8-2016

THE NECK AS A POTENTIAL SITE FOR VESTIBULAR TACTILE SENSORY SUBSTITUTION

Kelly A. Morrow
Northern Michigan University, kmorrow@nmu.edu

THE NECK AS A POTENTIAL SITE FOR VESTIBULAR TACTILE SENSORY SUBSTITUTION

By

Kelly Morrow

THESIS

Submitted to
Northern Michigan University
In partial fulfillment of the requirements
For the degree of

MASTERS OF SCIENCE

Office of Graduate Education and Research

August 2016

SIGNATURE APPROVAL FORM

The Neck as a Potential Site for Vestibular Tactile Sensory Substitution

This thesis by Kelly Morrow is recommended for approval by the student's Thesis Committee and Department Head in the Department of Psychology and by the Assistant Provost of Graduate Education and Research.

Committee Chair: Dr. Mounia Ziat Date 05/02/2016

First Reader: Dr. Sheila Burns Date 05/02/2016

Second Reader (if required): Dr. Scott Drum Date 05/02/2016

Department Head: Dr. Paul Andronis Date 05/02/2016

Dr. Robert J. Winn Date
Interim Assistant Provost of Graduate Education and Research

ABSTRACT

THE NECK AS A POTENTIAL SITE FOR VESTIBULAR TACTILE SENSORY SUBSTITUTION

By

Kelly Morrow

To determine if the neck could be used a site for vestibular-to-tactile sensory substitution, two experiments were performed to take an in-depth look of the tactile sensitivity of the neck and how it responds to vibrotactile stimuli. Experiment 1 explored how participants respond to a vibrotactile neck device, the Arraysense, and how well this device conveys information about a single contact point on the participant's skin. Results showed that determining the exact point of stimulation is difficult for participants, but they can identify the area of stimulation with ease. Additionally, our results showed that the front of the neck has pointedly lower accuracy rates than other areas, despite the duration or frequency used. This information led us to explore the spatial acuity of the neck in Experiment 2, where we used a two-point orientation discrimination task. Results showed that tactile sensitivity around the neck is uniformwith exception to the very front of the neck. From these two experiments it can be concluded that the neck can convey tactile information and additional studies should further explore the best tactile features for a successful vestibular-tactile sensory substitution.

ACKNOWLEDGMENTS

I would like to first thank my advisor, Dr. Mounia Ziat for all of the help and guidance over the past two years, as well as my co-authors Reza Taghavi and Daniel Wilbern for making the first experiment of this thesis possible. Additionally, I would like to thank Molly Harden, Min Park, and Alanna Cooper for assisting me in the second half of my thesis. Lastly, many thanks to Dr. Sheila Burns and Dr. Scott Drum for being on my thesis committee and helping me through the process.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The purpose of this thesis was to determine if the neck region is a viable site for vestibular-to-tactile sensory substitution. Sensory substitution became popular in early 1970s when Paul Bach-y-Rita developed his visual-to-tactile sensory substitution (TVSS) to help blind people to perceive their environment by converting visual pattern into tactile pattern (Bach-y-Rita, 1967; Bach-y-Rita, 1971; discussed in Chapter 1). Our initial motivation was driven by the availability of a vibrotactile neck device (the Arraysense) that uses 14 vibrating motors to deliver tactile stimulation around the neck. Because of the proximity of the neck with the vestibular system (inner ear), we wondered whether the ArraySense could successfully deliver directional information, and in turn be used to aid those who suffer from vestibular system damage. Vestibular-to-tactile sensory substitution generally uses a vibrotactile or electrotactile device that informs the user when they have deviated from an upright posture, allowing them to correct their stance and keep upright.

In order to see how well the neck conveys vibrotactile information, two studies have been conducted. First, we investigated how participants responded to the sensation of vibrotactile stimulation on the neck from the ArraySense device. The second study focused on the tactile acuity around the neck and how accurate participants are able to correctly identifying precise points of stimulation using the two-point orientation discrimination task (Weber, 1834; Tong, Mao, & Goldreich, 2013).

Our initial goal was to disturb the vestibular system using either a motion platform or a galvanic vestibular stimulation (GVS). In either cases, we would attempt to create an experimental model of vestibular dysfunction by creating disruptions in participants' balance, and use the ArraySense to redress the participant's posture by providing directional information around the neck. However, due to the cost and availabilities of both systems as well as the lack of research on the neck, we focused on psychophysical measurements that have been rarely investigated previously on this specific part of the body. Therefore, the first step before determining whether the neck conveyed directional information, was to assess how accurately and easily participants could detect a single point of vibrotactile stimulation from the Arraysense.

In the first experiment, we used two vibration frequencies and two durations to explore which type of stimulation was accurately detected. More precisely, the aim was to identify whether some locations on the neck are better than others, as well as determine which of the two chosen frequencies and durations most effectively deliver vibrational cues.

The results of Experiment 1, published in the proceedings of IEEE Haptics Symposium 2016, showed that the neck does not convey vibrotactile information precisely enough for participants to be able to detect the precise contact point of stimulation, despite stimulus location, duration, and frequency. Instead, participants were able to detect the general area of stimulation with great accuracy. Given this information, it appears that all the 14 motors are not necessary for this body area, and the neck could potentially be used as a potential site for interpreting and perceiving tactile information. The most interesting result is that the front of the neck is the least sensitive area which suggests that the receptive field sizes at the front of the neck are larger than those in other areas. This led us to investigate the tactile acuity of the neck using a modified version, suggested by Tong and colleagues, of the two-point threshold to validate or invalidate the results of the first experiment (2013).

In the second study, we used a modified drafting compass to determine thresholds of different locations of the neck, specifically the locations that were considered the best sites for vibrotactile stimulation based on the results of the first study. Using two-point orientation discrimination, we were able to draw a sensitivity map of the neck (Tong, Mao, and Goldreich, 2013).

Before presenting these two studies, the first chapter gives an overview of sensory substitution in general, vestibular sensory substitution in particular, as well as a brief explanation of the vestibular system that is presented along with devices and studies that have previously used the neck as a site of stimulation for clinical applications.

Ultimately, with these two studies in mind, we would like to improve the design of the Arraysense to assist those who suffer from vestibular loss or damage, but also provide readers and future researchers with information about the neck for potential clinical application. Our results should be of value to future investigations already planned in Dr. Ziat's lab and open up a wide range of experimental questions for upcoming students. Our work already triggered a new design of the ArraySense since the number of motors have been reduced from 14 to 10 motors. Finally, we hope to test the efficiency of this device with people suffering from vestibular loss and provide them with a less invasive device than ones in existence on the market.

CHAPTER ONE: SENSORY SUSBTITUTION FOR VESTIBULAR LOSS

INTRODUCTION

The neck is an important part of the human body that connects the head, and therefore the brain to the rest of the body. Comprised of muscles and bones, the neck supports the head and is the highway of communication between the brain and the body. Socially, the neck considered a private area: when touched, it is often considered an invasion of space. Despite the privacy of the neck, its location is ideal for a range of clinical applications, from a collar to prevent supine sleep in sleep apnea patients to treating spatial neglect in stroke patients. One clinical application of the neck not yet been explored is the use of the neck as a potential site for sensory substitution, more specifically, vestibular-to-tactile sensory substitution. Considering the neck's proximity to the vestibular system, stimulation from a sensory substitution device could be integrated fast and efficiently, based on the spatial rule of multisensory integration. This rule states that stimuli close spatial proximity are more likely to be integrated and perceived as stronger (King & Palmer, 1985; Meredith & Stein, 1983; 1986; Holmes & Spence, 2005).

1. WHAT IS SENSORY SUBSTITUTION?

When one of the sensory systems is partially or completely lost, it is possible to use a different modality (for instance touch) to convey information that is no longer available through the missing sense (Ziat et al., 2007; Ziat et al., 2014). This concept, known as sensory substitution, uses available sensorial modalities to substitute the missing modality using artificial sensory information and routing it through an intact sense. Because of lifelong perceptual learning and brain plasticity, it is possible for the brain to adapt neurochemically and or structurally when using these adaptive tools and strategies (Gilbert, Sigman, and Crist, 2001). With training and time, the brain reinterprets the artificial information and uses it to compensate for the missing sense, allowing individuals with sensory loss to make sense of their environment (Bach-y-Rita & Kercel, 2003).

1.1 THE TVSS

The most well-known sensory substitution device is the tactile visual substitution system (TVSS) designed by Paul Bach-y-Rita and colleagues in the seventies (See Figure 1). Using a video camera that acts as an "eye", this system aids the blind to "see" using the skin. Visual information from the camera is processed through a computer and after being simplified to black and white pixels, is converted into vibrotactile information displayed on the participant's back using a 20 x 20 matrix of tactors (Bach-y-Rita et al., 1967; Bach-y-Rita, 1971). Using the TVSS, blind individuals were able to actively perceive objects and navigate their environment, especially when they were controlling the camera themselves.[1] Visually impaired participants were able to perceive their surroundings, and bypass the non-functioning sensory organ, the same way sighted persons use their eyes to see the world. Bach-y-Rita's research was not only helpful for the blind community, but also open new directions of perceptual research and brain plasticity. Not only did TVSS users developed a new way of perceiving their world, but their visual cortex (V1) was

[1] When the camera was manipulated by the experimenter and was static, TVSS users' perception was limited to simple geometrical shapes and tickling sensations on the skin. When the users moved the camera themselves, the perception of objects increased and were not felt anymore on the skin but in the 3D space surrounding them (known as Object's exteriorization). This supports the idea that action is a key component to perception and perceptual experience using the TVSS is similar to a visual experience.

activated when using the TVSS, conveying the idea the device created new pathways to allow V1 to receive visual information (Bach-y-Rita, 1972; 1990)

FIGURE 1: A BLIND PARTICIPANT USING THE TVSS (FROM BACH-Y-RITA, 1971).

1.2 THE VOICE

In addition to visual-to-tactile sensory substitution, visual-to-auditory is another common type of sensory substitution. The hallmark device for this type of substitution is the vOICe, one of the first affordable substitution devices created by Peter Meijer in 1992. Using a small camera, mounted on a pair of glasses and connected to a computer, the vOICe converts gray scale images from the camera into corresponding sounds. The image is converted into sounds by scanning from left to right at a rate of one frame by second (See Figure 2). The higher the pitch, the higher the elevation on the visual pattern on the screen. For instance, if the pitch is rising, the visual pattern is rising from left to right such a diagonal line with 45 degrees. Additionally, sound intensity corresponds to brightness: A louder sounds indicates a bright visual pattern and a quieter sound indicates a darker visual pattern.

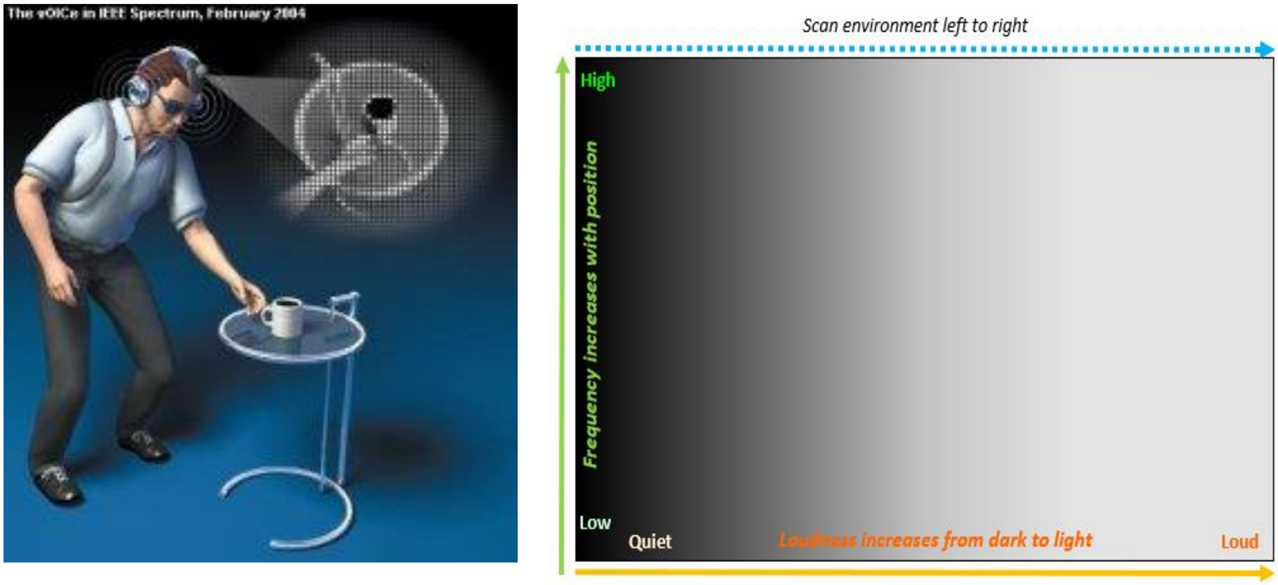


FIGURE 2: A.) THE VOICE (IEEE SPECTRUM, 2004). B.) SCHEMATIC LAYOUT OF THE VOICE (ADAPTED FROM STILES & SHIMOJO, 2014)

For the scope of this thesis, we were interested in sensory substitution devices that could compensate a deficient sense of balance, due to loss or damage to the vestibular system, using touch specifically on the neck. Using the same concept described earlier, these devices often use the tactile modality to inform patients about their body posture, and when it becomes unstable. Both electro-tactile and vibrotactile feedback have been used to stimulate multiple areas including head, trunk, and tongue. While the neck has been used a site for other clinical applications, to our knowledge it has not been considered as a potential site for a vestibular sensory substitution. First, we will give a brief overview of the vestibular system in the next section followed by the devices used to help with vestibular loss.

2. THE VESTIBULAR SYSTEM

The vestibular system is one of the three systems that contribute to balance in humans. Our posture and balance in the environment is achieved by integrating different sensory cues from visual, proprioceptive, and vestibular inputs (Watson & Black, 2008). By integrating the information from all three sensory systems, the cerebral cortex and cerebellum control automatic movements and use contextual information to successfully navigate through the environment using vestibule-ocular reflex[2] and motor impulses to control eye movements and make postural adjustments (Watson & Black, 2008). When these systems detect deviation of bodily orientation, the brain interprets the information and a corrective torque to the posture is generated to prevent further deviation (Peterka, 2002).

When one of the three systems is compromised, the sense of balance and human posture are affected. Specifically, the vestibular system is crucial for navigating the environment. Comprised of the otolith organs and semicircular canals of the inner ear, this system senses body acceleration, head rotation, and orientation in space (Figure 3; Day & Fitzpatrick, 2005).

[2] The vestibulo-ocular reflex, or VOR, are eye movements that keep vision stable while the head moves. The semicircular canals measure rotation of the head, and transmit this information to the oculomotor nuclei of the brainstem, which innervate the eye muscles (“Vestibulo-Ocular Reflex (VOR),” n.d.).

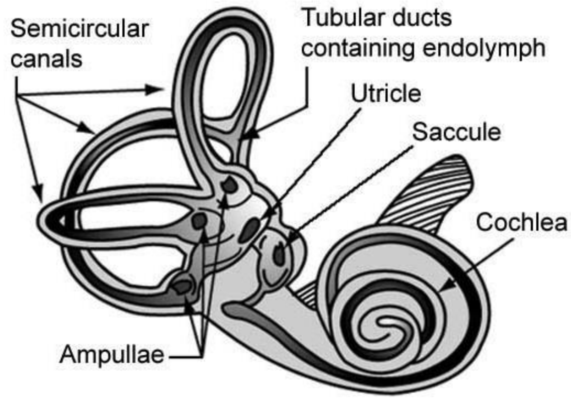


FIGURE 3: ILLUSTRATION OF THE INNER EAR. NASA, PUBLIC DOMAIN.

The otolith organs, the utricle and saccule, are responsible for sensing linear acceleration, including the force of gravity, and the three semicircular canals sense rotation. This system is in constant communication with the muscles, joints, skin, and eyes for continuous information about the body's orientation and acceleration (Angelaki & Cullen, 2008). Additionally, the vestibular system is often able to mediate sensory conflicts that may arise between the proprioceptive and visual system including visual illusions (Watson & Black, 2008). For instance, imagine a person standing on a boat in mostly calm water holding a rail for balance. Their vestibular and proprioceptive feedback at this time tell them they are standing still and upright. Another boat speeds past the person, leaving behind a wake making the boat unsteady and rocking in the waves. The visual input informs them they are no longer completely upright and simultaneously, the vestibular system (specifically the otolith organs) senses bodily tilt with each wave. Along with this information, the brain receives proprioceptive feedback, allowing them to make unconscious corrections in posture using muscles and joints. In this way, they are able to maintain an upright, steady posture even as the boat rocks from the wake. You can also trick your balance sense by looking straight ahead at the horizon (no motion). Even though they vestibular and proprioceptive systems are informing you otherwise (i.e., the boat is pitching), stabilizing the visual sense would create an illusion of stillness and reduce motion sickness.

Although the functions of the vestibular system are mostly subconscious, it is constantly in action by sending messages to the brain, even when the body is completely still (Angelaki & Cullen 2008). This system is susceptible to damage from a variety of factors including aging, injury, and uni- or bilateral disease[3]. When this system is destroyed or severely damaged, the individual no longer has the ability to correct their posture when deviating from an upright position and may suffer from symptoms including dizziness, vertigo, fatigue, and nausea (Watson & Black, 2008). Therefore, individuals have difficulty correcting body posture to prevent falling, and have performing daily life activities such as simply bending over or walking in the dark (Tyler, Danilov, & Bach-y-Rita, 2003; Danilov et al., 2007).

3. SENSORY SUSBTITUTION DEVICES FOR THE VESTIBULAR SYSTEM

There are several techniques that can help an individual compensate for vestibular loss including adaptation and habituation exercises (Deveze et al, 2013), aquatic physiotherapy, auditory feedback (Dozza, Horak, and Chiari, 2005), galvanic vestibular stimulation (Orlov, Stolbkov, and Shuplyakov, 2008), virtual reality programs (Georgescu, 2015; Rizzo-Sierra, Gonzalez-Castaño, & Leon-Sarmiento, 2013), and inner-ear prosthesis (Lewis et al., 2003; Chiang et al, 2011). Sensory substitution is an alternative solution that

[3] Affecting one (left/right) or both inner ears.

is less intensive and invasive than both galvanic vestibular stimulation (GVS) and inner-ear prosthesis. Treatment involving GVS requires sending electrical signal to the labyrinth of the inner ear; while inner-ear prosthesis consists of the installation of a device in the semi-circular canal or in the labyrinth of the inner ear. For vestibular substitution, head-body coordination is generally indicated using an artificial receptor stimulating the visual or tactile sense. These senses are the ones used for navigation and direction during vestibular loss (Bach-y-Rita, 2004; Horak, 2010). The newly received information gives the individual cues to maintain an upright posture and correct posture when needed.

One of the most well-known sensory substitution devices for vestibular loss is the Brainport Tongue Display Unit (TDU) which delivers electrotactile stimulation to the tongue (Bach-y-Rita et al., 1998; Tyler, Danilov, & Bach-y-Rita, 2003; Bach-y-Rita, Danilov, & Grimm, 2005; Bach-y-Rita, 2007; Uneri & Polat, 2009). The TDU (shown in Fig. 4) uses a 49-point (7x7) electrotactile array to convey sensory information to the user. Originally, the TDU was used for visual-to-tactile substitution (Bach-y-Rita et al, 1998) and its usage was later extended to vestibular-to-tactile substitution (Bach-y-Rita et al, 2005; Danilov et al, 2007). Using a 2-axis accelerometer mounted in a hard hat that is connected to the TDU, the electro-tactile vestibular substitution system (ETVSS, also called the BrainPort balance device) stimulates the tongue of participants when a postural adjustment is needed to keep upright posture (Bach-y-Rita, 2005). After a brief training period of 15 to 40 minutes, patients showed immediate increased stability and balance. After five training sessions, these post-training effects lasted anywhere from 4 to 12 hours (long-term residual effects), and after 40 sessions over 8 weeks, a single participant had residual effects over the following 8 weeks (Bach-y-Rita, 2004).

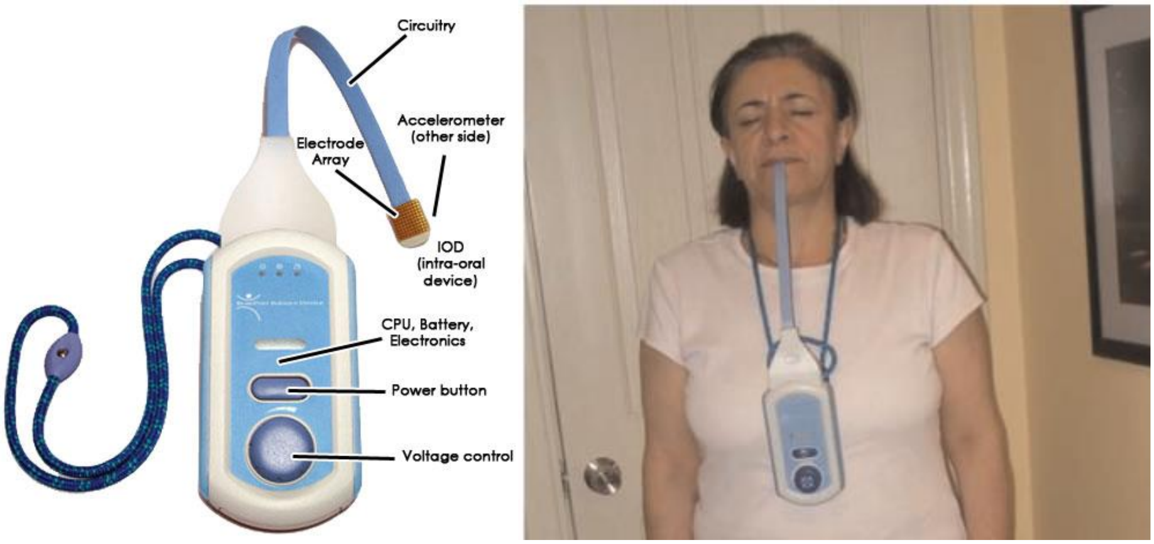


FIGURE 4: A.) SIMPLIFIED BRAINPORT BALANCE DEVICE (RETRIEVED FROM: HTTP://SCIENCE.HOWSTUFFWORKS.COM/BRAINPORT2.HTM) B.) PATIENT USING BRAINPORT BALANCE DEVICE (POLAT & UNERI, 2010)

Other devices tested areas such as the trunk (Dozza et al, 2008; Janssen et al, 2010; Seinko et al., 2008) and head (Goebal et al, 2009), shown in Fig. 5. Most of these investigators showed the use of vibrotactile biofeedback significantly increases stability and improves balance and posture. Additionally, studies acknowledged that self-confidence, training, and alertness significantly impacted how much these devices helped (Janssen et al, 2010).

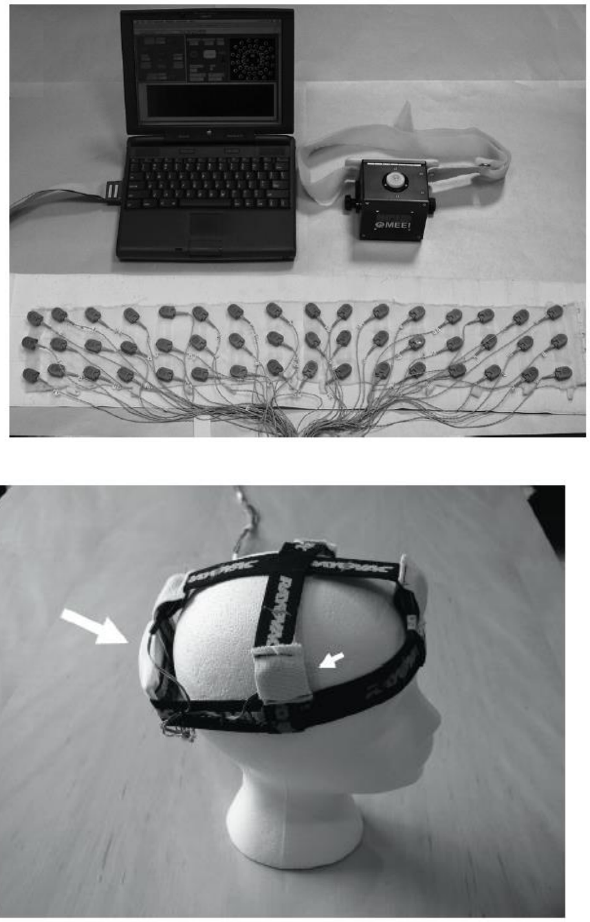


FIGURE 5: A.) 3X16 TACTOR ARRAY (SEINKO ET AL, 2008). B.) HEAD-MOUNTED VIBROTACTILE ARRAY (GOEBAL ET AL, 2009).

4. WHY THE NECK?

Although researchers have used many areas on the body for receiving artificial sensory information, the neck is one area that has not been closely studied. Because of the proximity of the neck to the inner ear and its ability to tilt in all cardinal directions, sensory information could be integrated fast and effectively (Meredith & Stein, 1983; King & Palmer, 1985; Meredith & Stein, 1986).

The neck has been used for a multitude of clinical applications, including treatment of spatial neglect in stroke patients and in the disruption of supine sleep of sleep apnea patients. The success of these applications demonstrated that the neck conveyed vibrotactile information easily, and was a viable body region for comfortably wearing a vibrotactile collar, even while sleeping.

The first researchers to investigate the effects of vibrating neck muscles were Lackner and Levine in 1979. The researchers stimulated the sternocleidomastoid muscle unilaterally and bilaterally and found that in a dark room, the vibrations caused illusory body movements. Bilateral vibrations caused participants to feel the illusion of their head extending, and unilateral stimulation created a sensation of rotating the head to the opposite side of the vibration (Lackner & Levine, 1979). Biguer et al. discovered tactilely stimulating a muscle creates a muscle lengthening illusion, producing a sense of apparent motion of the body. Additionally, vibration of the neck modifies visual representation of directions (Biguer et al., 1988).

Later, Karnath et al. studied vibrational stimuli applied to the neck as a potential treatment of spatial neglect patients who could not orient or react to features in their environment on the contralateral side of the brain hemisphere damaged by stroke. They found that by applying vibrations to the neck muscles, contralesional neglect of visual stimuli was reduced (Karnath, Christ, & Hartje, 1993). Furthermore, Schindler and colleagues found contralesional vibrotactile neck stimulation improves standardized visual exploration training in patients suffering from spatial neglect (Schnidler et al, 2002). Additionally, another group of researchers observed neck vibration therapy significantly increases the effects of prism adaptation, a popular treatment option for spatial neglect (Sarevarsson, Kristjánsson, & Halsband, 2010).

Recently, researchers used a vibrating neck collar to treat sleep apnea. Using vibrotactile stimulation on the neck, they found neck vibrations could adequately disrupt supine sleep, where the patient was in most danger of breathing obstruction. Notably, this was accomplished without habituation to the sensation of vibration, making the collar a reliable method of interrupting supine sleep (Levendowski et al, 2014).

Other investigators also looked at the effects of vibration on neck muscles in healthy subjects while walking. In one study, researchers utilized continuous vibration applied to the dorsal neck to elicite forward body sway and an increase in speed while walking in the direction the participant was heading (Ivaneko, Grasso, & Lacquaniti, 2000). In another study, vibrations applied to one side of the neck on the sternomastoid muscle caused a whole body rotation towards the opposite side of the vibration (Bove, Courtine, & Shieppati, 2002).

The above mentioned researchers showed the neck not only conveyed tactile information about direction, but also transmitted illusory motion and speed. Keeping this in mind, it appears as though vibrotactile neck stimulation can be used to change body direction and posture, making it a potential candidate for counteracting incorrect posture from vestibular dysfunction. Before testing whether the device is able to provide directional information, it is important to understand how well the device can convey information to the user about contact point and what factors could affect the transmission of the information. The next chapter details the first study to investigate human perceptual thresholds of vibrotactile stimuli around the neck at two different frequencies and stimulus durations.

CHAPTER TWO: THE EFFECTS OF DURATION AND FREQUENCY ON THE PERCEPTION OF VIBROTACTILE STIMULATION ON THE NECK

1. INTRODUCTION

This first study was conducted to assess participants' response to vibrotactile stimulation delivered on the neck by the Arraysense and determine how well participants could distinguish between points of stimulation on the neck. Keep in mind this was the first experimental study conducted using this device. Therefore, all 14 motors of the ArraySense were randomly activated with a frequency and duration pairing. To investigate what stimulus frequency and duration best conveyed the contact point of stimulation, we assessed two frequencies (75Hz and 150Hz) and two durations (250ms and 500ms) using the experimental design described below. From this study we were able to better understand how well the neck conveyed vibrotactile information, and how the device might be improved for a better sensing.

2. MATERIALS AND METHODS

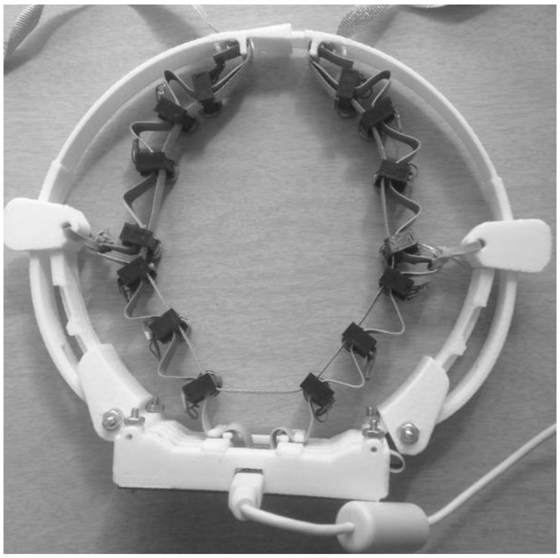
2.1 PARTICIPANTS

20 students (11 female; Mean age: 20.58, SD = 3.40) of Northern Michigan University participated in this study. The study was approved by the Northern Michigan University institutional review board and the students were offered course extra credit for participation.

2.2 APPARATUS AND STIMULI

The ArraySense (Taghavi, 2011) is a vibrotactile neck device that is comprised of 14 small, shaftless, vibrating motors (0.39" x 0.13") manufactured by Jameco Reliapro

(Belmont, CA). All motors are controlled by a custom designed circuit board powered by an Antel AT32UC3B microprocessor and are housed in a collar worn around the neck (Figure 6a). A representative image that showed motor location on the neck was used as a reference by participants for responses (Figure 6b).



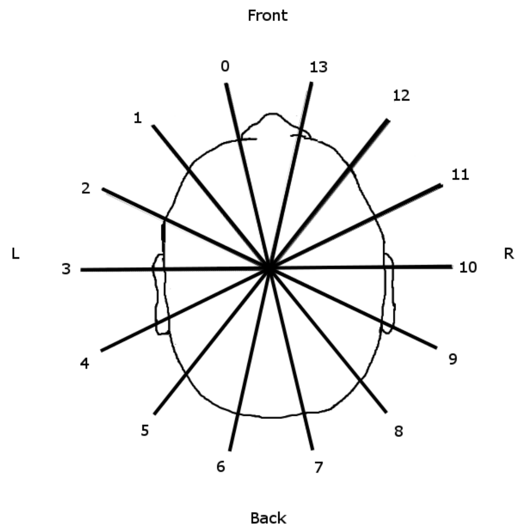


FIGURE 6: A.) THE ARRAYSENSE DEVICE, B.) REPRESENTATIVE CHART USED AS A REFERENCE FOR PARTICIPANTS' RESPONSES.

2.3 PROCEDURE

After signing the consent form, participants sat comfortably on a chair in front of a table where the representation chart (Figure 6b) was displayed. Before starting the experiment, the researcher placed the Arraysense on the participants' neck and presented a brief habituation trial[4]. During the experiment, two frequencies of 150 Hz and 75 Hz (i.e., 150 Hz was perceived as the higher magnitude, 75Hz perceived as a lower magnitude) were tested for two stimulus durations (250 ms and 500 ms). These intensities were chosen

[4] In this trial, each motor vibrated once in numerical order at the higher frequency (150Hz) to avoid any startle responses in the recorded trials.

prior to the study because they were considered to be distinguishable, comfortable, and did not cause too much distortion with the 3D printed collar. The experiment consisted of 224 randomized trials (i.e.,14 motors x 2 frequencies x 2 duration x 4 repetitions), divided into two consecutive sessions of 6.26 minutes, that were completely randomized, and each trial was followed by a 3 second pause to prevent adaptation or after effects for a total of approximately 20 minutes. Participants reported their answer verbally, indicating the number on the chart that best matched the perceived stimulation point on the neck. Participants' performance was solely defined as their ability to correctly indicate the motor number of the stimulation.

3. RESULTS

A three-way, repeated measures ANOVA with the factors motor, intensity, and duration was performed on participants' responses using SPSS. The dependent variable for the analysis was the correct number of identifications. Only significant results are reported.

The main effect for the factor motor was significant [$F(13, 143) = 8.29$, $p < 0.0001$, $\eta^2 = 0.046$], meaning that the location of the motor had an impact on the number of correct identifications. A significant interaction effect was also found between duration and motor [$F(13, 143) = 3.681$, $p < 0.0001$, $\eta^2 = 0.162$], frequency and motor, [$F(13, 143) = 2.258$, $p < 0.05$, $\eta^2 = 0.106$], and between motor, frequency, and duration [$F(13, 143) = 3.035$, $p < 0.0001$, $\eta^2 = 0.138$]. To break down these interactions, simple pairwise comparisons were performed. The significant interactions are shown in representative charts (Figures 7 and 8). Using unique character identifiers for each motor (e.g. motor 0 is represented by a filled, blue circle, motor 8 is represented by an unfilled green square). When a motor's unique identifier is on the line of another motor, it represents a significant difference in accuracy.

For instance, in Figure 7A (which represents T1F1 250ms, 75Hz trials), motor 0 had significantly different accuracy rates from all other motors besides motor 13.

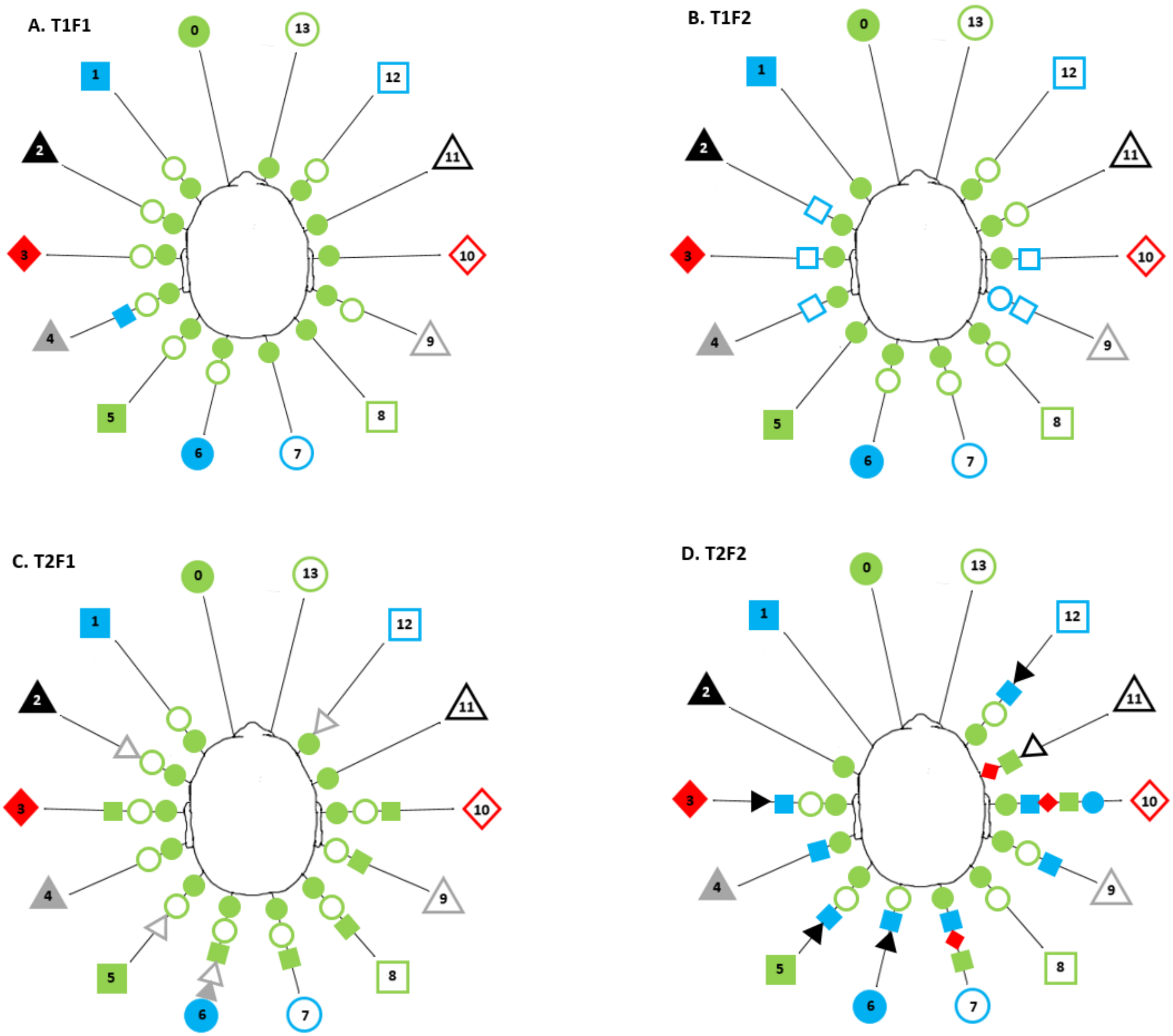


FIGURE 7: WITHIN-CONDITIONS COMPARISONS: SPATIAL LAYOUT OF THE MOTORS AROUND THE NECK. EACH MOTOR IS REPRESENTED BY A UNIQUE SHAPE AND COLOR COMBINATION. SIGNIFICANT DIFFERENCES BETWEEN MOTORS ARE REPRESENTED ON EACH LINE BY THEIR UNIQUE IDENTIFIER.

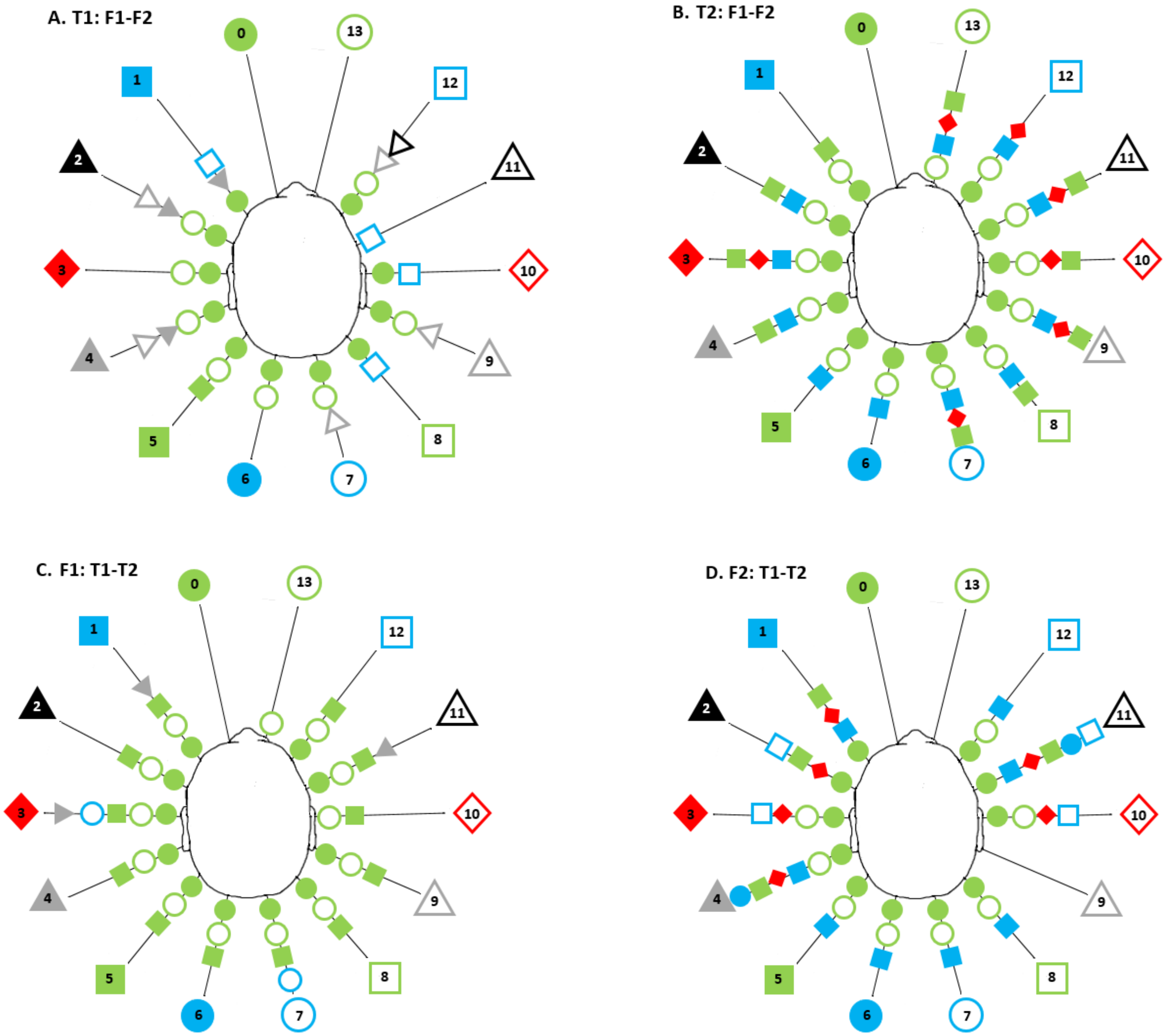


FIGURE 8: BETWEEN-CONDITIONS COMPARISONS: SPATIAL LAYOUT OF THE MOTORS. EACH MOTOR IS REPRESENTED BY A UNIQUE COLOR AND SHAPE COMBINATION. SIGNIFICANT DIFFERENCES ARE SHOWN AS THE UNIQUE IDENTIFIER OF THE MOTOR ON THE ARRAY OF ANOTHER MOTOR.

3.1 Within-Conditions comparison

Figure 9 shows a polar plot of the motors compared to one another within the same trial type. In all four condition types, performances for motors 0 and 13 are significantly lower than motors 1 through 12. This suggested low vibrotactile sensitivity at the front of the neck region, regardless of duration or frequency. The results also illustrated highly significant performances for motor 5 related to T2 duration and frequency F1. Furthermore, the same trend was observed for motor 12 for T1F2 and motor 3 for T2F2 trials.

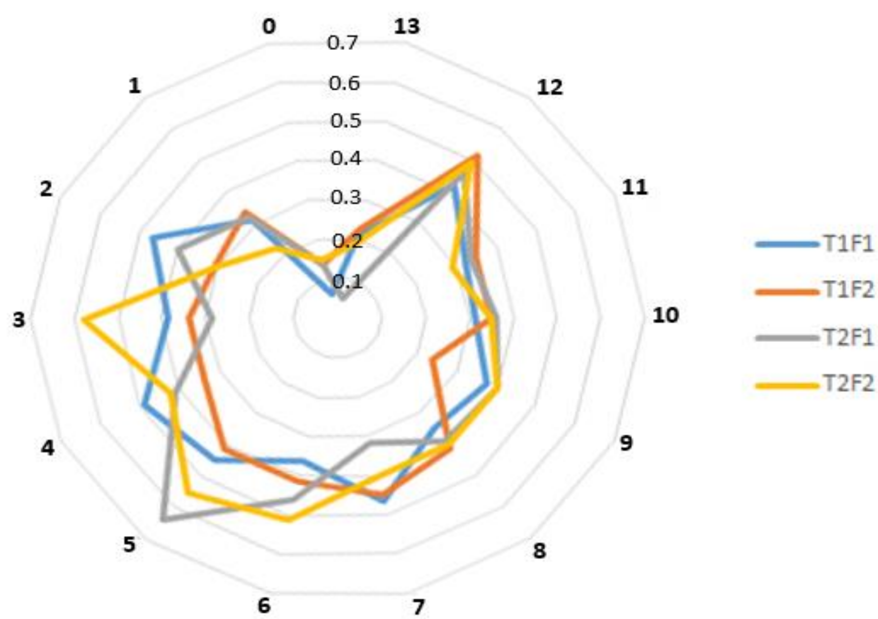


Figure 9: Polar plot of percentage correct for each motor at duration (T1, 250ms and T2, 500ms) and both frequencies (F1, 75Hz, F2, 150 Hz).

3.2 Between-Conditions Comparison

Figure 8 displays between-conditions simple effects across both frequencies (F1 and F2) and durations (T1 and T2). Again, motors 0 and 13 performance levels were significantly lower for all condition types. Comparatively, both frequencies for duration T1 (Figure 8a) show significant improvement in performance for motor 12 and a decreased performance for motor 9, as depicted in Figure 4. Difference of performances between frequencies for duration T2 were less obvious. As a whole, this duration created perceptual noise which made it more difficult for participants to determine which motor was vibrating (Figure 8b). When comparing durations to each other for frequency F1 (Figure 8c), motor 5 still had one with the best performances (Figure 10). Finally, when comparing T1 to T2 for frequency F2 (Figure 8d), we observed increased performances in motors 5 and 12 that represent contralateral points on the neck.

3.3 PERFORMANCES WITH ERROR RATE ± 1

It is obvious from the results that detecting the correct location of the motor was a tedious task for participants. However, when including the adjacent motor, either on the left or the right of the stimulus location, their performances greatly improved. Figure 10 displays the percentage correct with an error rate by ± 1 (left or right adjacent motor), for all motors, showing performance rates clearly above chance (defined as 1/14 = 0.07) as opposed to Figure 9. Performances for motor 0 and 13 were still lower than motors 1 through 12, which corroborated the idea that the front of the neck was not a valid site for precise vibrotactile location with the chosen durations and frequencies.

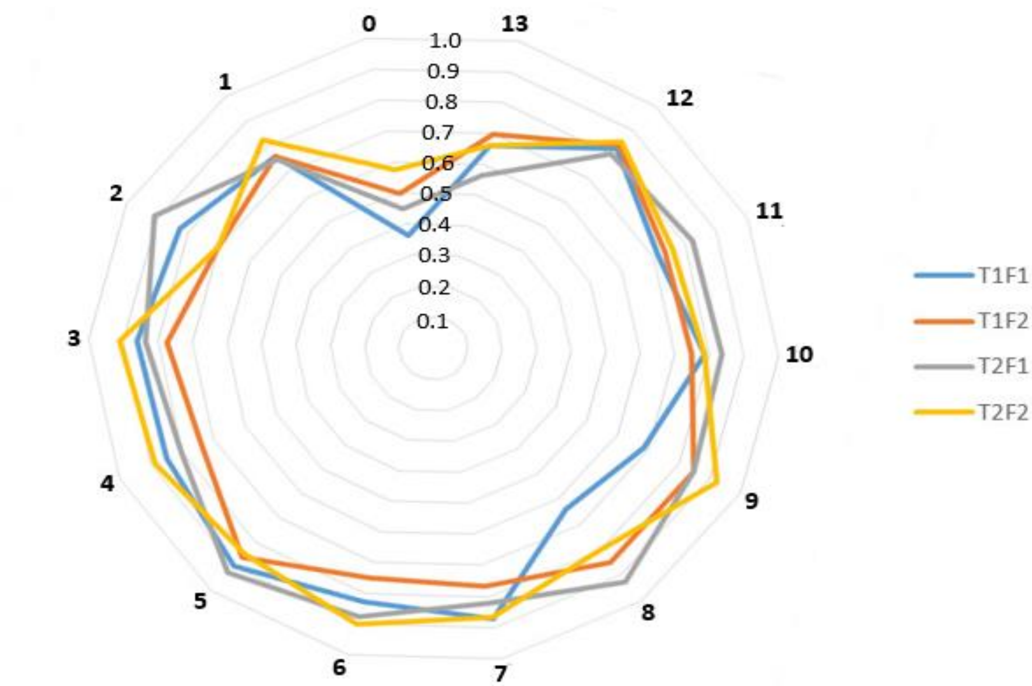


FIGURE 10: POLAR PLOT OF PRECENTAGE CORRECT FOR EACH MOTOR AT EACH DURATION (T1, 250MS, T2, 500MS) AND EACH FREQUENCY (F1, 75HZ, F2, 150HZ) WHERE PERFORMANCE IS DEFINED AS THE ABILITY OF PARTICIPANTS TO INDICATE THE AREA OF STIMULATION WITHIN A THREE MOTOR RANGE (± 1 OF THE ACTUAL MOTOR).

4. DISCUSSION

We demonstrated significantly lower performance rates for motors 0 and 13. Conversely, motors 1 through 12 have performed at rates fairly consistent within each condition. These results suggested lower sensitivity to vibrotactile stimulation at the front of the neck with the current configuration. It is possible that vibrational cues need to be of a higher frequency and/or longer duration to be correctly perceived. Additionally, the very front of the neck, where motors 0 and 13 are positioned, may have lessened tactile sensitivity, caused by their proximity to the laryngeal prominence (Adam's apple). Overall, the difference in frequencies and durations did not significantly impact the rate of accuracy, although we see the higher frequency used, F2, generated noise between motor accuracies, which led to lower performance rates of some motors, while others were improved (motors 5, 3 and 12).

Participants also had difficulty determining the exact location of the stimulation point, but were able to identify without major effort the approximate location of the vibrations, as shown by performances with an error rate of one. This indicated that the neck may not be sensitive enough to pinpoint exact stimulation points, but was able to perceive general areas of stimulation with great accuracy. This needs to be confirmed by future studies investigating spatial acuity and the distribution of receptive fields.

In future studies, we plan to activate two or three motors at the same time to assess participants' perception of directional information. For instance, stimulating three adjacent motors simultaneously would create only four or five points of stimulation, rather than 14. This would be consistent with previous literature that found accuracy rates increased from 74% with 12 tactors to 97% with 6 tactors when vibrotactilly stimulating the abdomen (Cholewiak, Brill, and Schwab, 2004). The same research group also found participants to perform better when there was a reference point (e.g., referencing the naval as 12 o'clock, spine as 6 o'clock). It may be beneficial to use this type of referencing to change the position of the current motors (see Figure 11).

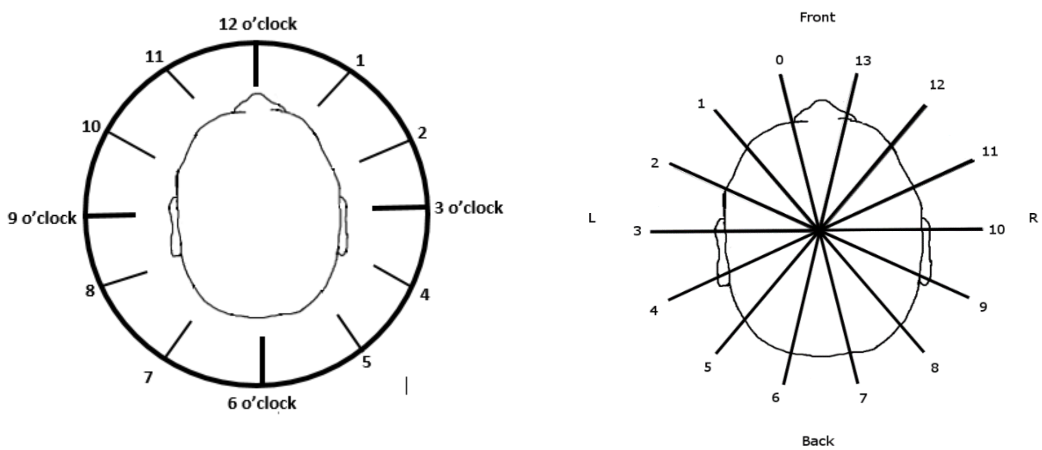


FIGURE 11: PROPOSED REFERENCE CHART VERSUS CURRENT REFERENCE CHART.

Finally, several authors (Cholewiak & Collins, 2003; Hamburger, 1980; Vierordt, 1870) suggested using an anatomical landmark to improve the accuracy of perceived vibrations. This fact was inconsistent with our results, whereby the laryngeal prominence seemed to distort vibrational cues. As a result, we suggested modifications of the ArraySense design by reducing the number of motors and changing their spacing around the neck.

Past investigators, when utilizing increased space between vibrotactile stimulation sites, observed enhanced ability to distinguish the point stimulation (Cholewiak & Collins, 2003). Due to the closeness of the motors of the Arraysense, we believe that decreasing the amount of motors used, or increasing the number of motors activated in a trial would increase the accuracy rates of participants. However, before therapeutic applications are considered more studies must be done to fine-tune stimulus duration, intensity, and spacing to ensure the most efficient vibrotactile stimulation for the neck is used.

5. CONCLUSION

The results of Experiment 1 showed that the neck is not sensitive enough to vibrotactile stimulation to perceive fine touch (exact contact point), but can convey crude (rough area of stimulation) touch with great accuracy. We also showed that the front of the neck seems less sensitive versus other neck regions. This result, in itself, led us to investigate the tactile sensitivity of the neck by performing an acuity test in Experiment 2 and is presented in the next chapter.

CHAPTER 3: TWO-POINT ORIENTATION DISCRIMINATION OF THE NECK

INTRODUCTION

Based on the results obtained in Experiment 1, we were interested in the tactile sensitivity of the neck that could be measured using spatial acuity techniques that are described below. Most acuity studies focused on other body areas and to our knowledge this is the first study that tested neck sensitivity.

1. SPATIAL ACUITY

1.1 TWO-POINT THRESHOLD

Ernst Heinrich Weber (1795-1878) is often reputed as the first physiologist to look at touch purely experimentally (Jütte, 2008). Known mostly for his careful experimentation and documentation of the two-point threshold, Weber contributed a wealth of literature to the study of touch and inspired other physiologists to pursue the study of touch. A large part of Weber's physiological career was spent studying the peripheral nervous system, which led him to develop experiments about the human sense of touch.

One of Weber's most renowned findings was differentiation of human skin related to sensitivity and discrimination of stimulation depending on the location, which he documented in the text De Subtilitate Tactus (Weber, 1834), commonly shortened to De Tactu. Weber tested the sensitivity using a protractor-like device that the observer placed simultaneously on the skin with the patient's eyes shut. Much of Weber's research was carried out on his own body which he carefully documented in seven detailed charts describing the sensitivity of various parts of his body. Weber came to find that as the two points of the compass came closer together, there was a certain point where the two points of pressure could no longer be experienced as separate stimuli (Figure 12). This phenomenon became known as the just-noticeable difference, or Weber's law. Weber's explanation for the just-noticeable difference was that the skin was organized in small "feeling circles," and when two sensations are located in different feeling circles they can be differentiated and when they fall into the same circle, they can no longer be distinguished (Grunwald & John, 2008). The discovery of the skin's fluctuating two-point threshold maintains relevance in modern physiology and is still used to map stimulation sites used effectively for tactile applications and clinical assessment.

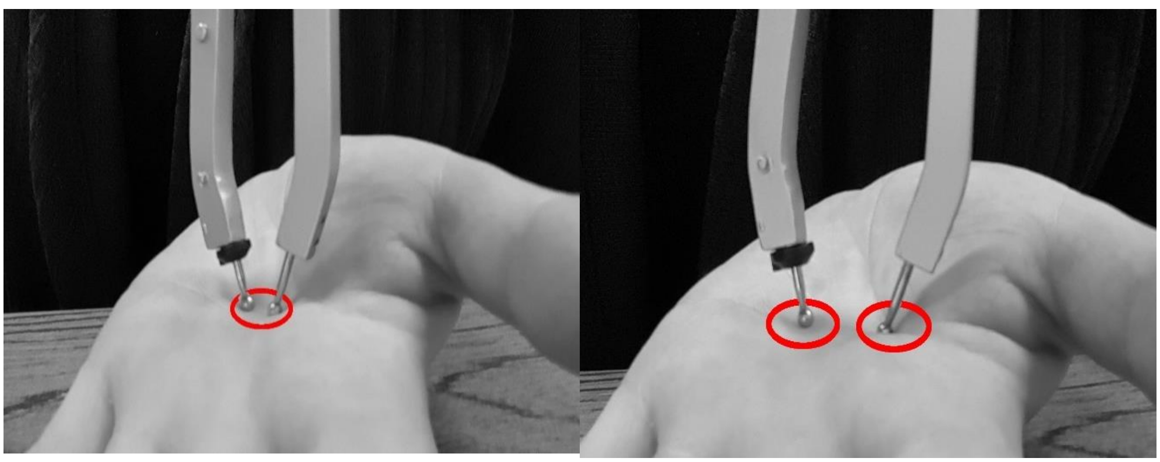


FIGURE 12: ILLUSTRATIVE EXAMPLE OF TWO-POINT DISCRIMINATION (NOT TO SCALE). LEFT) PERCEIVED AS ONE POINT, RIGHT) PERCEIVED AS TWO POINTS

Although two-point threshold is still widely used among clinicians, this classical method of measuring tactile sensitivity has been criticized for not measuring the true tactile acuity of the skin. Previously, researchers who used two-point threshold designs found participants claimed to be able to distinguish two points of stimulation on the finger pad, even when there was no separation between the two points (Johnson & Phillips, 1981;

Tong, Mao, and Goldreich, 2013). Therefore, many experimenters question the validity of two-point discrimination and have moved to other methods of measuring tactile acuity. While both of these measures have their own issues, they provide researchers and clinicians with a truer measurement of tactile acuity.

1.2 Grating Threshold

The grating threshold task was developed to approach the problem of the difficulty to quantify textures to be analyzed. Using different sizes of grooves and ridges, researchers have a precise measurement of the stimulus- the width of the grooves and ridges. Easily manipulated, grating threshold has allowed researchers to investigate tactile acuity of different parts of the body using a vertical/horizontal test. In this type of study, grooved stimuli are presented with ridges oriented either horizontally or vertically, and the participant indicates which orientation they believe the stimulus is. In the past sixty years, these studies have been conducted to measure tactile acuity of various body parts (mainly the hands and arms) in both typical and atypical patients (Lederman and Taylor, 1972; Lederman, 1978; Johnson & Philips, 1981; Morley, Goodwin, and Darian-Smith, 1983; Van Boven & Johnson, 1994; Essock, Krebs, and Prather, 1997; Craig, 1999; Grant, Thiagarajah, and Sathian, 2000; Craigh & Lyle, 2001; Goldreich & Kanics, 2003).

After many attempts to make 3D grating stimulus that would work to measure neck spatial acuity, we concluded that this type of design was not suitable: We used grating stimuli that varied from 6mm to 35mm in diameter and observed that control participants were not able to determine the orientation of grating despite trying them on various locations of the neck (see Fig. 13). Given these observations, we explored an alternative method suggested by Tong, Mao, and Goldreich. described below.

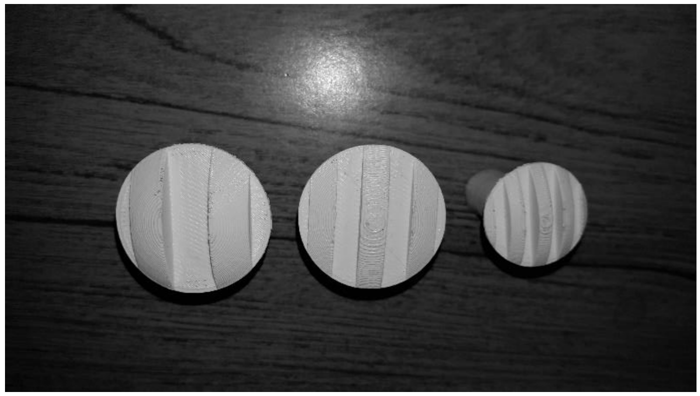


FIGURE 13: 3D-PRINTED GRATING STIMULI MADE IN LAB. SIZES FROM LEFT TO RIGHT: 6MM, 3MM, AND 1.5MM.

1.3 TWO-POINT ORIENTATION DISCRIMINATION

Two-point orientation, the method used in Experiment 2, is a relatively novel measure of spatial acuity that combines orientation discrimination of grating stimuli tasks with the use of two-point threshold technique (Tong, Mao, and Goldreich, 2013). When comparing the results of a two-point discrimination (2PD) task and two-point orientation discrimination task (2POD), the authors argued that a 2PD task presented non-spatial cues that allowed participants to discriminate small compass tip separations, even when set at zero. Craig and Johnson (2001) favored a response magnitude cue due to the nature of receptive fields or the neural activation of several afferent fibers. In other words, it is possible the brain detects the presence of two point and one point based on the number of afferent fibers activated, even if participants do not perceive the two points as such. In order to avoid an unattended non-spatial cue, Tong and colleagues suggested the 2POD task relied on perception rather a response magnitude cue by stimulating participants with two contact points rather than one versus two contact points design used in 2PD tasks (Tong, Mao, and Goldreich, 2013).

This second experiment was performed to determine the spatial acuity of the neck. From Experiment 1, we learned that the neck does not have very fine discrimination of vibrotactile stimuli, but is sensitive enough to convey an area of stimulation. Using a 2POD method, we performed this study to further explore the discriminative abilities of the neck in different locations.

2. MATERIALS AND METHODS

2.1 PARTICIPANTS

Sixteen students of Northern Michigan University between the ages of 18 and 22 (11 female, M=19.44, SD=1.16) with an average neck circumference of 36.02cm (range= 33-43.6 cm) participated in this experiment. Participants were screened for any learning disorders or sensitivity issues that may impact their ability to complete this study with a short pre-study questionnaire (See Appendix A). The study was approved by the Northern Michigan University IRB and participants were offered extra credit for various psychology courses. Additionally, five other participants (three females) between the ages of 19 and 23 (M= 20.2, SD= 1.79) with an average neck circumference of 36.3cm (range= 29.5-46cm) served as a control.

2.2 APPARATUS AND STIMULI

An iGaging Digicompass and Divider was used to deliver the two-point stimulation on the participant's neck. The compass was modified by supergluing two 2mm sterling silver to the sharp tips to ensure participants' comfort and safety (Figure 14). The compass's zero point was calibrated where the two ends touched.

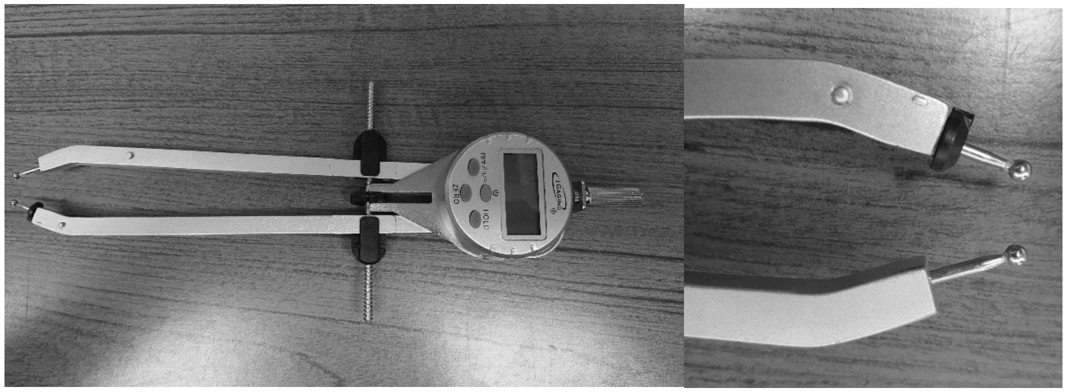


FIGURE 14: IGAGING DIGICOMPASS AND WITH MODIFIED TIPS. TIPS ARE 2MM STERLING SILVER BALLS.

2.3 PROCEDURE

Prior to the study, participant neck circumferences were measured with a soft tailor's measuring tape. The total length was then divided into eight equally spaced stimulus locations then marked on the participant's neck using an eyeliner crayon that could be easily removed after the study. Participants were shown and held the modified compass to assure they felt comfortable having their necks touched with the ends and were told to inform the experimenter at any time if they felt uncomfortable during the study.

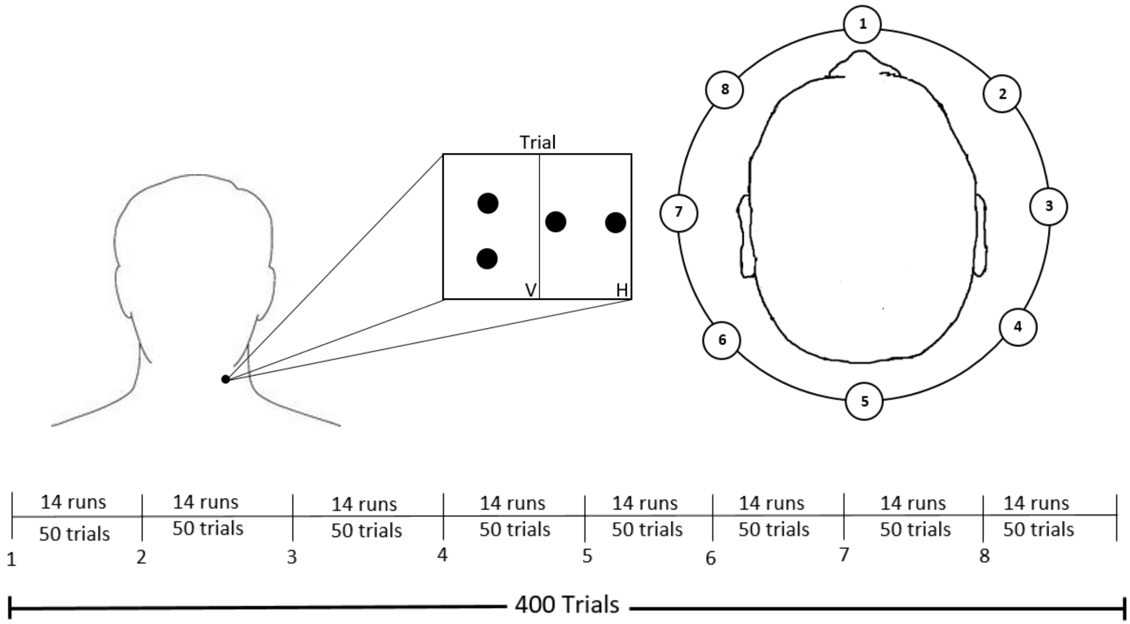


FIGURE 15: EXPERIMENTAL DESIGN LAYOUT FOR EXPERIMENT 2. EACH TRIAL CONSISTED OF TWO CONTACT POINTS (ONE VERTICALLY ALIGNED, THE OTHER HORIZONTALLY ALIGNED). EACH BLOCK CONSISTED OF 50 TRIALS AT A DIFFERENT LOCATION AROUND THE NECK FOR A TOTAL OF 400 TRIALS. FOR EACH 50 TRIALS, THERE WAS AN AVERAGE OF 14 RUNS OR REVERSAL POINTS.

Block order was pre-determined using an AB-BA scheme (i.e.,ABCDEFGH would be the first participant's order of sites, BCDEFGHA would be the second). Each trial consisted of two contacts with the compass: one with compass tips aligned vertically, the other with tips aligned horizontally; their order was randomized. Participants were asked to verbally indicate whether the vertically orientated stimulation came before or after horizontal stimulation by responding 'one' for before and 'two' for after while wearing blacked-out safety glasses. Responses were recorded by a second experimenter in the room. Using the 2-up-1-down staircase method, the width between the two compass points was incremented after two consecutive correct responses and decremented after each incorrect response by

0.5mm. The distance between the compass tips ranged from 10 to 20mm, with 19 different distances equally spaced between 10 and 20mm (10mm, 10.5mm, 11mm, …, 19.5mm, 20mm) with each block starting at the mid-point of the range, 15mm[5]. Each site stimulation site received 50 trials (one block) for a total of 400 trials, and ~14 runs, where a run is defined as the trials between reversal points, i.e. when the change of direction occurs (Figure 15). The study took approximately 1.5 to 1.75 hours to complete.

3. DATA ANALYSIS

The threshold for each site was determined by taking the average of the reversal points of each participants' blocks of trials, disregarding the first reversal point (Kühner, Boubb, Bengler, and Wild, 2012; Levitt, 1970). To determine whether different location sites present difference in sensitivity, thresholds were analyzed using a one-way repeated measured ANOVA with site as a factor.

Correlations between sex and threshold, and neck circumference and threshold were also computed.

4. RESULTS

The one-way repeated measures ANOVA performed on SPSS revealed that only stimulation sites 1 and 7 were significantly different from one another [$F(7, 70) = 4$, $p = 0.01$, $\eta^2=0.222$]. Figure 16 shows the average threshold (in millimeters) for each stimulation site. Additionally, Table 1 shows a summary of participant data and individual

[5] Control participants were tested with a range of 10-30 mm with trials starting at 20mm (mid-point). Because the range was set too high, these participants did not have ~14 runs for each block, instead they only had ~5. Therefore, the range was shifted from 10-20mm with a starting point of 15mm.

thresholds for each stimulation site, and Table 2 displays the actual data from a representative participant.

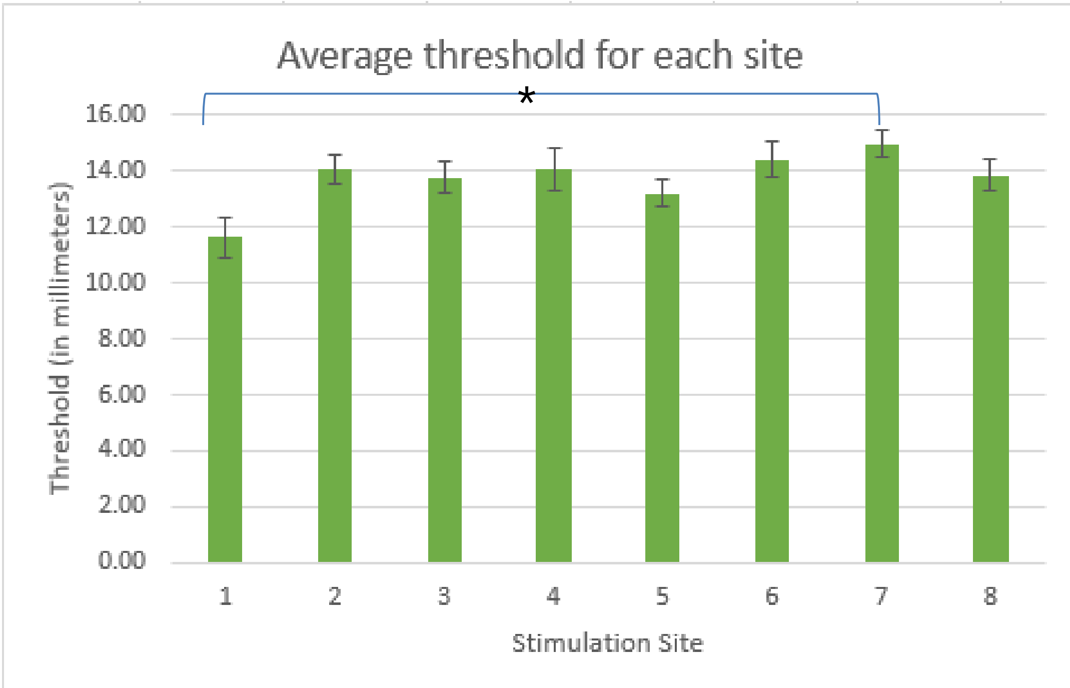
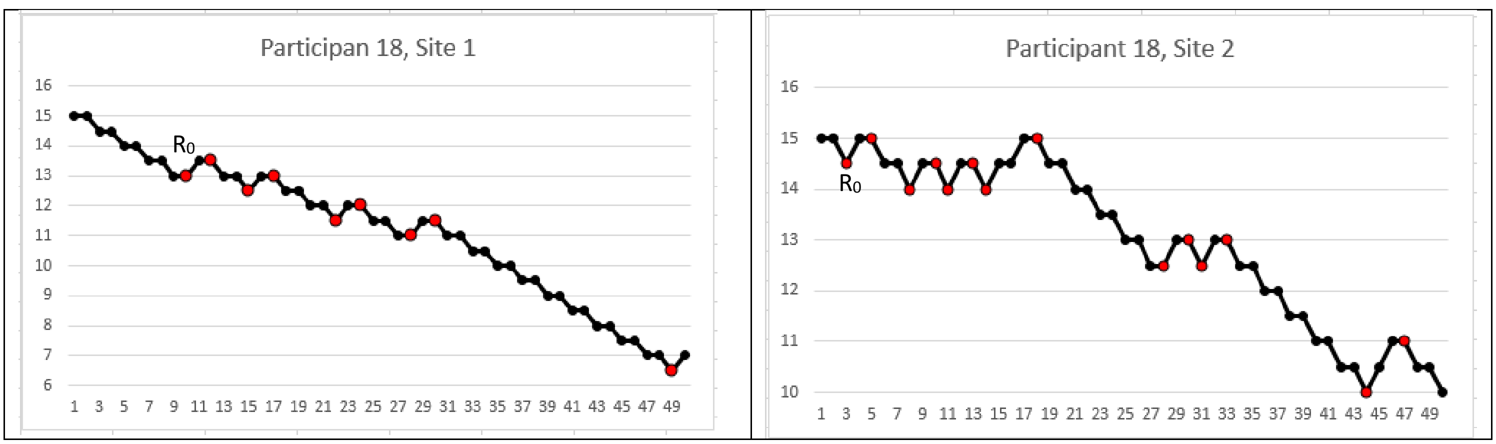


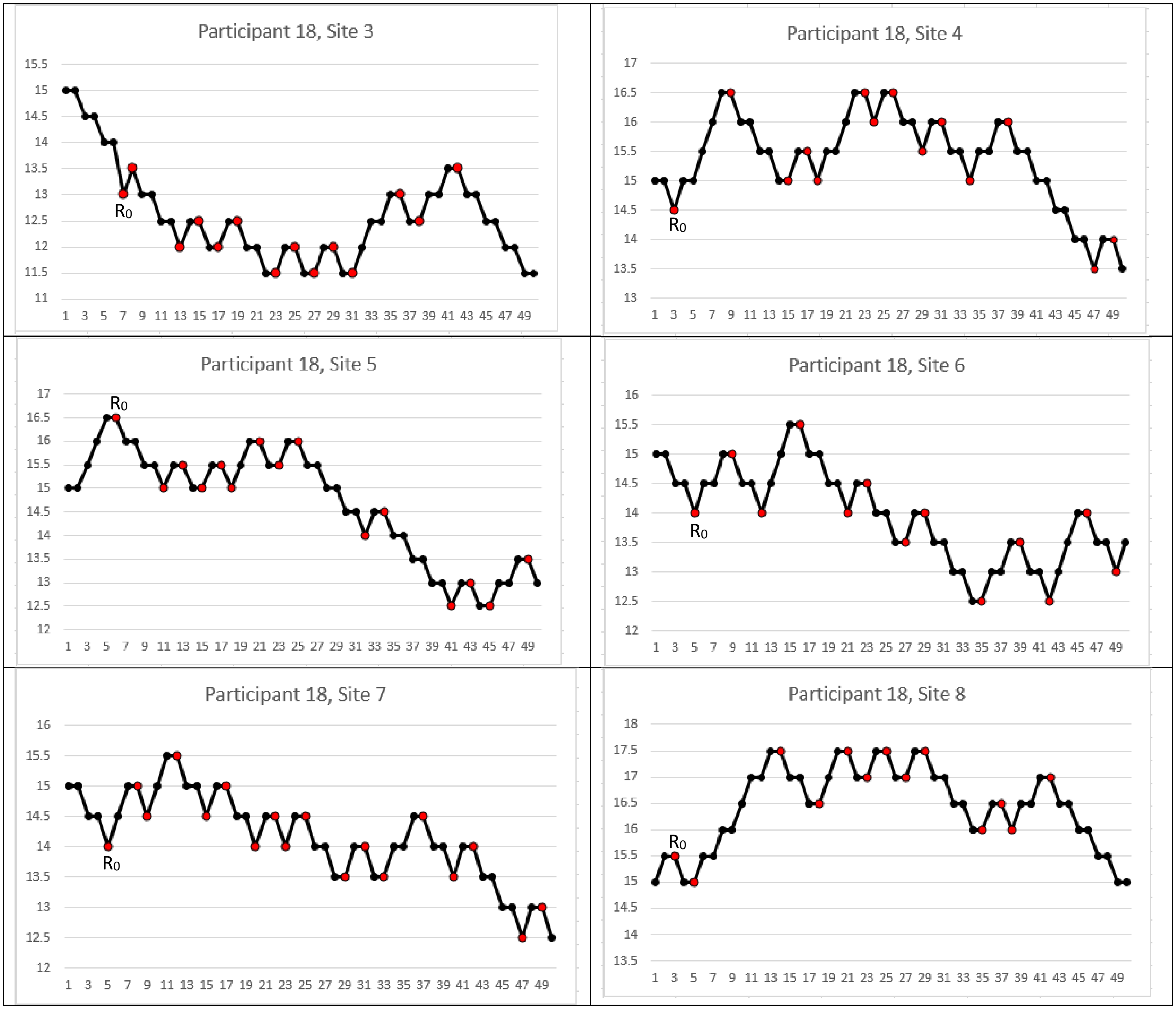
FIGURE 16: SHOWS THE AVERAGE THRESHOLD (IN MILLIMETERS) FOR EACH STIMULATION SITE ASTERISKS REFER TO SIGNIFICANT DIFFERENCES BETWEEN SITE THRESHOLDS.

Table 1: Individual thresholds for each stimulation site, with neck circumference (in Centimeters), handedness, age, and sex of each participant.

Part.	Age	Hand	Sex	Neck	S1	S2	S3	S4	S5	S6	S7	S8
P1	22	R	F	35.8	13.83	12.4	10.13	11.94	16.09	12.5	14.5	16.04
P2	19	L	M	35.5	13.56	14.8	18	12.3	12.36	16.11	16.19	15.9
P3	20	R	F	32.5	14.41	17.92	16.15	14.36	12.72	16	14.19	14
P4	19	R	F	39.5	8.9	10.8	12.5	11.38	15.33	10.85	14.07	11.85
P5	18	R	M	35.7	12.54	13.14	11.75	7.93	11.54	11.56	14.19	14.33
P6	20	R	M	39.5	11.4	13.04	12.43			13.75	11.65	15.04
P7	19	R	F	36	14.33	14.15	16.21	12.93	14.78	14.78	14.55	12.63
P8	19	R	F	33	11.85	12.89	13.69	12.54	12.61	14.69	17.36	9.75
P9	20	R	M	43.6	13.45	14.89	13.46	17.55	14.74	17.73	16.94	13.88
P10	21	R	F	33	5.5	14.75	14.36	13.73	15.69	15.44	14.67	13.03
P11	20	R	F	35	11.28	15.45	13.06	19.64	11.93	14.27	14.1	13.18
P12	18	R	F	36	11.44	13.31	12.31	15.46	13.54	13.83	14.12	16.77
P13	19	R	F	31.5	9.78	13.27	14.3	12.2	9.67	10	12.18	9.33
P14	18	R	M	36.5	7.14	13.38	12.1	16	13.99	14.63	14.68	13.96
P15	21	R	F	37.2	10.67	12.59	12.7	15.92	10.67	14.42	19	14.42
P16	18	R	F	36	16.33	18.64	17.15	17.55	12.6	20.31	17.35	17.64

Table 2: Trial blocks of Participant 18 with reversal points shown in red. The first reversal point, R_0, is not included in threshold calculations.





5. DISCUSSION

The results showed that neck sensitivity is relatively uniform across all the tested location when using 2POD task. While sites 1 and 7 had significantly different thresholds, it is apparent the significance is due to the slightly higher threshold of site 7 and slightly lower threshold of site 1 (Figure 16). Even the front of the neck, which seems to be less sensitive to vibrations in Experiment 1, has similar acuity that other sites of stimulation. Moreover, the front of the neck seemed to have slightly better spatial resolution than other sites, although it was only statistically different from site 7, which had the highest threshold. It is important to note that the locations tested were changed as participant performances seemly improved with the existence of a reference point (Cholewiak & Collins, 2003; Hamburger, 1980; Vierordt, 1870).

CONCLUSION

Our results showed that the neck is a viable location for tactile stimulation. Although we did not directly test vestibular-tactile substitution on the neck, the two studies serve as the first steps in determining the best parameters for developing a device that will deliver vibrotactile feedback with great accuracy and precision by providing guidelines for future studies.

From Experiment 1, we showed that the ArraySense can potentially and roughly convey tactile information in a specific neck region. However, certain changes should be made in the design by reducing the number of motors on the collar or firing the motors in rapid sequences to convey direction. Once the Arraysense's ability to convey directional information is established with the rapid sequencing of motors, this set-up can be used in future studies that disturb the vestibular system using a motion platform. Finally, when cconsidering the tested frequencies and durations, the motors positioned on the front of the neck did not convey the location of vibrotactile information even when a ±1 error rate was included. The front of the neck's poor accuracy in Experiment 1 can be attributed to a phenomena called bone conduction. We believe the cartilage at the front of the neck leads to propagation of vibration, making it difficult to distinguish. With this in mind, it is important to pay special attention to calibrating the direction and frequency of the vibration at the front of the neck to convey vibrotactile information to this area efficiently and effectively.

The results of Experiment 2 showed mostly uniform tactile acuity around the neck. While factors like age, sex, neck circumference and handedness could potentially effect thresholds, there were not enough participants to draw conclusions on correlations between sex, neck circumference and threshold levels. Additionally, participants in this study were all of the same age range (18-22), and only one participant was left-handed. Therefore, it may be beneficial to replicate this study using more participants of different age ranges, especially of older populations, to get a more representative sample of those who suffer from vestibular loss.

The conflicting results of Experiments 1 and 2 suggest the nature of the stimulus and design of the ArraySense are responsible for the poor performance of the ventral midline neck area, not the sensitivity of the neck. Important factors, like the presence of cartilage at the ventral midline, must be taken into account to avoid or counteract bone conduction when using the ArraySense. Higher frequencies should be tested and currently, we are working on changing the design of the ArraySense to improve its efficiency.

The uniformity of the neck's spatial acuity make the neck is a suitable candidate for directional information and therefore for tactile sensory substitution research and more particularly vestibular-tactile sensory substitution.

REFERENCES

Angelaki, D., Cullen, K. (2008). Vestibular System: The Many Facets of a Multimodal Sense. *Annual Review of Neuroscience*, *31*, 125-150.

Bach-y-Rita, P. (1990). Brain plasticity as a basis for recovery in humans, *Neuropsychologia, 28*(6), 547-554.

Bach-y-Rita, P. (1967). Sensory plasticity. Applications to a vision substitution system. *Acta Neurologica Scandinavica, 43*(4), 417-426.

Bach-y-Rita, P. (1971). Neural Substrates of Sensory Substitution. *Pattern Recognition in Biological and Technical Systems*, Proceedings of the 4th Congress of the Deutsche Gesellschaft für Kybernetik held at Berlin, Technical University.

Bach-y-Rita, P. (Ed.). (1972). *Brain mechanisms in sensory substitution*. Academic Press.

Bach-y-Rita, P., Kaczmarek, K., Tyler M., Garcia-Lara, J. (1998). Form perception with a 49-point electrotactile stimulus array on the tongue: A technical note. *Journal of Rehabilitation Research and Development. 35*, 427-430.

Bach-y-Rita, P., Kercel, S. (2003). Sensory substitution and the human-machine interface. *TRENDS in Cognitive Sciences, 7*(12), 541-546.

Bach-y-Rita, P. (2004). Tactile Sensory Substitution Studies. *Annals for the New York Academy of Sciences, 1013*, 83-91.

Bach-y-Rita, P., Danilov, Y., Tyler, M., Grimm, R. (2005). Late human brain plasticity: Vestibular substitution with a BrainPort human-machine interface. *Plast & Rest Neurol, 4*, 31-34.

Biguer, B., Donaldson, I., Hein, A., Jeannrod, M. (1988). Neck Muscle Vibration Modifies the Representation of Visual Motion and Direction in Man. *Brain*, 111.

Bove, M., Courtine, G., Schieppati, M. (2002). Neck Muscle Vibration and Spatial Orientation During Stepping in Place in Humans. *Journal of Neurophysiology, 88*, 2232-2241.

Cholewiak, R., Collins, A. (2003). Vibrotactile localization on the arm: Effects of place, space, and age. *Perception & Psychophysics, 65*(7), 1058-1077.

Craig, J. (1999). Grating orientation as a measure of tactile spatial acuity. *Somatosensory & Motor Research, 16*(3), 197-206.

Craig, J., Lyle, K. (2001). A comparison of tactile spatial sensitivity on the palm and fingerpad. *Perception & Psychophysics, 63*(2), 337-347.

Danilov, Y.P., Tyler, M.E., Skinner, K.L., Hogle, R.A., Bach-y-Rita, P. (2007). Efficacy of electrotactile vestibular substitution in patients with peripheral and central vestibular loss. *Journal of Vestibular Research, 17*(2-3), 119-130.

Day, B., Fitzpatrick, R. (2005). The vestibular system. *Current Biology, 15*(15), R583-R586.

Dozza, M., Horak, F., Chiari, L. (2007). Auditory biofeedback substitutes for loss of sensory information in maintaining stance. *Experimental Brain Research, 178*, 37-48.

Dozza, M., Wall III, C., Peterka R., Chiari, L., Horak, F. (2008). Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss. *Journal of Vestibular Research, 17*, 195-204.

Essock, E., Krebs, W., Prather, J. (1997). Superior Sensitivity for Tactile Stimuli Oriented Proximally-Distally on the Finger: Implications for Mixed Class 1 and Class 2 Anisotropies. *Journal of Experimental Psychology, 23*(2), 515-527.

Georgescu, M. (2015). Is virtual reality better than platform-based vestibular rehabilitation methods? *Journal of International Otology, 11*, 20.

Goldreich, D., Kanics, I. (2003). Tactile Acuity is Enhanced in Blindness. *Journal of Neuroscience, 23*(8), 3439-3445.

Grant, A., Thiagarajah, M., Sathian, K. (2000). Tactile perception in blind Braille readers: a physophysical study of acuity and hyperacuity using gratings and dot patterns. *Perception & Psychophysics, 62*(2), 301-312.

Gilbert, C., Sigman, M., Chis, R. (2001). The Neural Basis of Perceptual Learning. *Neuron, 31*, 681-697.

Grunwald, M., John, M. (2008). German pioneers of research into human haptic perception. Human perception: Basics and applications, 15-39. Basel, Switzerland: Birkhäuser.

Holmes, N. P., Spence, C. (2005). Multisensory Integration: Space, time & superadditivity. *Current Biology, 15*(18), R762–R764.

Horak, F. (2010). Postural Compensation for Vestibular Loss, *Restorative Neurology and Neuroscience, 28*, 57-68.

Ivaneko, Y., Grasso, R., Lacquaniti, F. (2000). Neck muscle vibration makes walking humans accelerate in the direction of gaze. *Journal of Physiology, 525*, 803-814.

Janssen, M., Stokroos, R., Aarts, J., van Lummel, R., Kingma, H. (2010). Salient and placebo vibrotactile feedback are equally effective in reducing sway in bilateral vestibular loss patients. *Gait & Posture, 31*, 213-217.

Johnson, K., Phillips, R. (1981). Tactile Spatial Resolution. I. Two-Point Discrimination, Gap Detection, Grating Resolution, and Letter Recognition. *Journal of Neurophysiology*, *46*(6), 1177-1191.

Jütte, R., (2008). Haptic perception: An historical approach. Human Haptic Perception: Basics and Applications, 3-13. Germany: Birkhäuser.

Karnath, H., Christ, K., Hartje, W. (1993). Decrease of contralateral neglect by neck muscle vibration and spatial orientation of trunk midline. *Brain, 116*, 383-396.

King, A., Palmer, A. (1985). Integration of visual and auditory information in bimodal neurons in the guinea-pig superior colliculus. *Experimental Brain Research, 60*, 492-500.

Kühner, M., Bubb, H., Bengler, K., Wild, J. (2013). Adaptive Verfahren in der Psychophysik. *Ergonomie*, 26.

Lackner, J., Levine, M. (1979). Changes in Apparent Body Orientation and Sensory Localization Induced by Vibration of Postural Muscles: Vibratory Myesthetic Illusions. *Aviation, Space, and Environmental Medicine, 50*, 346-354.

Lederman, S., Taylor, M. (1972). Fingertip force, surface geometry, and the perception of roughness by active touch. *Perception & Psychophysics*, *12*(5), 401-408.

Lederman, S. (1978). "Improving one's touch" … and more. *Perception & Psychophysics, 24*(2), 154-160.

Levendowski, D., Seagraves, S., Popovic, D. (2014). Assessment of a Neck-Based Treatment and Monitoring Device for Positional Obstructive Sleep Apnea. *Journal of Clinical Sleep Medicine*, *10*, 863-871.

Levitt, H. (1970). Transformed Up-Down Methods in Psychoacoustics. *The Journal of the Acoustical Society of America, 49*(2), 467-477.

Lewis, R., Gong, W., Ramsey, M., Minor, L., Boyle, R., Merfeld, D. (2003). Vestibular adaptation studied with a prosthetic semicircular canal. *Journal of Vestibular Research*, *12*, 87-94.

Meredith, M., Stein, B. (1983). Interactions among Converging Sensory Inputs in the Superior Colliculus. *Science, 221*, 389-391.

Meredith, M., Stein, B. (1986). Visual, Auditory, and Somatosensory Convergence on Cells in Superior Colliculus Results in Multisensory Integration. *Journal of Neurophysiology, 56*, 640-662.

Morley, J., Goodwin, A., Darian-Smith, I. (1983). Tactile Discrimination of Gratings. *Experimental Brain Research, 49*, 291-299.

Orlov, I., Stolbkov, Y., Shuplyakov, V. (2008). Effects of Artificial Feedback to the Vestibular Input on Postural Instability Induced by Asymmetric Proprioceptive Stimulation. *Neuroscience and Behavioral Physiology, 38*(2), 195-201.

Peterka, R. (2002). Sensorimotor Integration in Human Postural Control. *Journal of Neurophysiology, 88*, 1097-1118.

Sarevarsson, S., Kristjánsson, Á., Halsband U. (2010). Strength in numbers: Combining neck vibration and prism adaptation produces additive therapeutic effects in unilateral neglect. Neuropsychol Rehabil, 20, 704-705.

Schindler, I., Kerkoff, G., Karnath, H-O, Keller, I., Goldenburg, G. (2002). Neck muscle vibration induces long lasting recovery in spatial neglect. *Neural Neurosurg Psychiatry, 73*, 412-419.

Sienko, K., Balkwill, M., Oddsson, L., Wall, C. (2008). Effects of multi-directional vibrotactile feedback on vestibular-deficient postural performance during continuous multi-directional support surface perturbations. *Journal of Vestibular Research. 18*, 273-285.

Stiles, N., Shimojo, S. (2015). Auditory Sensory Substitution is Intuitive and Automatic with Texture Stimuli. *Scientific Reports, 5*, 1-14.

Taghavi, R. (2011). High resolution feedback using tactile semaphores. *7th international conference of GLS Conf.*, 238-247.

Tong, J., Mao, O., Goldreich, D. (2013). Two-point orientation discrimination versus the traditional two-point test for tactile spatial acuity assessment. *Frontiers in Human Neuroscience, 7*, 1-11.

Tyler, M., Danilov, Y., Bach-y-Rita, P. (2003). Closing an open-loop control system: Vestibular substitution through the tongue. *Journal of Integrative Neuroscience, 12*, 159-164.

Uneri, A., Polat, Ş. (2009). Vestibular rehabilitation with electrotactile vestibular substitution: early effects. *Eur Arch Otorinolaryngol, 266,* 1199-1203.

Uneri, A., Polat, Ş. (2010). Vestibular substitution: comparative study. *The Journal of Laryngology & Otology, 124*, 852-858.

Van Boven, R., DDS, Johnson, K. (1994). The limit of tactile spatial resolution in humans: Grating orientation discrimination at the lip tongue and finger. *Neurology, 44,* 2361-2366.

Vestibulo-ocular reflex (VOR). (2016). In *Encyclopædia Britannica*. Retrieved from http://www.britannica.com/topic/vestibulo-ocular-reflex.

Watson, M., Black, F. The Human Balance System: A Complex Coordination of Central and Peripheral Systems. Vestibular Disorders Association.

Weber, E. H. & Weber, E.H., 1795-1878. De Tactu & Weber, Ernst Heinrich, 1795-1878. Tastsinn und Gemeingefühl (1978). *The sense of touch*. Academic Press for Experimental Psychology Society, London

Ziat, M., Lecolinent, E., Gapenne, O., Mouret, G., Lenay, C. (2014). Perceptual strategies under constrained movements on a zoomable haptic mobile device. *Lecture Notes on Computer Science.*

Ziat, M., Gapenne, O., Stewart, J., Lenay, C. (2007). Haptic recognition of forms at different scale: A comparison of two methods of interaction. *Interacting with Computers*, *19*, 121-132.

APPENDIX A

Two-Point Orientation Discrimination (2POD) Task Pre-Study Questionnaire

Sex: Male ____ Female ____
Age: ________
Handedness: Right _____ Left _____

Question:	**Yes**	**No**	**Details:**
Do you have any neurological disorders that may impact your ability to complete this task? If so, please describe.			
Do you have any learning disabilities that may impact your ability to complete this task (i.e., ADD, ADHD, dyslexia)? If so, please describe.			
Have you ever had a surgical operation anywhere on your neck? If so, please the location and give the approximate date of surgery.			
Have you ever had received an injury to your neck? If so, please describe what type of injury and include an approximate date.			
Have you been diagnosed with touch defensiveness, or a hypersensitiveness to being touched?			
Have you been diagnosed with diminished sense of touch?			
Have you been diagnosed with diabetic neuropathy, or nerve damage caused by uncontrolled blood sugar levels?			