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Master's Thesis
Academic Year 2020

Tactile Body-Globe – Using Body as Spatial Globe Interface for Vibrotactile Display of Temporal Data

Keio University
Graduate School of Media Design

Edward C. Wu

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Edward C. Wu

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Abstract of Master's Thesis of Academic Year 2020

Tactile Body-Globe – Using Body as Spatial Globe Interface for Vibrotactile Display of Temporal Data

Category: Science / Engineering

Summary

As technology becomes more ubiquitous, more data are also being generated by machines. In addition, technological advancement in sensors has further allowed us to collect data beyond our perceptual human senses. While all of these meant that we are able to observe and see the world in a brand new way, data obtained from these devices still need to be process in a manner for us human to understand.

While our cognitive ability to comprehend data can be enhanced through computer-aided processes, the vast majority of understanding the data has been through the form of visualization, particularly via graphs and charts [1]. This method still applies even if the data's original source comes from something our body is capable of perceiving through the senses, such as sound and touch.

Tactile Body-Globe aims to use vibrotactile responses as a new method for data interpretation, especially in regards to using human body as a spatial mapping for geolocation data around the world. Through the use of the body's torso to provide intuitive spatial orientation and as a vibrotactile interface, it allows the user to understand and interpret data via haptic feedback. This, along with visual data representation, helps users to better interpret data, especially when the data can be presented along a timeframe.

Keywords:

Multisensory feedback, Multiple-resource model, Data interpretation, Vibrotactile, Tactile display

Keio University Graduate School of Media Design

Edward C. Wu

Contents

List of Figures

List of Tables

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Chapter 1

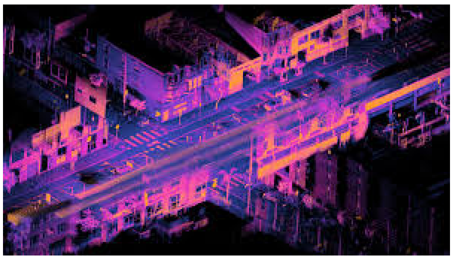
Introduction

1.1. Information Gathering and Processing

Since the dawn of the Information Age, the amount of data generated and gathered has been growing exponentially. From scanned images of text-written copies to computers generated quantitative log files, it has not only provided us with the fuel we need for big data analysis, but also allow us to record, understand, and make discoveries of phenomenon about our world.

Advancements in sensors technologies has allow us to collect data well-beyond the limitations we can perceive via our five senses, ranging from infra-red cameras to capture heat sources we cannot see with our naked eye, to LIDAR sensor that uses light to map the world around us in real time. Our ability to retain data has also drastically increase, thanks to the miniaturization of modern storage devices and the interconnectivity between computer via the internet.

Source: "Air Monitoring station, Reno, Nevada" by brewbooks is licensed under CC BY-SA 2.0



Source: "File:Ouster OS1-64 lidar point cloud of intersection of Folsom and Dore St, San Francisco.png" by Daniel L. Lu is licensed under CC BY 4.0

Figure 1.1 Different forms of data gathering and analysis

1.2. Visual Representation of Processing of Data

So how do we analyze the data we have obtained from the devices? One of the most common method is through visual representation, such as display in charts and diagram. For researchers and scientist, knowing how to interpret and analyze data is fundamental in making discoveries and insights. Data visualization has a long history and is also built upon a foundational guideline, with several design and explored method on how to best represent data from a variety of different sources and mediums. [2]

According to Edward Tufte ' s book on Visual Display of Quantitative Information, Graphical Excellence can be defined as " well-designed presentation of interesting data, a matter of substance, statistics, and design". While statistically speaking, data can be represented and described with numbers on values such as means, standard deviations, etc., unwanted errors can also emerge in the data, and can cause huge differences in our perception of the actual data. [2]

One of the most famous example is Anscombe's quartet constructed by statistician Francis Anscombe in 1973, where dataset have identical statistic property but different distribution, as you can see in the figure below [12]. It it used to showcases the importance of visual representation of data and how it can help us better understand the data in terms of its flow, where statistical properties of different dataset might end up being identical.

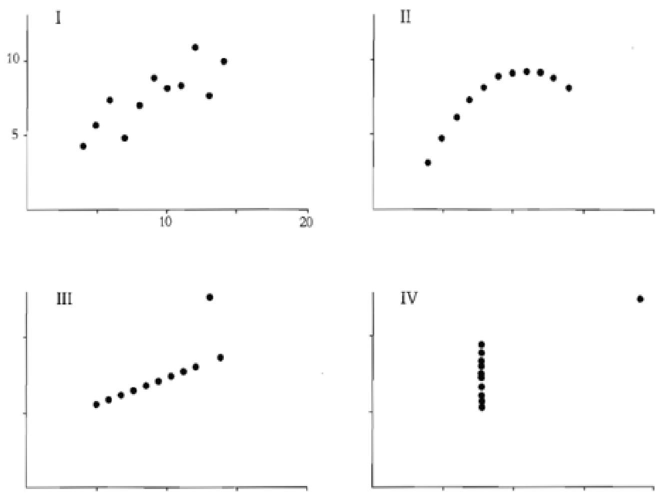


Figure 1.2 Anscombe ’ s Quartet: Showcasing the importance of graphing data visually to avoid errors [2]

With proper design of Visual Data Representation, a lot of details can be denoted and span across several different mediums. For example, prior to the development of video recording technologies, motion can be represented by capturing and graphing out data through a consistent timeframe. Through setting “key” values such as footprints of horse movement to line-capture of human-body skeleton outline, researchers are able to understand the changes that partake each frame of the data, and thereby understand the movement motion through graphical representation of still-frame datasets. [2]

Furthermore, instead of using labels for locations, values can be represented involving displaying data across multiple geolocation in the form of 3D maps. For example, the top right figure showcases a representation of Air Pollution across California Region using 3D graphical representation across 2D landscape of the mapping area. Another example is Choropleth map, which is commonly used for statistical representation of area population. As the famous saying goes “a picture is worth a thousand words ” , the combination of intuitive graphical elements and legends such as bars, charts, and coloring allows users to quickly perceive the data in general without having to dig into the details within the datasets. [2]

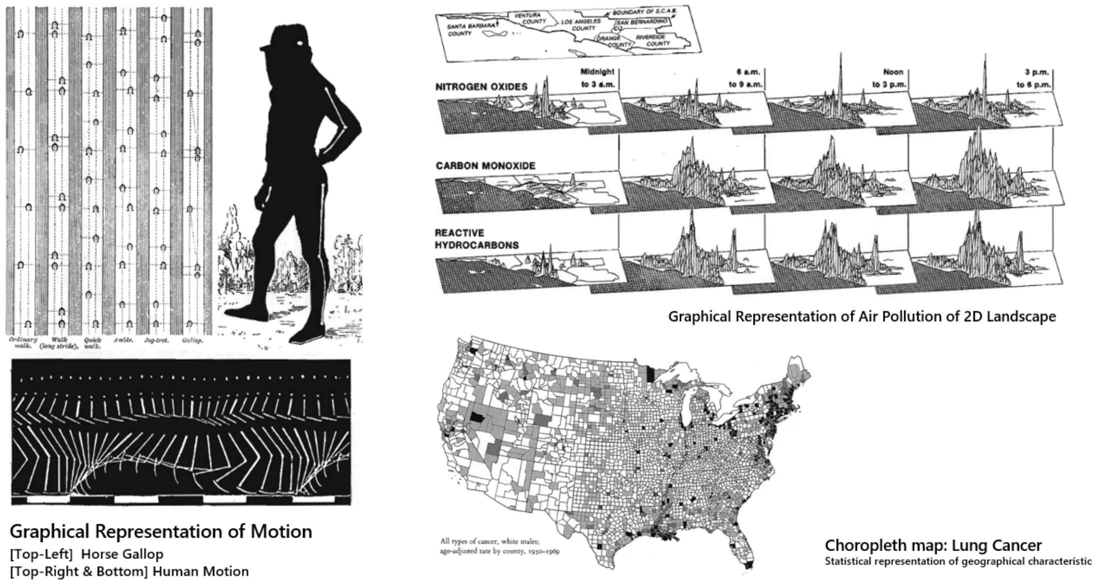


Figure 1.3 Example of different visual data representation design and its use cases [2]

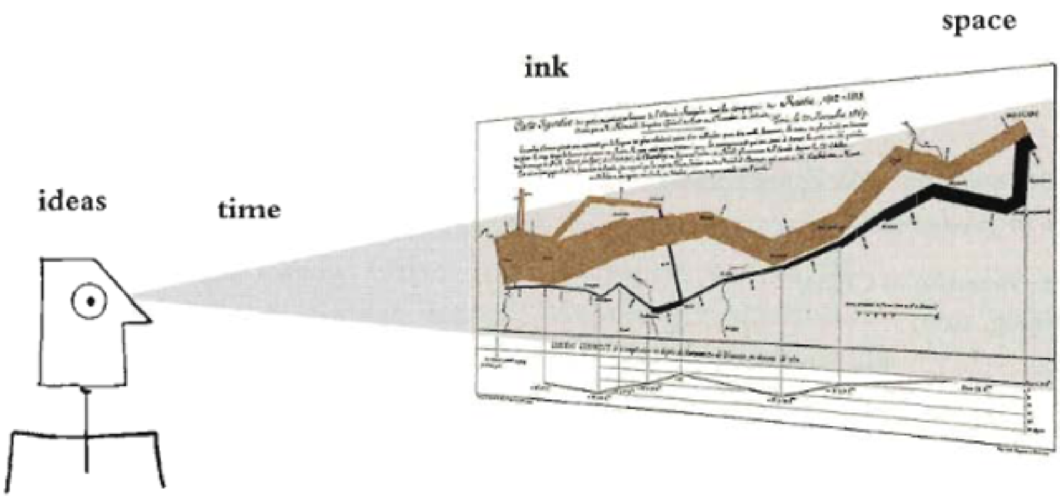


Figure 1.4 Visual Representation of Principle of Graphical Excellence - Edward Tufte [2]

To sum up, according to Tufte, achieving Graphical Excellence and Integrity is to give "the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space"[2]. In other words, through proper techniques and graphical design on displaying data visually, complex dataset can be represented with clarity, precision, and efficiency [2].

With recent advancementment in Machine Learning and Big Data Mining technologies, it has further emphasized the need of novel and intuitive methods of data representation analysis.While most of modern-day data are handled and processed by computers into formats us human can understand, some data may be lost during the transcription, and increase cognitive capacity is needed as data complexity increases.

In this thesis, I plan to explore new method in understanding and interpreting data. Rather than focusing on visualizing data the traditional way, I plan to focus my research on the use vibrotactile feedback as a medium to aid our understanding of the data, especially in a spatial concept.

However, one question that came into mind is why is data being so focused on, what about all of the other senses on our body?

1.3. Scope of Research

With skin being the largest organ on our body and large enough to be used as a surface for interface of sensory feedback, we intend to make use of this unique property and our human body's orientation as an intuitive display for location-based data, especially in regards cylindrical or spherical mapping, such as a globe mapped onto the body.

The purpose of this research is to explore new method in understanding and interpreting data. Rather than focusing on visualizing data the traditional way, I plan to focus my research on the use vibrotactile feedback as a medium to aid our understanding of the data, especially in a spatial concept. Through using our body as a spatial reference as a globe of the world, it provides us another "platform" to navigate and understand the data, just like how grids and axis in graphs works. Apart from this, vibrotactile feedback may also provide a method more closely associated with the original source of the data, such as vibration or wave/seismic based datasets. Furthermore, we intent to find out whether data displayed non-visually through the form of vibration can help enhance users in data analysis and user experience.

In summary of, the thesis can be summed up to provide the following contributions:

- Evaluation of the use of non-Visual Data Representation and its effect on user's cognitive ability to perceive and understand data
- Evaluation of Vibrotactile Display on Body in regards to World-wide based datasets
- Evaluation of raw data values (e.g. Magnitude, Frequency, Patterns, etc.) in Vibrotactile-based medium that is closer in original and perceived initial state.

1.4. Thesis Outline

This thesis will consist of the following Chapters:

- Chapter 1: Consist of the introduction in regards to how we approach data analysis in the modern world
- Chapter 2: Consists of related works in cognitive science on multi-sensory and multi-modal theory, non-visual approach to data interpretation, along recent advancement in wearable haptic technology
- Chapter 3: Explain the Concept design of Tactile Body-Globe
- Chapter 4: Explains the System Implementaion, Experimental Setup, and Data analysis of Tactile Body-Globe
- Chapter 5: Conclusion of the entire thesis

Chapter 2

Literature Review

2.1. Enhance Working Memory through Multi-sensory Response

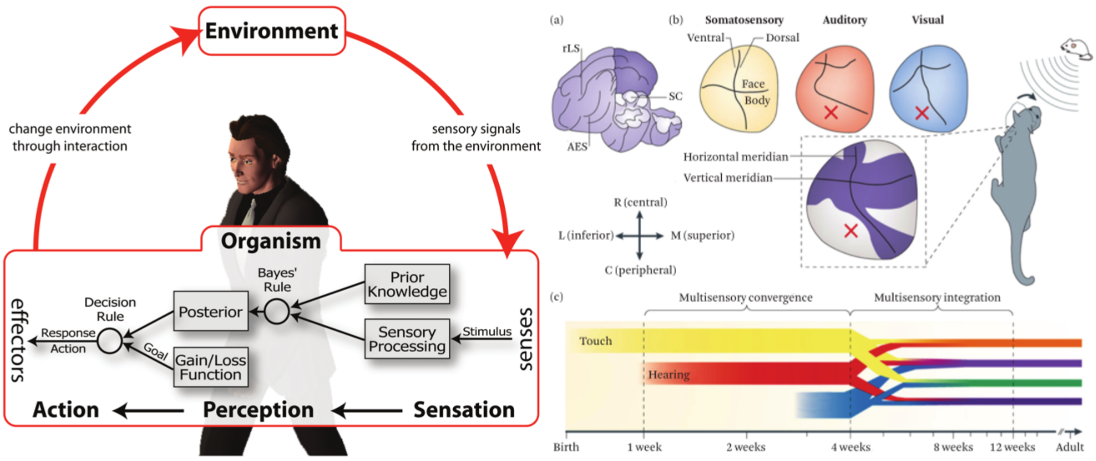


Figure 2.1 Perception-action loop [3]

During the last three decades, literature studies in the field of cognitive neuroscience and experimental psychology discovered that human brain process data in a multi-modal manner [3]. In other words, research shows that our sensory inputs are interconnected and collectively processed by our brain, and therefore it does not make sense to study the stimulation of a sensory response based on one sensory input. The shift in research from unimodal to multimodal meant moving to Gestalt Theory, which can be summarized as "the whole is greater than the pieces combined.

There is also common consensus on limited resource theories, which mentions the bottlenecks involved in human brain processing capacity. Examples includes Working Memory theory, Multiple Resource theory, and Cognitive Load theory, which all address how our brain tries to conserve energy and mental resources through optimizing performance on task [4].

According to the study on "The Impact of Multimodal-Multisensory Learning on Human Performance and Brain Activation Patterns", our human brain is inherently both multimodal and multisensory [4]. This means that our brain is able to unify all the multisensory inputs into one common language, which are then used to create the world we perceive. However, our body is also capable of multimodal response. Furthermore, research has shown that "spatial and temporal proximity influence the salience of a multisensory" perception, which "exhibit multisensory enhancement" that causes super-additivity, which can "produce responses larger than the sum of the two modality-specific sources of input" and is associated with task success [4]. On the other hand, when there is a mismatch or "lag" between the timing of the data, it increases the mental resources as the brain tries to adapt and fortify its multimodal construction based on multisensory information.

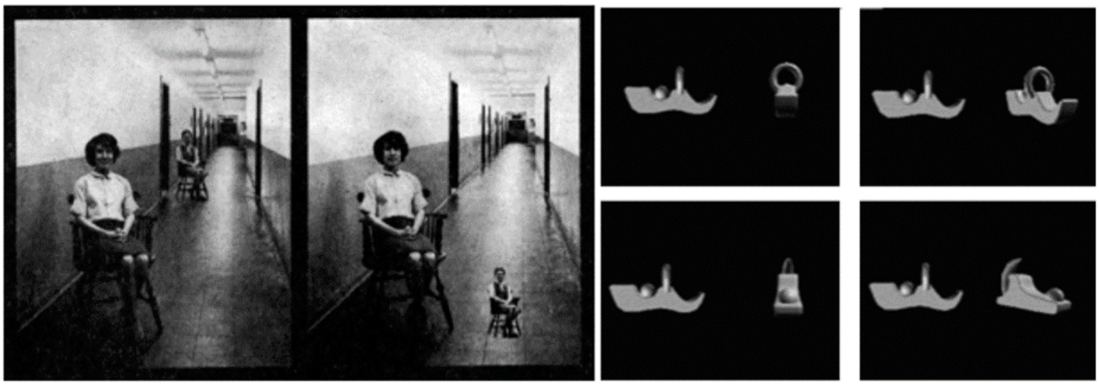


Figure 2.2 Visual Illusions Examples where our brain senses doubt [4]

In this thesis, our goal is to generate super-additivity multisensory enhancement through visual and vibrotactile responses, which inherently should increase user ' s mental capacity and help them better understand the data.

2.2. Non-Visual Data Representation

In this section, we will explore researches related to Non-visual Data Representation and see how data can be display non-visually or encoded and understood through non-visual terms.

In particular, two areas of researches focusing on the senses of touch and hearing will be discussed in this section regarding Non-Visual Data Representation:

- Data Sonification: The use of Sound both as a medium and as a directional source for data representaiton
- Data Tactilization: The use of tactile, touch-based response to encode data across different parts of the body.

2.2.1 Data Sonification

One area of research in Non-Visual data representation can be classified as Data Sonification. According to Bruce Walker, sonification can be defined as the use of "non-speech audio to convey information" where it can generate scientific result [13]. Walker notes that the benefits of using sound for data representation includes opening up a new display medium with distinct advantages in temporal patterns, new tools that are engaging, and the ability of use for people with visual disabilities. One example of data sonification would be the Geiger Counter, where radiation levels are being displayed through a series of beep in certain temporal pattern. In a study conducted by Walker, he ask participant to rate "sound" in terms of temperature, pressure, velocity, and size, and wonder if there is a stereotype consensus among participants The result showed participant were able to find positive correlation with heat where higher with higher frequency (from water boiling), while negative correlation can be found with size, where participant explain how smaller object usually produce higher pitch [13].

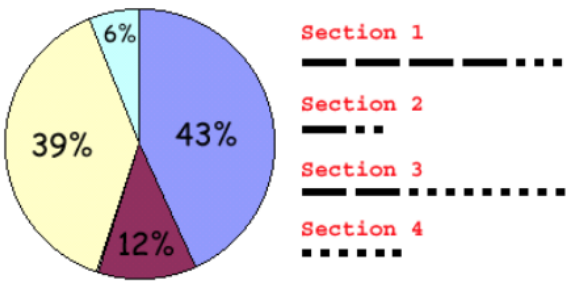


Figure 2.3 Using Sound to Encode Data: Example showcasing Pie Chart Percentage values converted into Morse Code and played via sound [5]

Aside from temporal studies, different type of sound itself can also be used generate data representation. A research done by Carney & Lee explores use of sound in data analysis involving traditional data graphs such as Choropleth Map, Pie Chart, etc., with the focus of using sound as temporal pattern rather than alertness or tactile response [5]. The study uses US Census data, and generate sonification of choropleth map of population in each state based on pitch. The pie chart of employment and unemployment rate data is then represented by playing piano and trumpet sound in morse code, respectively. The result from the research showed that while participants were not able to recall the data in detail, they were able to clearly identify markers such as instruments in relation to employment and unemployment [5].

Adding spatial modality into the mix also opens up a whole different usage for data sonification. For example, sound changes depending on you are stationary or moving due to Doppler Effect. With this in mind, the same aspect can be used as ways to guide. The Spatial Audio Data Immersive (SADIE) Project developed by Bukvic et. al aims to explore both immersive sonification in multidimension spatial data and developing intuitive approaches for aural data [14]. Results from the study has shown that users are able to more accurately pinpoint sources of the input in comparison to when participants are wearing headphones. One of Project SADIE ' s goal is sonifying Geospatial Big Data data obtained from low-Earth orbit and be mapped out, and test to see whether data analysis can be done better through using spatial sonification technique.

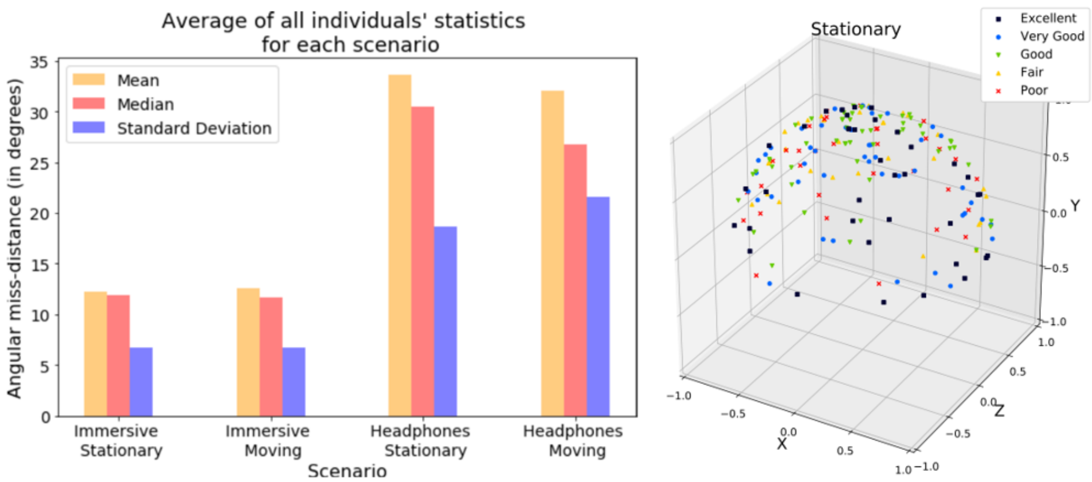
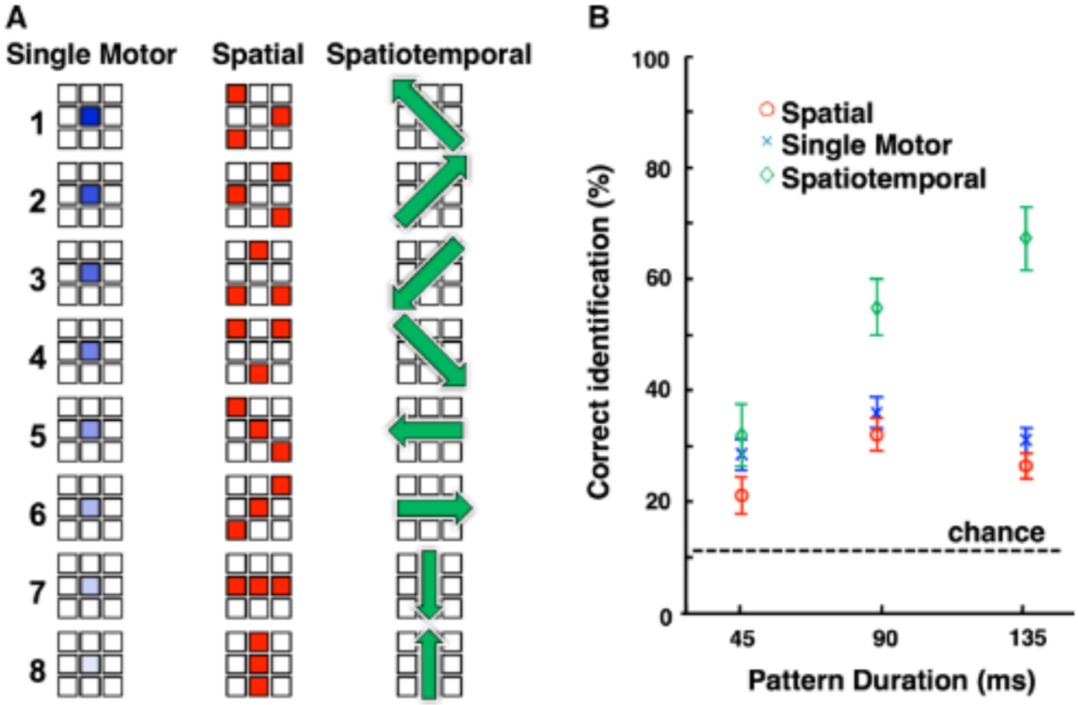


Figure 2.4 SADIE Project - where users are ask to identify sound sources in spatial environment [4]

2.2.2 Data Tactilization

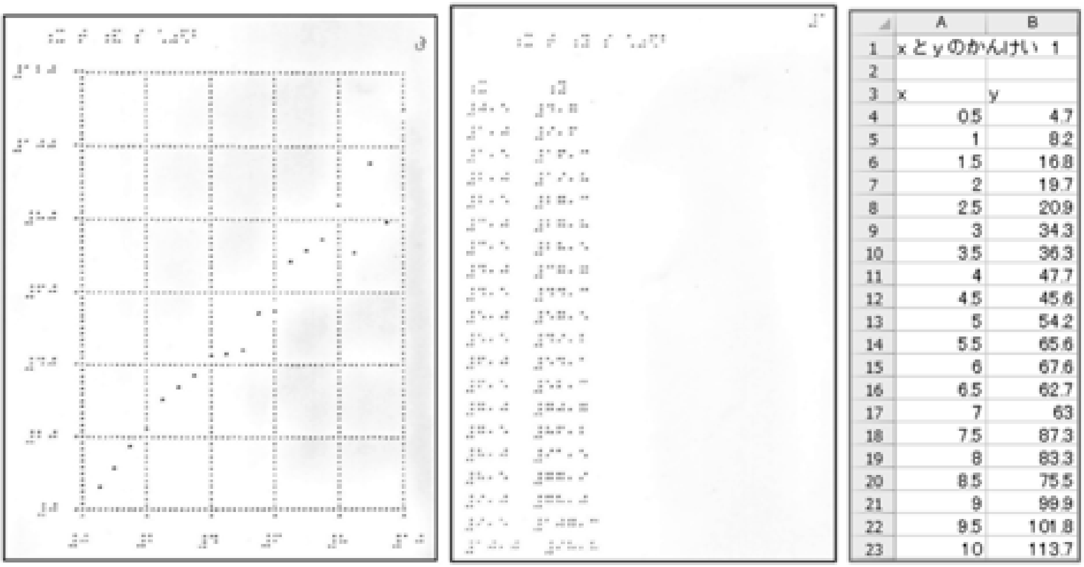
Another area of non-Visual data representation is through tactile display. The tactile sensation can be generated both ways: via active actuators or passive ones like tactile book for people who are visually disabled.



(Source: Using space and time to encode vibrotactile information - (Novich & Eagleman 2015)

Figure 2.5 Vibrotactile Patterns and its perception by users [6]

There has been on-going research to explore how tactile sensation can be used to relay information. One study by Novich & Eagleman explains how tactile response can be used to display high-throughput data such as speech onto our body [6]. With a 3-by-3 grid of tactile actuators, Novich and Eagleman were able to allow participants to learn and understand haptic encoding in correspond to patterns. While the study was not done through continuous pattern, it showcases the possibility for data to be encoded and explained the best way for tactile feedback to be understood.



	A	B
1	xとyのかんけい 1	
2		
3	x	y
4	0.5	4.7
5	1	8.2
6	1.5	16.8
7	2	19.7
8	2.5	20.9
9	3	34.3
10	3.5	36.3
11	4	47.7
12	4.5	45.6
13	5	54.2
14	5.5	65.6
15	6	67.6
16	6.5	62.7
17	7	63
18	7.5	87.3
19	8	83.3
20	8.5	75.5
21	9	99.9
22	9.5	101.8
23	10	113.7

(Source: Effectiveness of Tactile Scatter Plots - Watanabe 2018))

Figure 2.6 (left to right) Tactile Graph, Tactile Table, and Actual Data [7]

However, both ways can be generated into data interpretation that allows the user to feel the data in a different manner. A study done by Watanabe & Mizukami explored how to best represent scatterplot data to blind people via tactile graph, tactile table, and electronic table (where the computer help dictate the data to the user) [7]. The result showed that tactile graph took the shortest time for user to understand the data, followed by tactile table.

2.3. Wearable Haptic Technologies and its Application

Recent advances in technology has also allowed tactile actuator to become smaller and possible to create a wearable haptic interface on the body. As of now, there are several examples of Full-body Haptic suit capable of delivering haptic sensation across the skin of the torso.

One of the limiting factors of haptic display on torso is the amount of resolution our body can understand via the two-point discrimination test [15]. Through research on average torso size and two-point resolution found on the body, it was found that about maximum of 25 actuators can be applied at the same time [6,16]. With modern technology in miniaturizing the individual actuators, it is now possible to cheaply install and design haptic wearables that allows our "skin" to have maximum resolution.

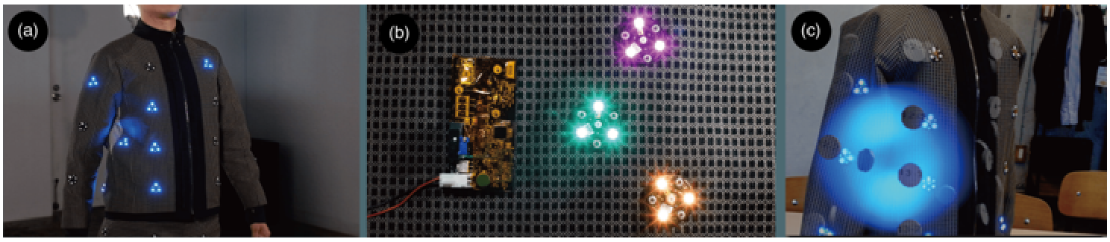


Figure 2.7 Wearable Haptic Suit: Synesthesia Wear [8]

An example is a study which uses vibrotacile with vision to help with tracking and locate object. For example, Synesthesia Wear allows the user experience haptic feedback through different location on the torso to allow spatial haptic experience in mixed-reality [8]. The wireless capability of the suit allows the user to roam freely. And through triggering events in the actual world or virtual reality environments, vibrotactile feedback can be sent to the individual tactor units to relay the proper haptic experience to the user.

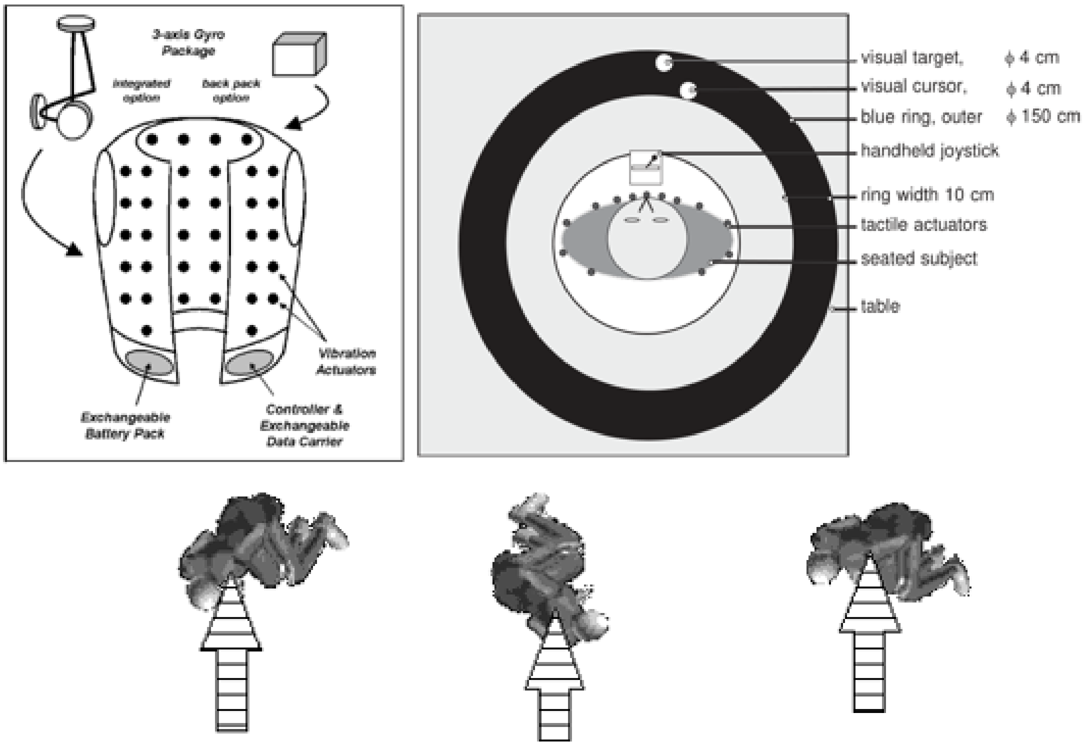


Figure 2.8 (Top-Right) Cross-Modal Visual and Vibrotactile Tracking [9]
(Top-Left & Bottom) Tactile Suit used for Astronauts Gravity Orientation [10]

For real world use cases, actuators around the torso can provide a sense of direction and orientation, thereby relaying directional information to users. Through the use of the spatial orientation of the body, individual vibration on different part of the torso can help provide information relative to the user's location and bearing. One example is to apply wearable haptic vest in spacesuit to help astronaut in their task. In space, due to the lack of gravitational pull, it is hard for astronauts to know which way is the proper orientation. Van Erp's research design focuses explores the use case of haptic wearable device and how it can be use in the ISS (International Space Station) for purposes ranging from locating object or expressing messages to guiding astronaut in emergency situations. [10]

Figure 2.9 Example of Forearm-based Wearable Haptic [17, 18]

Furthermore, even wearable haptic device in the formarm, abiet bounded by the limited space of tactile feedback, can allow users to learn words through phonemic-based tactile codes [17, 18]. The research shown above showcases subjects that undergo through training are able to be able to tell phonetic, and eventually tell the difference and know how 500 words via controlled vibrotactile feedback from 22 tactors in the forearm. From the results in the paper, some group of participant were able to "acquire 325 to 417 words within 266 to 423 minutes (about 4.5 to 7 hours) of cumulative learning time" [17].

All in all, these example showcase the potential of wearable haptic technologies and its use cases that it can provide in terms of understanding and interpreting data.

Chapter 3

Tactile Body-Globe: Concept Design

3.1. Tactile Body-Globe Concept

Data itself comes in various mediums, formats, and values. This is why different graphical design representation are necessary to showcases the variety of different dataset in ways we can perceive and make observation of what is going on with the data. The same can be said about how multiple senses allow us to perceive and experience the world differently via each stimulus.

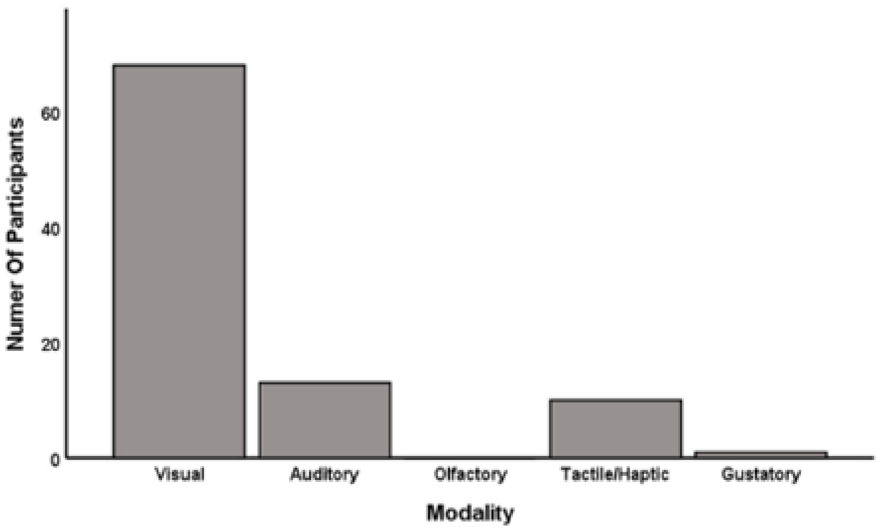


Figure 3.1 Survey on Losing Which Modality Scares You the Most [11]

According to a survey by Hutmacher on "Why Is There So Much More Research on Vision Than on Any Other Sensory Modality?", data showed that aside from visual, auditory and tactile/haptic comes close in 2nd and 3rd Place [11]. With "Skin" being the largest organ on our body, my research plans on to explore how data can be represented via Tactile/Haptic on our body, and use it as an interface similar to how charts and diagram are displayed in color on a 2D surface.

My research hopes create a new method of data representation involving data being represented non-visually through tactile/haptic feedback. The goal of the design is to provide an interface with the following aspects:

- Using human intuition and spatial recognition of our body to assist in data representation.
- Using vibrotactile feedback as a sensory stimulation to achieve multisensory enhancement.
- Explore new user experience design concept for non-visual data representation

This section will aim to explain the design concept behind Tactile Body-Globe and include initial prototype and preliminary testing of wearable haptic interface both in developing the pattern for encoding data and along with user feedback from the initial setup.

3.2. Design Overview of Tactile Body-Globe

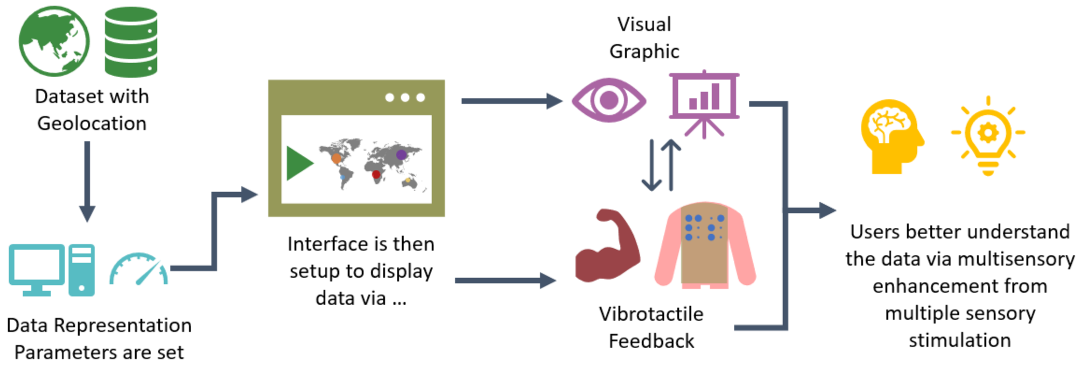


Figure 3.2 Concept Design Overview of Tactile Body-Globe

The overview design of Tactile Body-Globe can be summarized as taking geolocation-based data and output it both visually and haptically in tandem with each other to the user via an interface that involves visual and vibration feedback across the torso of the body. The main goal for this concept design is for the allow the user to experience new forms of data representation which involves the use of multisensory stimulus feedback and spatial orientation of the body as a canvas for location information.

In order to maximize the use of spatial orientation on the body, datasets with geolocation data are best for data representation. Example of such type of data includes weather forecast or climate change data, earthquake or wave/seismic-based datasets, and more. Geolocation data such as these that requires location-based information for further analysis are best for the implementation of Tactile Body-Globe interface.

Beside the metadata of the dataset, it is also essential to adjust and setup parameters that makes the most sense for vibrotactile data representation. This includes, but not limited to, the magnitude of the display, the type of pattern of display, the speed of the display, etc.

Table 3.1 Tactile Body-Globe: Implementation Process

Process	Explanation	Examples
Dataset with Geolocation	Data containing Spatio-geolocation information along with other values about that location	Climate Change around the world, Earthquake by coordinates, etc.
Data Representation Parameters	Data playthrough adjusted accordingly for best representation in Visual and Vibrotactile medium.	Speed of playthrough of data values, Vibration Area on body for each data value, etc.
Data Representation via Visual Graphic	Data represented via Graphic Information and Text Messages.	Display dates for each data frame, using legends and coloring to represent data values, etc.
Data Representation via Vibrotactile Feedback	Data represented through vibration response of each tactile unit on human body.	Higher Vibration = Higher Pitch, Larger Area of Vibration = Larger Value, etc.

Once the dataset are compiled and set to be represented both visually (based on interactive/animated visual-display) and haptically (based on pin-point vibrotactile response based on geolocation dataset), the dataset is then played through the interface, displaying data both visually and haptically.

Through the interface, it allows the user to experience multimodal and multisensory data both across the torso of the body and through the traditional visual display. This thereby enhances cognitive ability due to the additional sensory perception of the data, and provides a user with a new user experience of data interpretation for temporal data.

3.3. Hypothesis

Based on theory that multimodal-multisensory helps enhance user's capability through increased neural response, my hypothesis will be based on the following:

- Hypothesis 1: With additional sensory input via the form of Vibrotactile Feedback, participants should have better accuracy in answering questions regarding trends and peaks of the data over time for each country in comparison to visual, scatterplot graph only due to multiple resource theory [19]
- Hypothesis 2: With the use of the user ' s body as spatial orientation for world map (globe), user should be able to identify locations intuitively, which helps provide additional geolocation information to the user when triggered in different portion of the body (torso).

3.4. Prototype & Preliminary Test

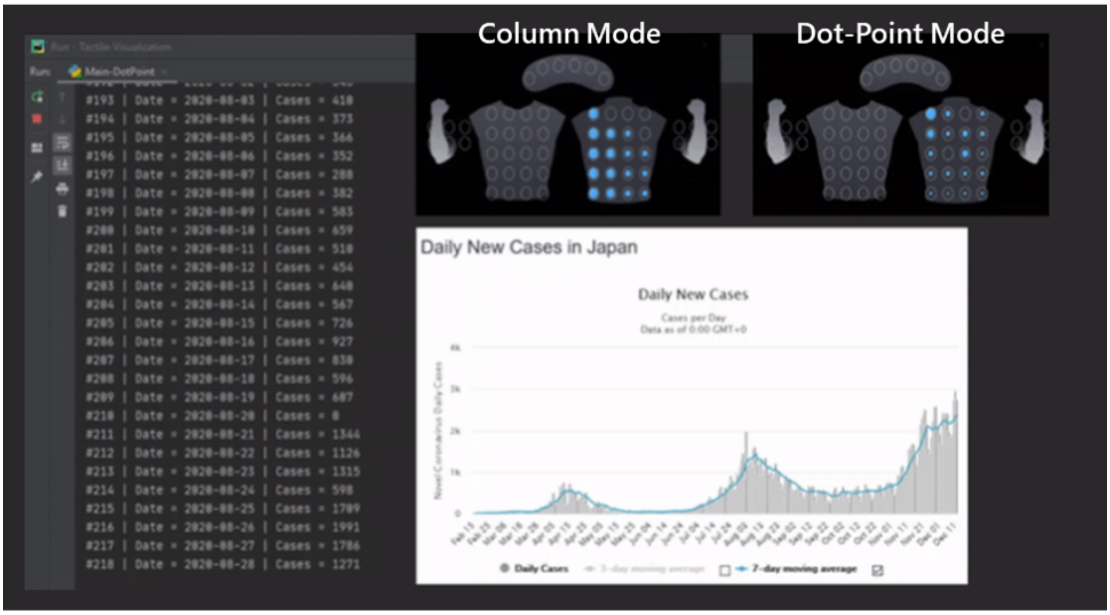


Figure 3.3 Preliminary Testing of Vibrotactile Design Pattern and Data Playthrough Speed

Initial test are conducted on the Wearable haptic device to explore the possible methods of data representation and also user experience parameters such speed an input settings for the interface.

Vibrotactile Display Format

Two method are being conducted to see the difference in user experience on data experimentation.

- *Column Mode:*
  In this mode, tactor units are set to display "bar-graph" like data via vibration, with intensity set on % of max cases recorded. Intensities of the individual tactors are also set to represent the value. For example, the higher the value, not only would there be more tactors vibrating in the column of the tactile suit, it also increases the overall intensity of all tactor units within the same column. Users feedback form this mode found that it is easier to tell "spikes" from the data compared to other modes of representation.
- *Dot-Point Mode:*
  In this mode, tactor units are set to represent each data value individually, providing a general overview of 20 days of data. Oldest data to newest data will move to the next adjacent tactor unit throughout the runtime, providing a mapped-out view and vibrotactile sensation of the average of 20-unit span of the data. Users noted that it's easier to view the overall trend of the data in this mode.

Vibrotactile Display Rate

Since the design involves "playing" temporal datasets by timeframes, the speed data is being cycled through is important for users to both understand the data while being able to focus and perceive a pattern throughout the run-through. Initially dataset were set to display from 150 to 300ms per data unit. Several users that tried the prototype commented on that "slower is better", "220ms better than 150ms", etc. This is then taking into consideration during the actual implementation step of Tactile Body-Globe, in which the length of the playthrough will depend on the size of the dataset.

3.5. System Architecture

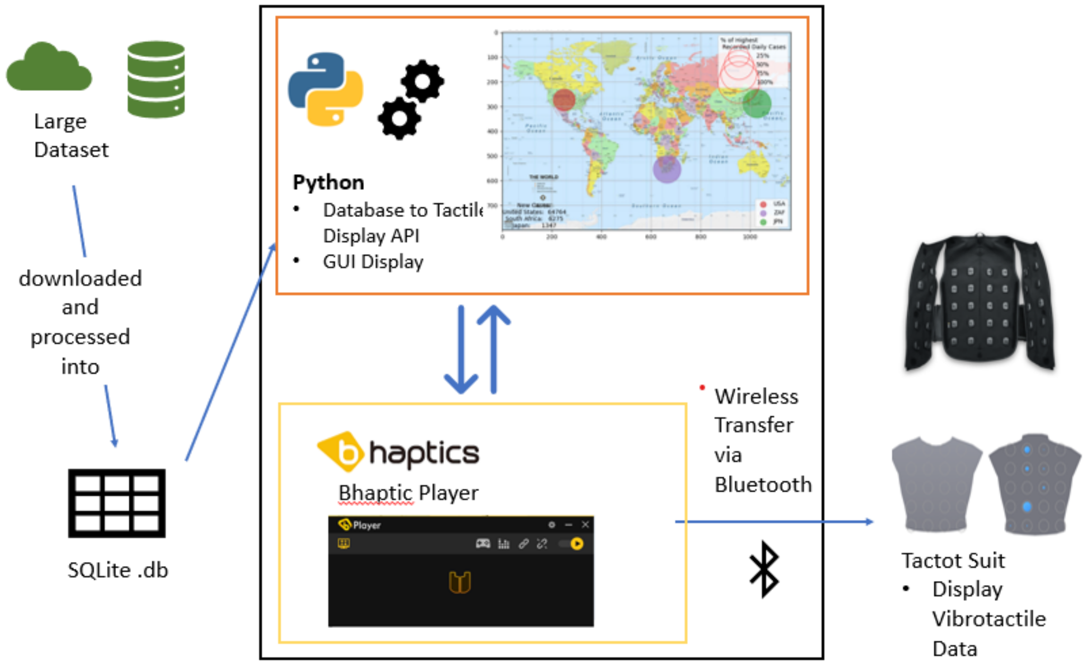


Figure 3.4 Planned System Integration Architecture for Tactile Body-Globe

From the feedback and suggestions obtained from the prototype and preliminary test, the overall system architecture would be setup as seen in the figure above.

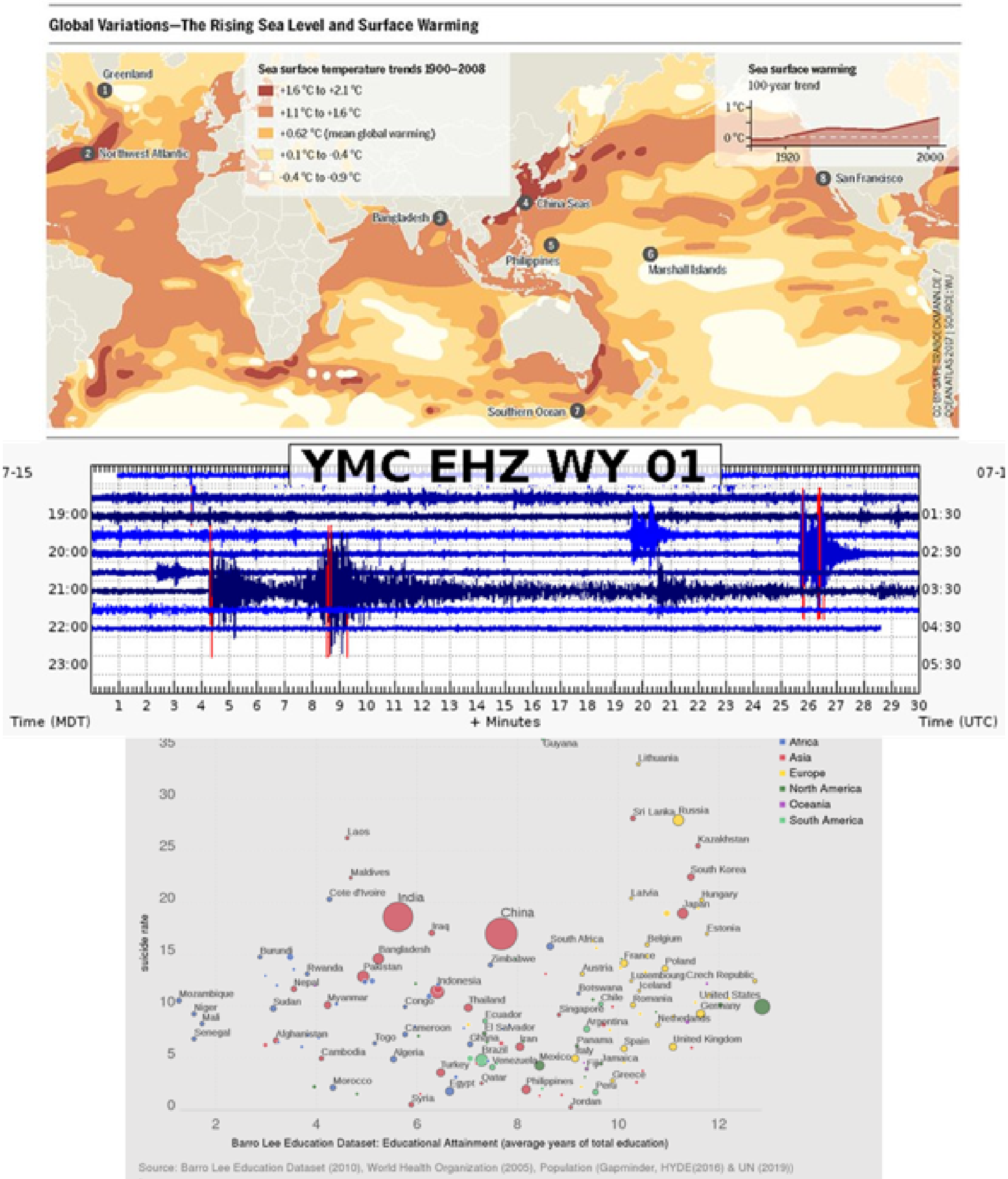
First of all, raw dataset files such as .db, .csv, .json, etc., that contain geolocation information as part of its data is obtained. The next step be using database management system (in our case SQLite)for easier api handling of data into the main program. In regards to the software, we use Python Matplotlib as visual display and Bhaptic Player ' s Python SDK Library for connecting and transferring vibrotactile triggers to the wearable haptic suit.

3.6. Possible Application for Tactile Body-Globe

In order for the concept design to enhance the user's capability in data interpretation, it is necessary to think about what type of datasets would make the most sense when displayed through vibrotactile feedback across the torso of the body. In addition, it is also important to think about what kind of pattern and expression that best make use of vibration as a medium to enhance the user's experience during the play-through of the dataset.

There are several useful scenarios that make use of both the body's orientation for spatial mapping of the globe and the sensory stimulus through vibrotactile. For example, seismic activities around the globe can be interpreted via Tactile Body-Globe for data analysis. This means that rather having traditional plotted list of, researchers can use wearable haptic suit to simulate an immersive spatial experience seismic activity around the world.

Another method is to include a haptic feedback on traditional data that are normally plotted out in histogram or scatterplot. With Tactile Bode-Glove, it allows and additional sense modality for experiencing data, especially in catching outliers or large magnitude changes across multiple different locations.



(Source: Creative Commons)

Figure 3.5 Examples of Possible Dataset and Visual representation that can be used for Tactile Body-Globe

(from top to bottom) Climate Change, Earthquake Seismic Graph, ScatterPlot with each circle representing a country

Chapter 4

System Implementation and Evaluation

4.1. System Implementation

This section will explain the system implementation in detail based on the system architecture proposed in Concept Design from the previous section. Additionally, this section will also explain the reasoning and point out what parameters are set and used for the experiment.

Source of World Data

With the widespread global pandemic of new Coronavirus happening during the time of writing this paper, we decided make use of this opportunity data regarding CoVID New Cases from each country for the experiment. The reason behind this is to first of all showcase how real-time data generated online can be applied in the experiment. Furthermore, it is also an interesting topic that can raises awareness to the participants participating in the experimental study on global trends of CoVID-19.

The data used in this experiment is obtain from " Coronavirus Source Data " created and published by ourworldindata.org, which is retrieved from John Hopkin's University's Coronavirus Resource Center, as mentioned by the author [20]. The .csv file form the website is then transformed into a SQLite Database, in which data values in particular from the columns labeled "iso_country" (3 Letter code), "dates", and "new_cases" were selected and parsed to be read into the system with their respective types as strings or as integers.

Since the website does a rolling-update of the latest data, in order to keep consistency across participants, the date is set to begin on Jan 23, 2020, and end on Dec 09, 2020. Data collected and parsed are form the countries United States (USA), South Africa (ZAF), and Japan (JAP). The countries are chosen due to noticeable difference between the new cases graph, and along with the distance apart from each other in the world map. In addition, the distance between each country from each other also helps in eliminating the effects of two-point discrimination among the body of the participant when wearing the BHaptic Suit.

BHaptics Tactot Suit

The vibrotactile hardware used for the experiment is bHaptic Tactot Suit [21]. It consists of an array of tactot (single vibration motor) capable of triggering vibration independently in regards to other. The total number of tactots on this device is 40, with 20 in the front and 20 in the back. The array is display in a 4 column by 5 row style. The battery and main control unit is attached in the back of the suit so the user can freely move and sit in the position they like.

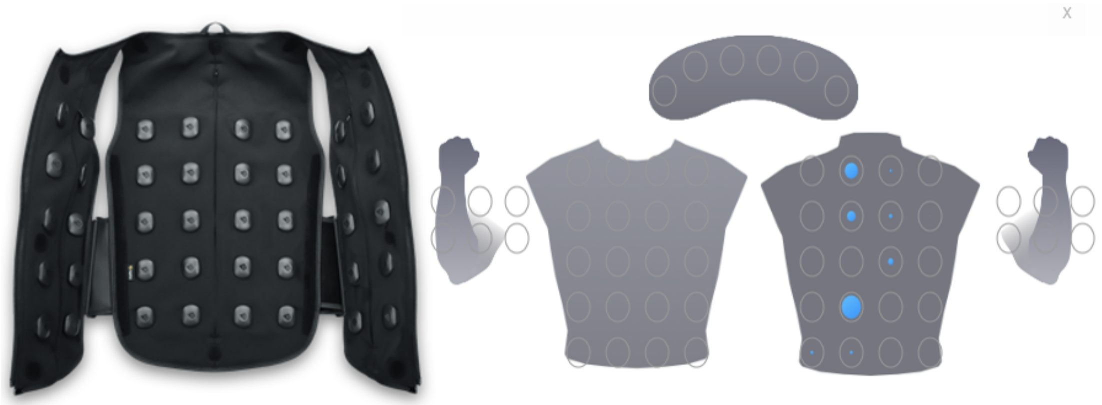


Figure 4.1 (Left) bHaptic Tactot Suit
(Right) bHaptic Player Overlay showcasing dots being triggered on the suit

Software API

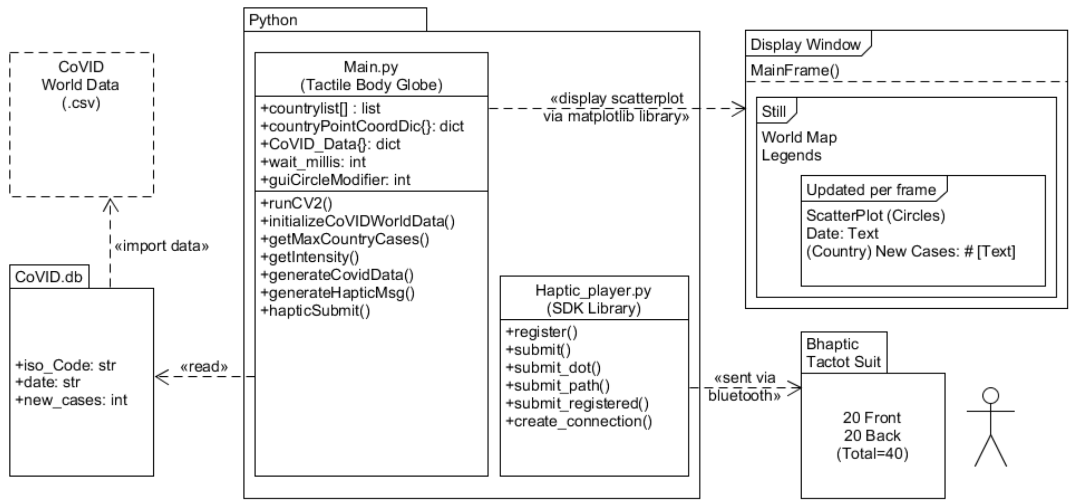
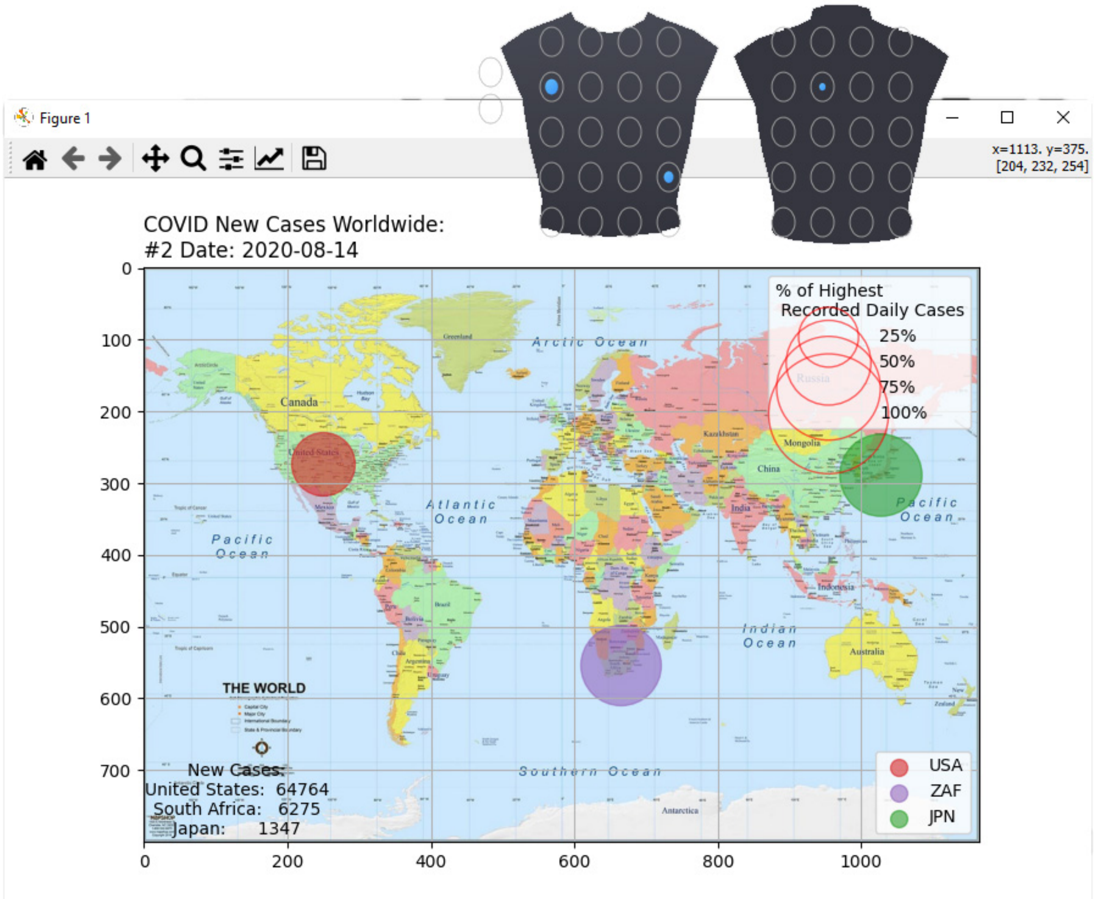


Figure 4.2 UML Display of Software Class and Interaction

The software for handling the vibrotactile encoding is done through Python (along with the use of tact-python library provided by bHaptics). The overall view of the inner working of the software can be seen in Figure (4.2).

Software API used for communication with the bHaptic Tactot Suit's backend is released by bHaptic, and can be obtained from the Github at `https://github.com/bhaptics` and along with installing bHaptic Player on the operating system running the program.

First of all, data used for the experiment is being generated into a SQLite.db file for reading. That database is then passed onto the python software where once started, would ask the user to pick through the map the country list of where they would like the data to be mapped on in the world map. After obtaining the coordinates, the data is then translated into both scatterplot display and vibrotactile display values. For the experiment based on the data of CoVID, data is set to showcase the percentage of maximum cases ever recorded via the entire timeframe of the data record. The intensity of the vibration is proportionate to each country ' s daily cases, which correspond to the scatterplot graph in terms of the size of the circle. The speed of update for vibrotactile feedback is set at a constant time of 0.2 sec per day, based on the guideline principle for Vibro-tactile display suggested by van Erp [22].



(*Note: Haptic Overlay Display is shown here only for visual representation purposes, and it not shown to the participant during the actual experiment)

Figure 4.3 Actual display interface showcasing the animated scatter plot data visualization along with Haptic Display Overlay*

4.2. Experiment Setup

4.2.1 Purpose of the Experiment

The purpose of the experiment is to showcase whether or not users (participants) are able to gain better understanding of data trend through spatiotemporal interface display data both visually and haptically. In addition, this experiment hopes to verify and support the assumption made in the hypothesis. This includes providing and intuitive user experience of data interpretation involving spatial orientation of body as a vibrotactile interface display. More importantly, this experiment is meant to demonstrate a new method toward data representation, focusing especially on how multisensory stimulus provides better cognitive and perception enhancement.

4.2.2 Procedure

First of all, a randomized order of the following 3 scenarios are being decided for the experiment run for the participant:

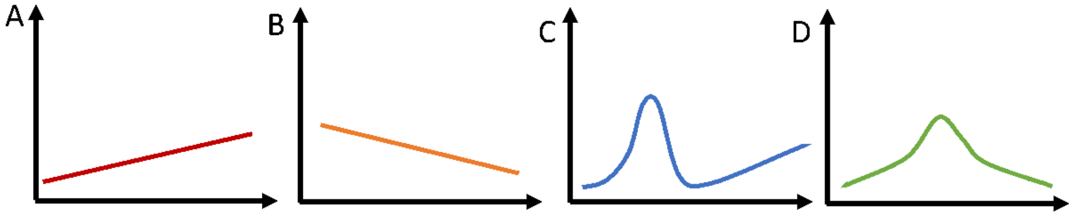
A) Data Visualization (Scatter Plot) + Vibrotactile Feedback

B) Data Visualization (Scatter Plot) Only

C) Vibrotactile Feedback Only

This is to prevent learning biases from multiple participants when running the same data multiple times. Furthermore, participant are expected to gain confidence after running different scenarios of what to correct answers are, and randomization helps in showcasing the true results of how well participant interprets the data. The participant is then asked for their background knowledge on CoVID new cases of the 3 countries we are interpreting the data on: United States, South Africa, and Japan. This should provide reference as to whether the participant is relying soely on the data representation through scenario, or basing their judgement on background knowledge.

Prior to the official scenario runs, participant gets to experience a demo run of 50 cases of Scenario A in order to be familiar and understand what the experiment feels like. Participant is also being told what they need to perform after each scenario ends, which involves asking the following set of question for each country as listed below:



(Visual Reference for multiple choice question on the trend graph)

Q: Which best describe your CoVID knowledge in regards to new cases of USA, South Africa, Japan?

A) Constant, and Trending Upward

B) Constant, and Trending Downward

C) Hump, and Trending Upward

D) Hump, and Trending Downward

The scenario is then performed in the randomized order decided in the starting phase. After each scenario of data representation is complete, participants are asked to fill out the survey and provide comments and feedback about the scenario. Participants are also encouraged to switch their answers if they view the recent scenario provided additional knowledge or better data representation that changed their data interpretation.

Once all the scenarios are finished, participants are then asked the following questions:

A) Is the orientation of the haptic vibration intuitive enough to tell what is going on in each country? (Scale of 1 to 10, 10 being strongly agree)

B) Which scenario do you think provided the best data representation user experience?

C) Which scenario did it stand out the most for you (in terms of recallability)?

They are also asked for general / demographic information in the survey such as age, height, gender, and whether or not they are color blind.

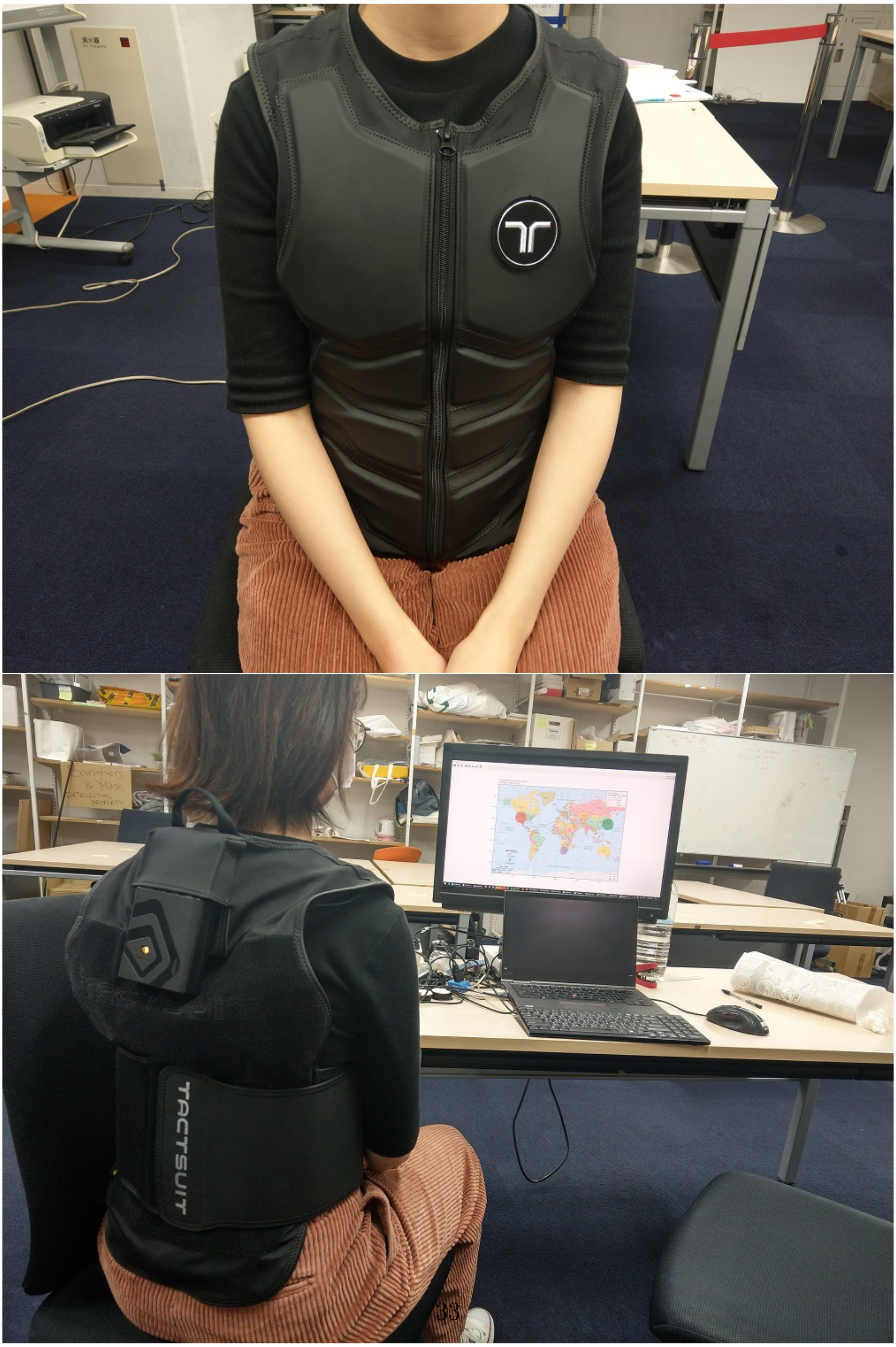


Figure 4.4 Picture of participant undergoing Scenario 1 test with both Visual and Vibrotactile Feedback

4.3. Result and Analysis

Overall, there are seven participants that joined the test of Tactile Body-Globe running on new cases of CoVID Data from USA, South Africa, and Japan. Both quantitative feedback and qualitative feedback are being obtained in the survey after each scenario as mentioned in the procedures.

4.3.1 Participants Result

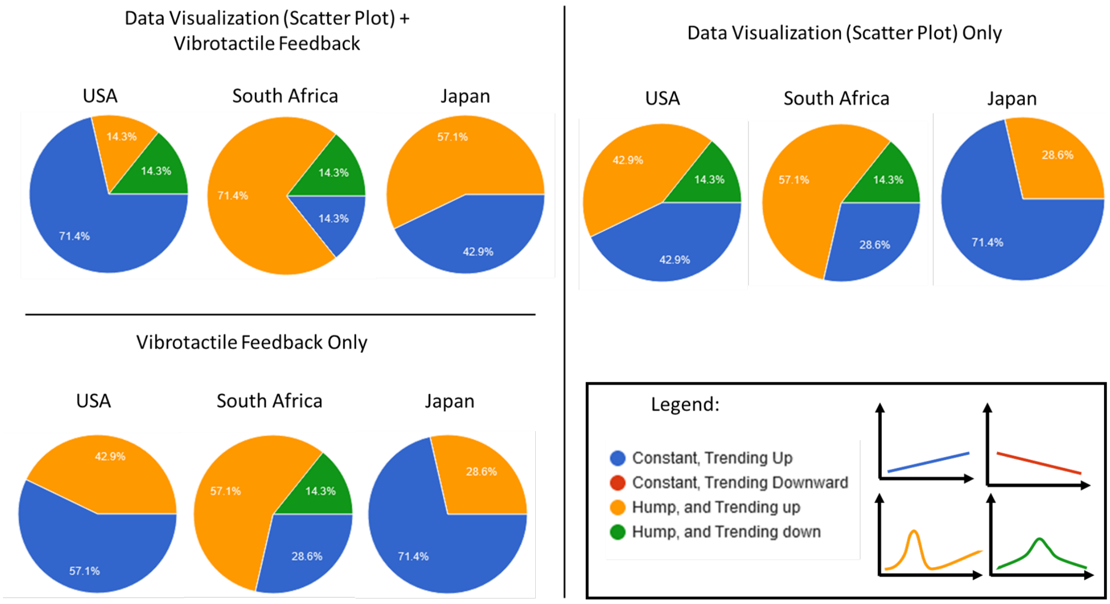


Figure 4.5 Result from Participant's decision on best fits of CoVID New Cases Graph per country from different Scenarios

This section provides the quantitative feedback of the experiment results from the aforementioned procedures. The diagram showcases the percentage amount of the participant ' s answers for each country based on the four different graph descriptions as defined in the legend (Figure 4.5). Since each participant undergoes a random order of scenario from Scenario A: Data Visualization (Scatter Plot) + Vibrotactile Feedback, Scenario B: Data Visualization (Scatter Plot) Only, and Scenario C: Vibrotactile Feedback Only, the result also take into account the average of participants possible learning biases when doing the experiment multiple time on the same data. Furthermore, participants are also encouraged to talk about and provide feedback about each scenario after the run is complete, as mentioned in the next section.

4.3.2 Participants Responses from Survey

This section provides the qualitative feedback of Tactile Body-Globe obtained from the comments and feedback questions asked during the end of each scenario run and at the very end of the experiment. Participants are asked to provide insights and feedback on the user experience of the device, such as how vibrotactile data interpretation affects the user ’ s perception and understanding during the experiment playthrough. Below are some quotes from what the participant says after each scenario.

Data Visualization + Vibrotactile Feedback:

- “ I can feel the Visual Data ”breathing” from time to time··· ”
- “ The sound also helped. ” - Generated from the individual tactor units
- “ The ”intensity” of the vibration quite matches the data ”

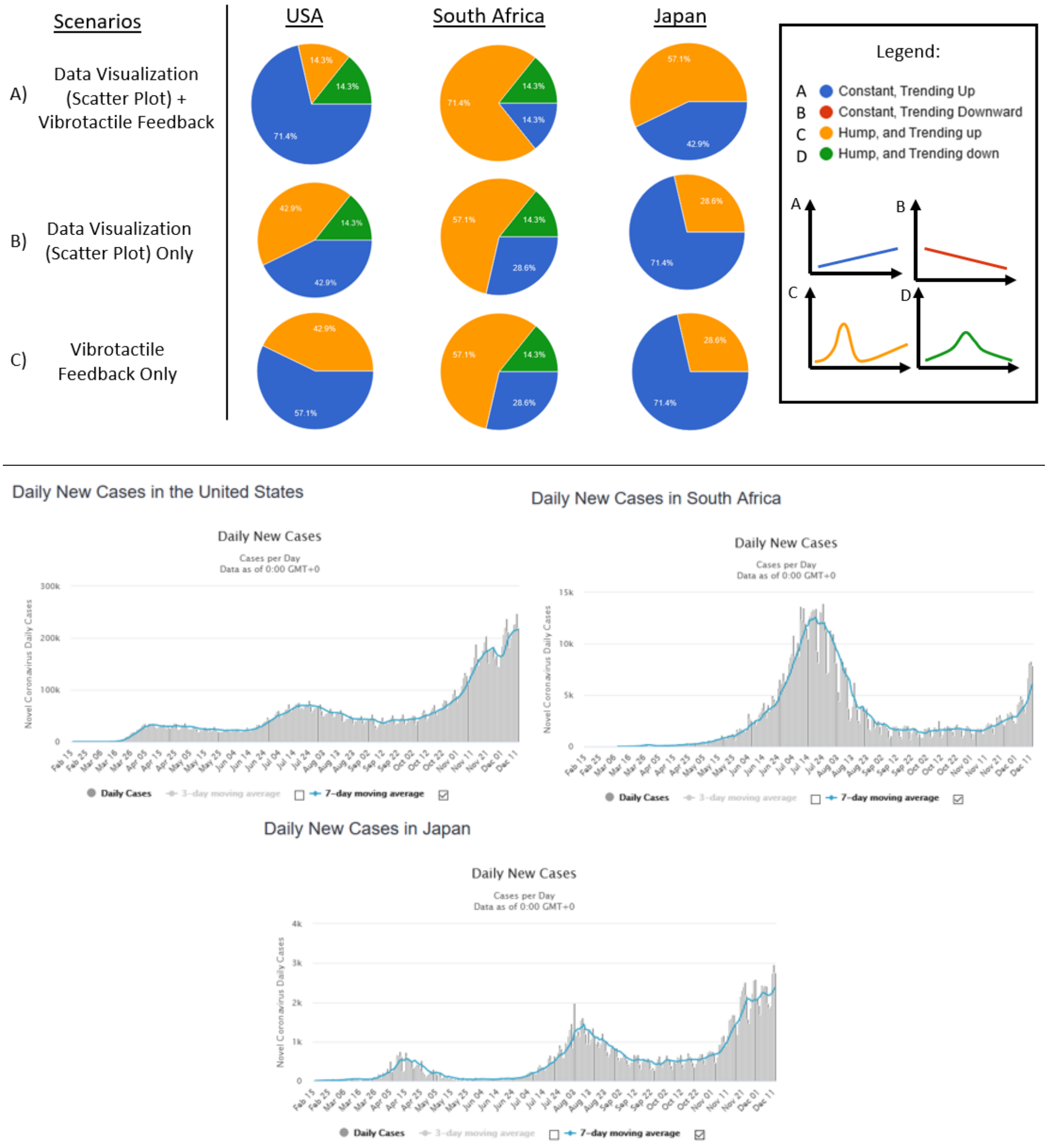
Data Visualization Only:

- “ Based answer of 2nd run (A), as it’s more convincing ” – Participant with 3rd run being data-visualization only
- “ Believe in 1st time Data ” – Participant having this scenario as 2nd run

Vibrotactile Feedback Only:

- “ Kinda hard to tell (as the vibration spreads) ” - Participant having this scenario as their 1st Run
- “ Picture first, then vibration, makes it easier to learn, though having Vibration in the end helps with recognizing data ” - Participant having this as their 3rd run

4.3.3 Discussion



(Trend Graph Data Source: Worldometer.info)

Figure 4.6 Comparison between Participant's Understanding and Actual Results
(Top) Participants' answer on the trend of the graph for each country
(Bottom) Actual data representing CoVID Daily New Cases of each country

This section aims to discuss the findings from the experimental results and also provide insights and observation as to what the result signifies in terms of both enhancement through multisensory stimulus and user experience of vibrotactile feedback. The first part will on the results of the survey and does the majority of the participants answer compare with the actual results. The second part would focus more on the qualitative analysis where quotes and feedback from participants are being discussed across each scenario and what findings are observed during the experiment from participants.

Significance of Results

Findings will be divided based on each country's actual data graph representation when compared to participants answer during each scenario. Afterwards, insights and key takeaways are observed when combining the analyses from all the comparisons.

- **CoVID Graph of USA**

  Starting off with USA, the actual data of the CoVID Daily New Cases graph can be most closely describe as displaying A) Constant, Trending Upward in general across the entire dataset, which is clearly better perceived by the participant answering after undergoing Scenario A, which consist of both visual and vibrotactile feedback.

  For Scenario B, the data shows majority of the people picking both A) and C) as answers, with a few participants picking D) Hump, and Trending down. For Scenario C, participants are divided upon answer A) and C) similar to Scenario B. Since vibrotactile feedback are better in emphasizing dramatic changes in comparison to visual-based feedback, some conclusion can be noted how vibrotactile feedback help prevent participants from thinking that the graph is a bell curve compared to trending upwards, though more participant is required to be certain of this feature.

- **CoVID Graph of South Africa**

  In terms of South Africa ' s dataset and result from Scenario A, 71% of the participants picked the answer C) Hump, Trending Upward as their answer for describing South Africa ' s trend of CoVID Daily New Cases graph, which is the correct answer as it is the closest representation of the actual graph obtained from Worldometer.info.

For both Scenario B and C, more than half of the participants also provided the correct answer of C) Hump, and Trending up, albeit with a higher error rate with more participant picking other answers such as A). Form this result, we can also denote that Scenario A provides participant with better perception based on the amount of people who got the answer correct form our observation. However, due to small sample size of the participant, more test would be necessary to be certain of the results.

- **CoVID Graph of Japan**

  For Japan ' s dataset, results from participant proves to be quite interesting due to the actual graph being quite debatable as to which one is the correct answer from the four options in the survey. Japan was picked as a country for the experiment mainly to address the issue of two-point discrimination. However, after checking the actual CoVID Daily New Cases graph, the trend contains a few " humps " along the range of the dataset, which can be argued to be both trending upwards (A), and humps (C).

  As a result, we can see that there is almost a 50-50 divide among the participants ' selection for A) Constant, Trending Upward, and C) Hump, and Trending up for Scenario A, while both Scenario B and C produce similar results where user believe that the graph is mostly trending upwards. One explanation for the result can be how Scenario A provided the participant with higher uncertainty level of " doubt " on the correct answers, as both A and C represent part but not all of the data.

  As stated by multiple researchers in the literature review section, based on Maximum-Likelihood Estimation Principle, additional sensory stimulus that are aligned increases neural response, which then affects the decision we make later based on the perception formed [3, 4]. This is due multisensory enhancement via visual and vibrotactile feedback which allows the user to get a more accurate perception of the data.

  In other words, the divide of answers between the participant could be explained with multisensory enhancement allowing users to acknowledge and capture more details of that data, hence providing more uncertainty as for which answers are correct in comparison to other single sensory-stimulus scenarios.

- **Key Takeaways:** In summary of, the experiment results from Scenario A having the most participants answering the survey correctly prove that additional sensory input allows participants to better perceive and understand the data more accurately in comparison to single stimulus form both via visual or vibrotactile display. This further confirms my hypothesis where additional sensory input via the form of vibrotactile feedback helps boost users understanding of the data through Multisensory Enhancement. Furthermore, through both the experiment and preliminary testing, the use of spatial orientation of the body as vibrotactile feedback indeed allow users to intuitively relate to geolocation-based dataset, especially in the form of a globe. This confirms my second hypothesis where users are able to intuitively link and extract spatial information through vibrotactile feedback on specific location around the torso, where it act as a spatial interface for the globe.

Interesting Insights

From the comments from the user, one thing that really caught my attention was how someone describe the user experience as if the data is "breathing" from time to time. Since the parameters for the data representation are done through scatter plot (where larger value = bigger circle) and vibrotactile vibration (where larger value = increased intensity), the combination probably provided another sense of what the data "feels" like when being played through in a timeframe format.

Another feature being noted was how "sound" actually also helped with data representation. The initial concept and design of the experiment is aimed toward touch and vision stimulus. However, sound produced by wearable device during operation was not considered. While its possible with different device or equipment its possible to dampen or amplify the sound stimulus to provide another component for data representation, it was not defined in the scope of this research. Nevertheless, the response did open up another component for this research, and would be interesting to see how much sound plays in the role of data interpretation in comparison to vibrotactile feedback.

For Data Visualization, there were a few participants that commented that they have higher trust on data from other scenarios. Also, participant in general did not provide much insights and comments for this scenario. One possibility is because graphical representation is quite common, and the run-through of the scenario was not particularly unique compared to the other two scenario runs.

Lastly, in regards to the scenario run of vibrotactile feedback only, there are some mixed comments in regards to user experience and interpretation of data. From preliminary tests and prototyping, users have responded how it is quite interesting and a new experience of “ feeling ” the data via vibration. However, some user finds it quite confusing, especially during times when high intensity vibrations are occurring in multiple places. While the unit are separated apart in an array format, the individual tactor units can still interfere with one another when set to high intensity. One possible way to solve this is to limit more of the range between the values depicting the data, such 0 to 80, or even calibrating based on users needs. One participant also noted how having gone through Scenario B first then Scenario C helps make the data easier to understand. All in all, this suggest that while there are certain cases where vibrotactile representation might not be as useful, it nevertheless provides an interesting interface for user to “ experience ” the data.

4.3.4 Limitations

There are also certain limitations that needs to be address with this experimental setup. One of them is the use of the same size of Haptic Suit across all participants. While we keep this issue in mind by having the survey include the participants height in order to adjust for errors in data collection, it ’ s also possible that different participants have different levels of two-point discrimination with their body [15]. Furthermore, with male and female body having different structure, this can also cause inconsistency in the interpretation of the data.

Chapter 5
Conclusions

In the field of Human-Computer Interaction, achieving higher bandwidth between humans and machine has often been part of the on-going goals of research in this field [23, 24]. While there has been a lot of researches done on improving our cognitive capability, such as transforming text into visuals from Wise et al., it was until recently and along with several technological breakthrough and miniaturization that allows more and more of our sensory [1, 23].

Similar to how charts and diagram allow data to be represented in a more intuitive manner for learning, this research demonstrate an alternative approach for data representation in non-visual format. This research signify the use of haptic technology to display and represent data, along with exploring the effectiveness and user experience of multimodal and multisensory enhancement of data interpretation based on both traditional visual interface and vibrotactile interface.

Contributions and Findings:

The present work contributes in area of exploring new method to represent data non-visually. Furthermore, it also proposes a new concept of using haptic wearable device on the torso to provide intuitive reference for spatial orientation of data, especially in regards to geolocation in a globe format.

Furthermore, this research also provides a novel design toward user experience for understanding data. Through the use of wearable suits with tactor unit placed in array, it is possible to use vibrotactile patterns and different intensities to provide a new medium for data representation. Furthermore, with multisensory enhancement from other display medium (visual scatter graph in this case), it provides user an additional stimulus feedback perception of the data value represented.

This research also provides insight toward using wearable haptic devices as an interface for data representation. One important takeaway is how the combination of visual and vibrotactile feedback in tandem can provide a new sensation such as "breathing" as data is being played through. Furthermore, this research also found out that due to the tendency of vibrotactile devices to create a buzzing sound, it also provided an additional reinforcement toward learning and perception through multisensory enhancement theory.

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