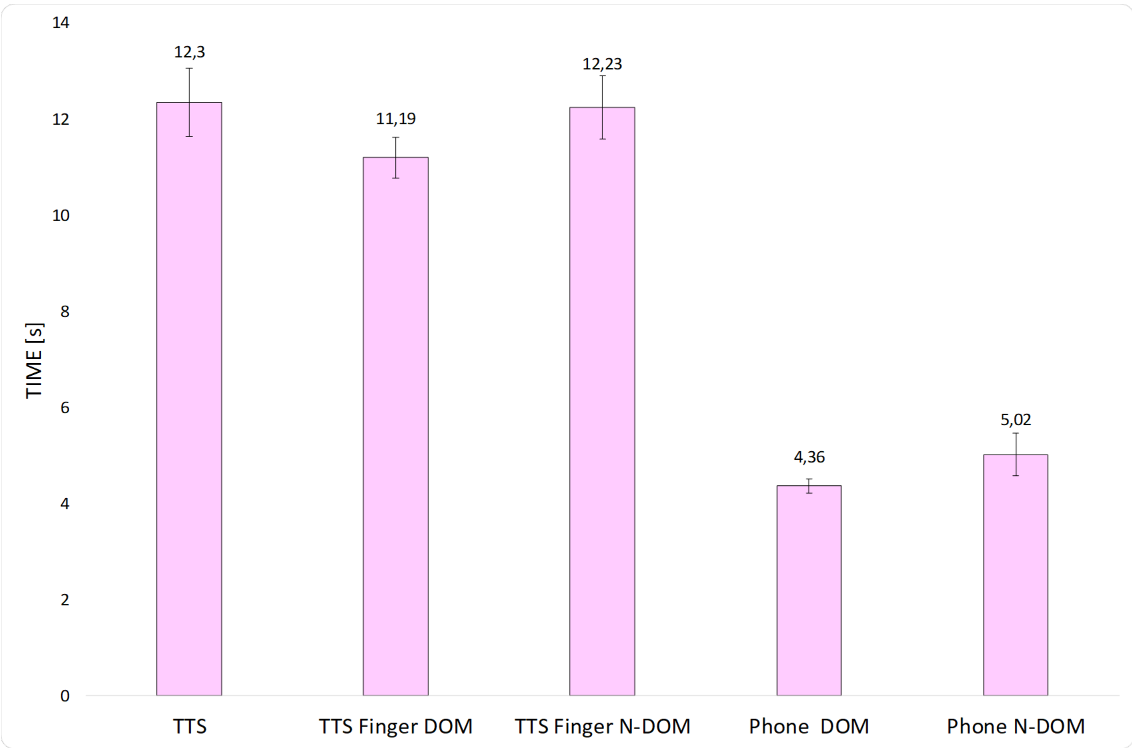


Figure 35: TTS–Tongue vs TTS–Hand

3.6 Keyboard Design

The choice of using a 7 electrodes keyboard has been analyzed by comparing results between the TTS device presented here and the TTS device presented in a previous study of Marjanovic et al. paper [43] in which the difference between a 9, 8 and 5 electrodes channel keyboard were analyzed.

The four different keyboards studied have different letters distribution among the electrodes present in the device.

- 9 Channels Keyboard (shown in Figure 36 (a))

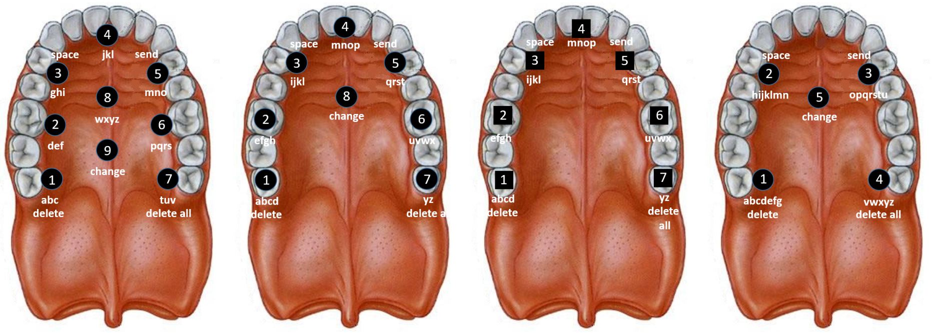
  Three letters are assigned to electrodes 1–5 and 7, while four letters are assigned to contact sites 6 and 8. Contact sites 1 to 7 cover the internal part of the upper dental arch, and electrodes 8 and 9 are positioned on the posterior area of the frontal teeth in the mid line of the upper pallet (Figure 36) [43]. By selecting the 9th contact, it is possible to access the "special character" in specific contact sites: delete (1st contact site), space (3rd contact site), send (5th contact site), and delete all (7th contact site). If the user needs to consecutively type two letters that belongs to the same key, it has to wait 1.5 seconds after the first letter is typed in order for the system to reset the keys.

- 8 Channels Keyboard (shown in Figure 36 (b))

  Four letters are assigned to electrodes 1–6 and just two to electrode 7. Contact sites 1 to 7 cover the internal part of the upper dental arch, and electrodes 8 is positioned on the posterior area of the frontal teeth in the middle of the hard palate (Figure 36) [43]. The 8th contact allows access to the "special character" in specific contact sites: delete (1st contact site), space (3rd contact site), send (5th contact site), and delete all (7th contact site). If the user needs to consecutively type two letters that belongs to the same key, it has to wait 1.5 seconds after the first letter is typed in order for the system to reset the keys.

- 7 Channels Keyboard (shown in Figure 36 (c))

  Four letters are assigned to contact sites 1–6, and two letters are assigned to contact sites 7. Positions 1 to 7, cover the upper dental arch, from molar to molar (Figure 36). By pressing for 2 seconds specific keys, the user is able to access the "special characters": delete (1st contact site), space (3rd contact site), send (5th contact site), and delete all (7th contact site) [43]. If the user needs to consecutively type two letters that belongs to the same key, it has to wait 1.5 seconds after the first letter is typed in order for the system to reset the keys.



(a) (b) (c) (d)

Figure 36: Keyboards: 9 (a), 8 (b), 7 (c) and 5 Channels (d)

- 5 Channels Keyboard (shown in Figure 36 (d))

  Seven letters are assigned to electrodes 1–3 and five to electrode 4. Contact sites 1 to 4 cover the internal part of the upper dental arch, and electrodes 5 is positioned on the posterior area of the frontal teeth in the mid line of the soft palate (Figure 36) [43]. By selecting the 5th contact is possible to access the "special character" in specific contact sites: delete (1st contact site), space (2nd contact site), send (3rd contact site), and delete all (4th contact site). If the user needs to consecutively type two letters that belongs to the same key, it has to wait 1.5 seconds after the first letter is typed in order for the system to reset the keys.

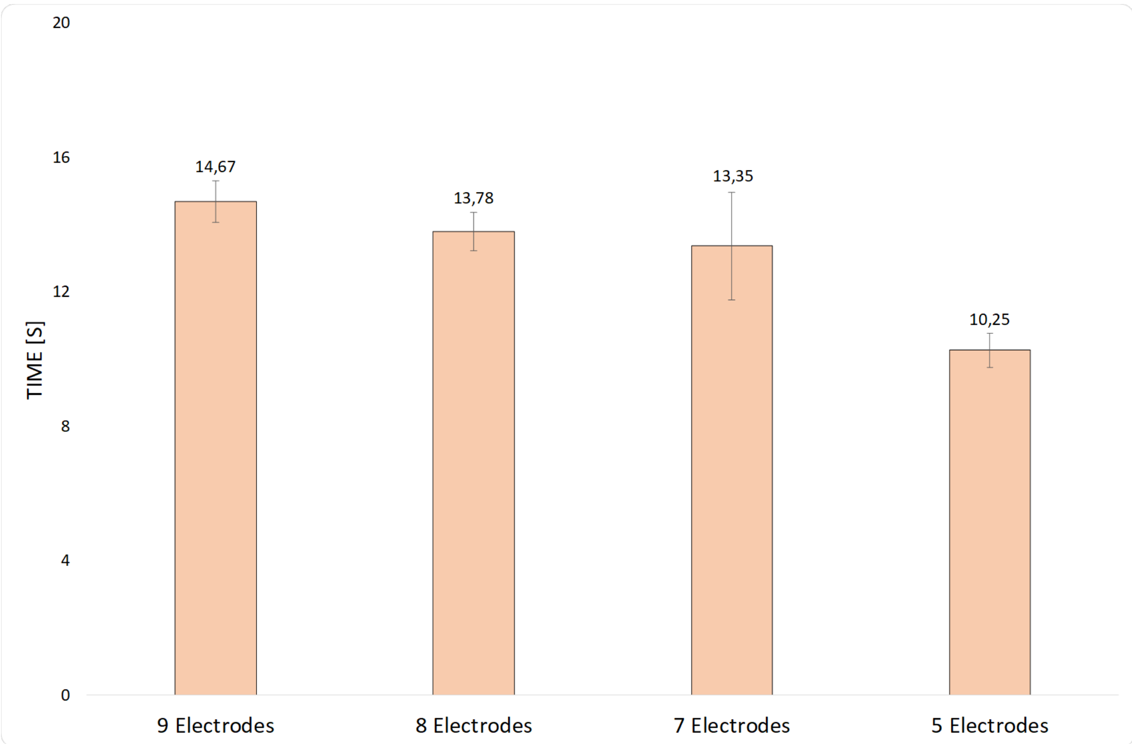


Figure 37: Different keyboards position test results

The results of the TTS performances using different keyboard layout is presented in Figure 37 and Figure 38. The Position test and Typing test (TTS, phone and finger) results were used in order to compare the layouts. In order to correctly compare the results between the 4 layouts, in both the Position and Typing tests, have only been considered the results in Day 1 and discarded the first 5 sequences, using only the last 10.

Figure 37 shows the results of the Position Test using the different layouts. The error bars show the standard deviation among the 10 sequences for each one of the different layouts. As presented, the 9 Channels configuration, with an average time of 14.7 seconds, has obtained the worst results. The 8 Channels configuration has obtained the third best result with a time of 13.73 seconds. The configuration that has reached the best result is the 5 Channels with 10.25 seconds, because of the very low number of electrode [43]. The 5 Channels keyboard also is the configuration that present the lowest standard deviation. The 7 Channels keyboard has obtained the second best result with an average time of 13.35 seconds.

Figure 38 presents the average typing results between the different keyboard layouts compared to the results obtained on a T9 keyboard and using the point finger on the TTS device, outside of the oral cavity. The best result is obtained by the 7 Channels keyboard with an average time of 22.78 seconds, while the 8 and 9 Channels has the second and third best results with respectively 25.31 and 28.94 seconds. As expected, the worst performance was obtained by the 5 Channels, with an average time that is almost twice the 7 Channels time (43.44 seconds) [43]. Using fingers as an input method to control TTS allows to obtain performances that are between 7.7 and 10.8% better, depending on the number of keys. Using the T9 keyboard on

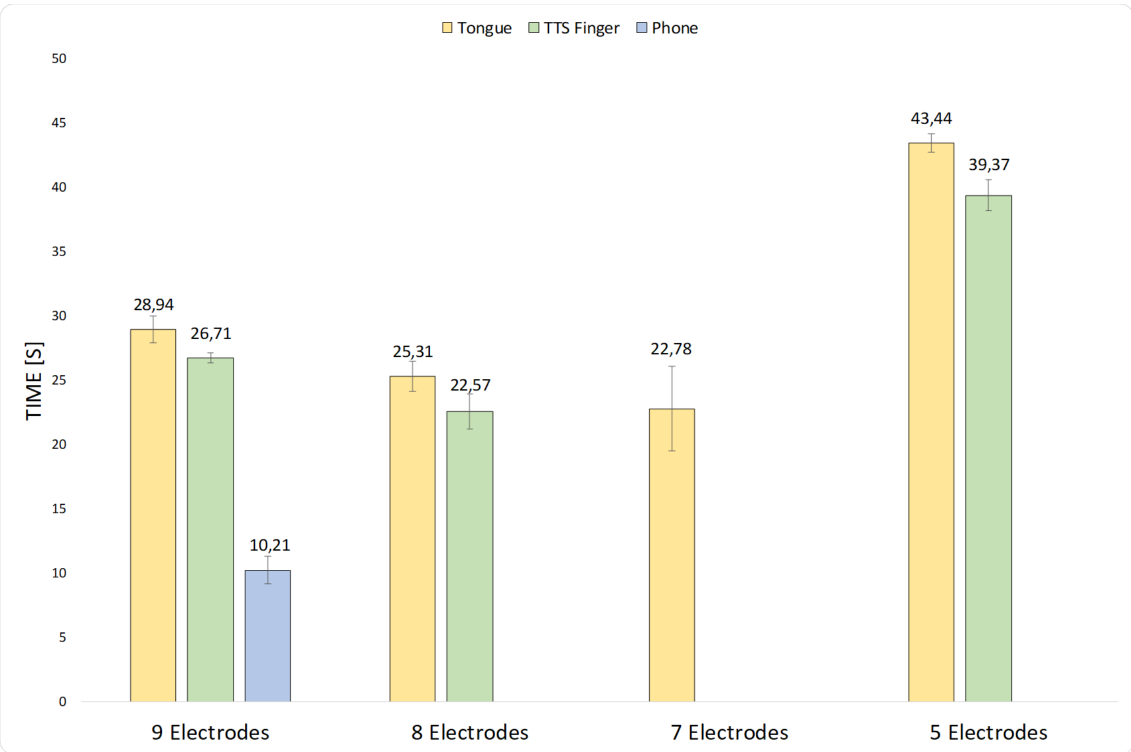


Figure 38: Different keyboards typing test results

smartphone to type takes 2.5–3 times less compared to the 9, 8 and 7 channels keyboard, while it takes more than 4 times less compared to the 5 channels keyboard, as shown in Figure 38

Based on the comparison of the two tests results, it is possible to say that the 7 Channels configuration is the better performing one, since it provides a very good combination of typing accuracy, touching precision (second best performance in the Position Test) and typing speed (best result in Typing Test).

3.7 TTS vs Competitor Devices

After having tested the performances of the TTS device, it is interesting to analyze them by comparing TTS with other competitor in the market or in the state of art. The key indicator used to compare the quality of the different performances is ccpm (correct characters per minute). TTS results expressed in ccpm have been calculated by projecting the Typing test results over one minute.

$$Performance\ [ccpm] = \frac{TC}{ATTT} \times 60 \tag{3.3}$$

Where TC is the number of Typed Characters in the phrase and ATTT is the Average Typing Test Time, calculated day by day. For example, the Day 1 average time needed to complete the Typing test is 24.28 seconds and the characters used to type the sentence "how are you!" are 12, so the ccpm performance of Day 1 is calculated with Equation 3.3 and is

$$Performance\ [ccpm] = \frac{12}{24.28} \times 60 = 29.65 \tag{3.4}$$

The competitors analyzed are MouthStick [20], Eye Gazer [23], Head Tracker [23], Sip and Puff [20] and ITC [29]. Their performances are also compared with PC QWERTY keyboards and T9 phone keyboards without word prediction.

The numerical results of the Eye Gazer and Head Tracker devices, shown in Figure 39, are the average real performances (not the estimated performances) presented in the Hansen et al. paper [23]. The two results are considered equal because the Hansen et al. paper claims that

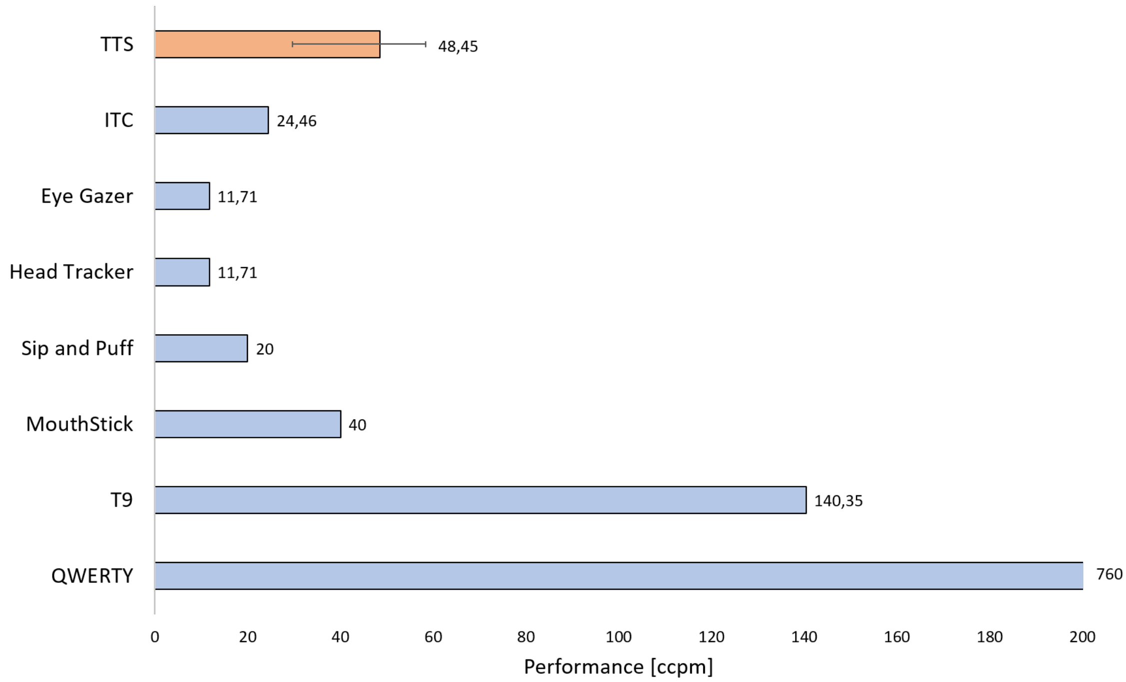


Figure 39: TTS vs Competitors

the two devices performances are very similar. In ITC, the numerical results considered are the average of the 3 subjects performances [29]. TTS and T9 keyboard ccpm results have been calculated using Equation 3.3, with ATTT equal to the average performances over the 7 days of tests (14.37 seconds for TTS and 5.13 seconds for phone). The error bar on the TTS histogram represents the performance in ccpm calculated using the average time performances obtained in Day 1 (left end) and in Day 7 (right end).

While the T9 and PC QWERTY keyboards are still a more efficient tool to quickly type word on devices (but are not usable in their standard configuration by disabled individuals), Figure 39 shows that, considering the average results over the 7 days of test (1 hour a day), TTS is capable of performance far better than all the competitors analyzed; the difference between TTS and the second best performing competitor, Mouthstick, is 8.45 ccpm. Considering the average length of english words as 8.23 characters [47], TTS allows to type 1.02 more words per minute compared to the second best performing device. Even only considering the performance of Day 1 (29.65 ccpm), TTS still delivers the second best performance, only behind the MouthStick, and 5.19 ccpm ahead of ITC.

CHAPTER 4

CONCLUSION

The goal of this work was to create a wearable, wireless, non–invasive, discreet and performing assistive device that could help people with different disabilities (from speech impaired to upper limb disabled) to communicate. In this work, have been presented different assistive devices and TCI interfaces that want to solve the same communication problems.

All of the devices presented have several limitations that can make them very unappealing to a possible final user. The most important issue with this category of products is the discreetness of the interface, since the users tend to prefer products that do not attract unwanted attentions [13]. Almost everyone of the competitor devices is not discreet; some of them have wires coming out of the mouth (ITC), some can only be used with large external device or cameras (Head Tracker and Eye Gaze) and others require external tools like sticks or headphones, or can cause fatigue or physical problems over time (Mouthstick and TDS).

The only discreet devices in the market are iTDS-2, MouthPad, Pallette. The limitations of these products are different: in some cases, the devices are not specifically designed to type, so they only allow to control a cursor on a personal computer.

From a functionalities point of view, based on our tests, TTS is the better performing device in term of typing speed. After only 7 days of practice (1 hour per day), the ccpm results achieved using TTS are far better than all the other devices.

In conclusion, TTS seems to be an effective solution to help solving communication problems for speech impaired individuals and people with upper limb disabilities. TTS has shown to be a wearable, wireless, non–invasive and discreet device that present itself as a better solution compared to other market products in terms of typing performances and design qualities.

4.1 Future developments

For future development, the focus will be directed towards reducing the footprint of the electronic in order to maximize the tongue mobility inside the oral cavity and to make the device even more discreet. In order to achieve this goal, it is possible to create a new board that includes both the Beetle BLE and MPR121 capacitive control and print it on flexible materials. By printing boards over flexible materials, it is also possible to create a unique piece that includes both the electrodes and the electronic, that is more easily attachable to the retainer.

Another important aspect is the possibility of using words prediction in the keyboard, feature that would increase considerably the typing performances and make the TTS device even more user–friendly. The smartphone application is also another feature that could be improved: the design can be modified in order to have a better user experience and better reading conditions, the functionalities can be improved by allowing direct Bluetooth activation from the app, without going through the settings of the smartphone. A version of the TTS app for iOS is also a possible future development to increase the number of TTS–compatible smartphones.

In order to validate the results achieved, TTS should be tested by multiple subject outside of our research group to analyze and compare the performances.

CHAPTER 5

DISCUSSION

The goal that was set at the beginning of the work was to develop a wireless, wearable, non–invasive, discreet assistive device to provide help for people suffering from communication disorders. Based on the device's design, the characteristics, the functionalities of TTS and the results presented, we were able to accomplish the goal we set in the early stages. In the following paragraphs are listed and described the qualities, strengths and features of the TTS device and are also pointed out the limitations that this work presents and the impact that the device could have.

5.1 Strengths

The most important aspects that characterize the TTS assistive device are the hardware and firmware design, which make the device portable, discreet, easy to use and easy to learn.

The portability is one of the great features of TTS. TTS is a wireless device that does not require any external attachment to devices such as personal computers due to the fact that the data are transferred via Bluetooth. Thanks to this feature, when the device is connected to a smartphone, it can be used outside without the burden of devices that are difficult to carry around.

Discreetness is an important quality that our device presents. In any assistive device, the discreetness of the interface is one of the most important aspect considered by both the developers and by the final users. Therefore, TTS is located inside the oral cavity in order to make it harder to notice and it does not attract unwanted attentions when the subject uses it.

The compactness of TTS is also a relevant quality. All the TTS electronic components are positioned on the palate and the design and dimensions of the device allow the tongue to move and operate with freedom and space.

The keyboard is one of the strengths of TTS. The keyboard design is very similar to the T9 keyboards that cellphones used to have before the touchscreen and smartphone era. This aspect makes it is easier for the final user to understand the functionalities and reduces the learning process. The keyboard also does not require difficult tongue movements or strong taps to type, which make it very user–friendly.

The haptic feedback is a very important feature that improves the usability of the device. TTS provides a haptic feedback to make the user aware that the characters that require a long–press action are reached (space, send and delete). The feedback is a quick and strong vibration that lasts 0.1 seconds. Another feedback that the device provides to make the electrodes more easily reachable is a set of small holes, drilled in the same position of the keys, to give the user's tongue a guide towards the key.

5.2 Limitations

In order to properly contextualize and analyze the results and the performances of the TongueToSpeech device, it is necessary to point out the limitations that this work presents.

The first and main limitation is that the tests were performed on a single subject (N=1) and on a single device. The test's subject is a member of the TTS device developing team and his insights on the project may have shorten the learning process that was presented in the results. It will be necessary to extend the tests on multiple subjects, of different ages and gender, in order to compare the results with the ones obtained in this work and to see if they present any significant difference.

Another limitation is that the testing methods that were used by our competitors to obtain the correct–characters–per–minute (ccpm) results of their devices were all different from the typing test that we designed and were also different from one another. This fact may have affected at some level the comparisons of performances that is described in our results. Given the different technologies, physics principles and keyboard layouts that are used in the competitors' devices, it may be hard to design a typing test that is able to describe the performances of all the assistive devices with the same effectiveness.

One other limitation is the fact that it was not performed any test related to the analysis of the precise duration of the battery under extended using conditions.

5.3 Impact

Communications disorders, both silent and vocal, are a very serious problem that affect the ability of the patient to interact and communicate with other people, both in his private and public life. The most common disorders that affect silent communication is spinal cord injury while the speech impairments are the most frequent cause of vocal communication problems. It has been estimated that, in the USA, 1 every 6 people was, is or will be affected by a communication related disorder or problem during his/her life [2]. This means that 16.66 % of the American population is or will be affected by these conditions, which leads to a total number of 53.83 millions of Americans. Given the number of people that are affected by these disorders, considering only the United States, there is a high need of solutions like TTS to overcome or alleviate communications problems.

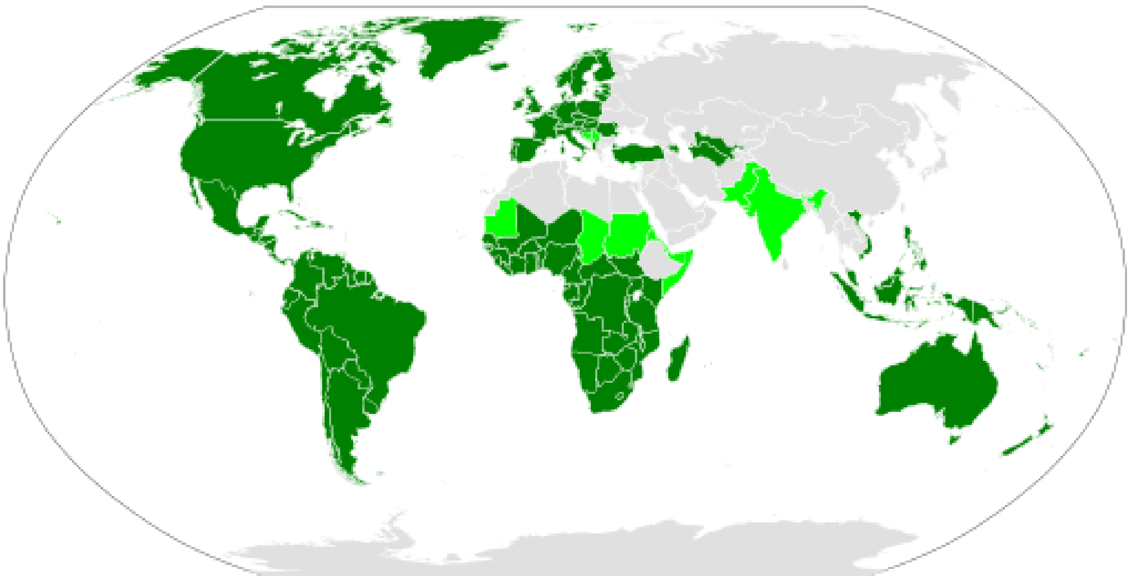


Figure 40: Latin alphabet distribution in the world [48]

Since the keyboard uses letters of the latin alphabet, the TTS device can also be used to solve communication problems in all the countries that uses the same alphabet (Figure 40), which means that North American, South American, Australian, African and European people could benefit from this device too.

APPENDICES

Appendix A

MEAN, VARIANCE AND STANDARD DEVIATION

During all the tests, Mean, Variance and Standard Deviation have been calculated using these formulas.

Mean:

$$\mu = E[x] = \frac{1}{N}\sum_{i=0}^{N} x_i \tag{A.1}$$

where E[x] is the expected value of x, N is the total number of elements and x_i is the i–th single element.

Variance:

$$\sigma^2 = E[(x - E[x])^2] = \frac{1}{N}\sum_{i=0}^{N}(x_i - \mu)^2 \tag{A.2}$$

where E[x] is the expected value of x, N is the total number of elements, x_i is the i–th single element and μ is the mean.

Standard Deviation:

$$SD = \sqrt{\sigma^2} = \sqrt{\frac{1}{N}\sum_{i=0}^{N}(x_i - \mu)^2} \tag{A.3}$$

where σ^2 is the Variance.

Appendix B

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Conference Proceedings:	Engineering in Medicine and Biology Society (EMBC), 2017 39th Annual International Conference of the IEEE
Author:	Nicholas Marjanovic
Publisher:	IEEE
Date:	July 2017
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11/2016–12/2016	CommunicaShirt, University of Illinois at Chicago, Chicago, IL, USA Team Members: Davide Marzorati, Ai Nhu Nguyen The aim for this project was to create a proof of concept device that would help deaf and mute people to communicate. CommunicaShirt is a T-shirt that embeds an LED matrix, and is connected via Bluetooth to a smartphone application. The user can talk or type in the application, and the corresponding text will be displayed on the LED matrix on the T-shirt. This way, it is possible for deaf people to read the text that appears on the shirts of other people, while for mute people it is possible to visually display to others what they would like to say.
09/2014–01/2015	All4Baby, E-Health Lab – Politecnico di Milano, Milan, Italy Team Members: Andrea Santoleri All4Baby is an Android application that helps pregnant women keep track of their pregnancy status and their babys growth. It also provides helpful advice on alimentation, diet, physical activities and breastfeeding. All4Baby can also be used by doctors, providing basic clinical data for gynecological exams and a database for the management of patients.
03/2014–02/2015	Analisi di Sequenze Genomiche per l'Identificazione di Motivi Funzionali, B3 Lab, Politecnico di Milano, Milan, Italy Team Members: Francesca Ceriani The aim of the project was to formulate hypothesis about the role of micro-RNA-122 (miR-122) in the Hepatocellular Carcinoma (HCC) using specific bioinformatics tools and to analyze the performances of the used softwares by comparing the predicted data with experimental data. This project is based on the Burchard et al. paper about micro-RNA-122 and HCC relationship.