Handheld Tactile Sensory Substitution for the High-Frequency Hearing Impaired

Jimmy Fong, Becky Jones, Jack Page, Ryan Thome, Matt Valaskey

ABSTRACT

Our research focuses on the development of a tactile sensory substitution device to provide missing high frequency sound information to persons with high frequency hearing loss (HFHL). Previous research has shown that high frequency consonants can be distinguished by their energy and frequency content. The sound signal of common words containing high frequency consonant sounds (California Consonant Test, CCT) was filtered into four separate frequency channels between 1.6 – 8 kHz. The sound present in each of the 4 channels was presented to the user via discrete vibrating motors, one placed at the tip of each of the 4 fingers. The vibrations give different patterns for different sounds, allowing the user to make a distinction between different high frequency sounds. This study will measure the subject's ability to identify the location of the vibration, i.e. which finger is activated, the ability to learn the specific patterns, and the ability to use the vibrating pattern to increase word recognition ability. We employed a preliminary practice session to acclimate the subject with the tactile substitution device and then the CCT was administered both with and without the tactile substitution device. The testing consisted of playing a recorded word from the CCT from a single computer speaker while simultaneously presenting the word's high frequency information via the four tactile stimulators and asking the subject to identify the played word from a closed set of four words.

INTRODUCTION

The number of hearing impaired Americans has more than doubled in the past 30 years with nearly 50 percent of Americans over the age of 65 affected [1]. It not only affects the elderly however, 1.4 million children under the age of 18 also have a hearing condition [2]. The most common type of hearing loss is sensorineural. About 90 percent of individuals who are hearing impaired have sensorineural hearing loss. This condition, also known as nerve deafness, consists of either damage to the inner ear or the nerves which transmit the messages from the ear to the brain. It is caused by disease, birth injury, or even aging. The most common form of sensorineural hearing loss is high frequency hearing loss. This is where an individual loses the ability to hear certain high frequency constants such as Sh, S, T, Th, P, or F sounds. Since these are some of the most common used consonants in the English language, high frequency hearing loss is truly detrimental to every day communication.

High frequency hearing loss is not easily medically fixed because it is caused by damage to the nerve, so sound cannot simply be amplified to assist a person with communication. For example, hearing aids do not do an adequate job of fixing this problem because they only amplify the sound. This is why sensory substitution has been chosen as a method to replace the lost hearing at high frequencies.

The goal of this project is to use sensory substitution, a technique for presenting environmental information missing in one sensory modality to another, to help replace this missing high frequency information. We proposed that a device that filters frequencies above 1,000 Hz into four bands and provided this information vibro-tactically to a subject would allow them to be better able to discriminate between high frequency consonant sounds, thereby assisting in everyday communications.

The device takes recorded sound, filters it into four different channels based on frequency, and then outputs all four channels to a sound card. The sound card outputs to a circuit that amplifies the sound and reduces the noise. The circuit then outputs to four vibrotactile transducers. The four transducers will then vibrate in response to high frequency sound inputs. Different fricative sounds will stimulate different vibrotactile transducers based on the frequency of the sound, allowing the user to associate a particular vibration with an unheard sound. Vibrotactile stimulation involves generating vibrations that activate mechanoreceptors in the skin. Vibrotactile transducers were chosen because of their ease of acquirement and implementation. Use of this device, to supplement for the loss of high frequency hearing, should aid the user in daily communications in regard to speech and hearing.

There are a few existing devices which aim to use sensory substitution by substituting for hearing using vibro or electro stimulation, but these products are made specifically for people with complete hearing loss. For example, the Tickle Talker™ uses vibrotactile stimulation on the fingers of the user. Each finger receives stimulation from a different range of frequency and based on the pattern, strength, and duration of the vibration, the user can pick out a certain frequency range. Since this form of sensory substitution covers the whole spectrum of hearing, it is not sensible for a person with only high frequency hearing loss to use the device. They would have to sift through way too much information to get the signals they needed. With such a large learning curve, the user must spend hours with the device to learn minimal amounts of words. For example, after more than 40 hours of training, a certain user could only identify 70 words [3]. The high frequency user could adapt at a much faster rate to only a high frequency stimulator because they are only missing certain sounds, not the entire spectrum. Other similar devices include the Tacticon 1600 and the Tactaid VII. The Tacticon 1600 uses electro stimulation by putting electrodes on a belt around the user's abdomen [4]. This device also covers the whole spectrum of hearing and has a steep learning curve. In similar ways, the Tactaid VII uses vibrations covering the entire range of human hearing [4]. The vibrators are attached to the user's sternum, each corresponding to a certain frequency range. However, no device currently exists on the market that effectively assists people with high frequency hearing loss in their every day communications.

MATERIALS AND METHODS

Device Design

The general function of the experimental device is to present the subject with a sample sound along with vibrational pulses that signify the presence of high frequency consonant sounds. The overall system consists of a laptop, a simple driving circuit, and a handheld device with four vibrating motors.

For the purposes of this study, the laptop was used to run a custom Java program that simultaneously played two versions of sample words from the California Consonant Test (CCT) to the subject and recorded their responses. The CCT is a variation of a forced response test where a word is played for the subject who then chooses the corresponding word from a list of four that vary in their initial and final consonant sounds. The CCT was chosen for this study because it emphasizes discrimination of consonant sounds and has proven useful in identifying consonant confusions for rehabilitation purposes [5]. The first version of the word is a standard wave file that was played to the subject through a small speaker. The second version of the word contains four tracks, each filtered to contain the frequency range of only its corresponding channel. This word is not played aloud, but each track containing only a specific frequency range is sent on to its respective channel in the driving circuit.

When the analog audio signal is played to the driving circuit each track is amplified in its respective channel. This signal is then compared to a threshold voltage. If there is a significant amount of sound energy in a channel's given frequency range, the threshold will be exceeded and a short 10 – 20 ms DC pulse will be sent to the motor of that channel. The strength and duration of vibration that a motor will undergo for a specific sound is then dependent upon the degree to which the short DC pulses overlap and the overall duration for which pulses are created. The motors used are four Solarbotics VPM2 flat disk motors that are housed in a handheld device that allows the motors to contact the fingertips of the user. The motors are housed in sponge rubber to isolate vibrations and allow the user to clearly identify which motor is providing the stimulus.

This system allows for the subject to be presented an auditory stimulus through the small speaker while also receiving tactile stimuli that signify the presence of high frequency sounds that may not be perceived or discerned through the auditory stimulus alone.

Frequency Range/Consonant Determination

The frequency ranges of the four channels were chosen through various types of spectral analysis of consonant sounds using COLEA, a free Matlab program designed specifically for speech analysis. Once the frequency characteristics of each high frequency consonant sounds was determined, the frequency ranges of the four channels were chosen to allow for the maximum number of consonant sounds to have a unique stimulus pattern across the four channels. Particular care was taken to ensure that a clear S/Sh distinction could be made, as this is a very important distinction that must be made for speech intelligibility. The frequency ranges of the four channels were then chosen as follows: Channel 1: 1.6-2 kHz (B, F), Channel 2: 2-3 kHz (F, CH, SH), Channel 3: 3-3.5 kHz (CH, SH), Channel 4: 4.5-8 kHz(S, SH).

Testing Protocols

The testing demographic consisted of five subjects (3 male, 2 female) with a mean age of 75 (+/- 4.4 S.D) years. Each subject suffered from high-frequency hearing loss (HFHL), as determined by an audiologist. Each subject was recruited for one session lasting one hour. Before the actual testing began, the participants were subjected to preliminary inspection. This inspection included a health questionnaire to ensure the participants had not been exposed to any substance that could alter their attention and mechanical abilities, including alcohol, caffeine, and prescriptions. It was then made certain that the subjects were not experiencing any insensitivities, numbness, or tingling of the fingers on the non-dominant hand. This was done verbally and visually, looking for calluses, scars, cuts, etc. If the participant passed the preliminary visual and verbal inspection, testing could continue.

A Von Frey Hair Test was used to test the sensitivity of individual fingertips. A fishing line 0.45 mm in diameter was lightly touched to each fingertip of the non-dominant hand in a swiping motion with enough force to slightly bend the fishing line. The participant needed to be able to identify which finger the stimulus was occurring on. If the subject could identify the stimulus on each finger, he or she continued with the testing.

A California Consonant Test (CCT) was administered using a java computer program. This test was given without the aid of the vibrotactile device. The CCT was developed to test the word recognition ability of individuals with HFHL by presenting a list of 50 target words, each stressing high frequency consonants, in closed set format with three incorrect choices. Each word was presented to the subject at 65 dBA from a computer speaker. The user selected to play the word using the computer program, then chose the word they heard from a list of four words. All 50 responses were logged. There was a 30 second time limit to answer, after which the question was marked incorrect.

The subjects were then tested using the device with vibrotactile transducers. Pure tones were delivered in order to isolate each tactor individually. Then dual tones were delivered in order to stimulate two tactors simultaneously. The participant had to be able to sense the stimulus on each finger and correctly identify which finger(s) were receiving the stimulus with 80 percent accuracy to continue on. Trial number was not limited, and if there was any doubt of the ability of the participant to sense the stimulus, testing was repeated. Each finger was stimulated at least once using pure tones and each combination of dual tones was tested at least once.

Next a consonant discrimination test was performed by playing s, sh, ch, f, and b sounds to the subject while he or she was using the device. Each specific consonant sound was played until the user could identify the pattern of vibrations associated with it by selecting the correct consonant choice using the java computer program.

After learning the vibration patterns associated with specific consonant sounds, the subject's word recognition ability was retested using the CCT method used in the baseline test, except now with the aid of the vibrotactile device. While the word was played through the speaker, a filtered version of the word was presented simultaneously via four tactile stimulators placed on the fingertips of the non-dominant hand. The subject was asked to identify the word presented from a list of four possible choices using the same computer program as before. Each trial with the tactile information presented was compared to the trial without the tactile stimulation for the same subject and analyzed through statistical means for significance.

Data Analysis

Overall, the data analysis was designed to yield results that conclude whether there was significant improvement in subjects' word identification ability when using the handheld device. A Student's t-test (paired, 1-tailed, directional) was used to compare the group of scores on the CCT before using our handheld device and the group of scores on the CCT while using our device. To determine if the each subject's training had influenced his or her performance on the CCT with the device, a non-parametric Spearman's rank correlation coefficient was determined. This non-parametric approach was utilized due to the limited sample size.

RESULTS

The Student's t-test conducted at a 95 % confidence interval determined whether to reject the null hypothesis H_0 (that the scores on the CCT were unaffected by the device; $\mu_0 = \mu_A$) and to accept the directional alternative hypothesis H_A (that the scores on the CCT significantly improved with using the device; $\mu_A > \mu_0$).

The results in Figure 1 show that three out of the five tested subjects improved on the CCT with the device showing subject 04 improving most dramatically by 18% .

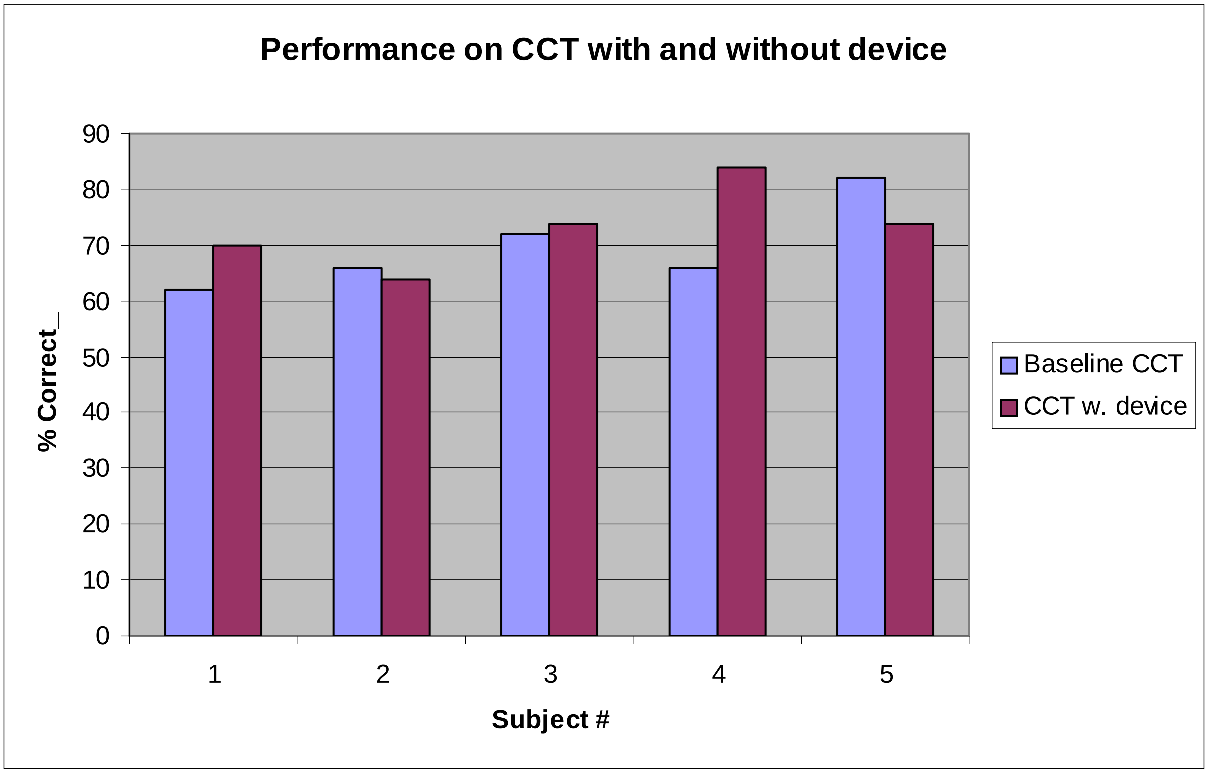

Figure 1: Bar graph of each subject's CCT score with and without aid of handheld device

The distribution of the CCT scores and the variance statistics are shown in Figure 2 with the average score of the subjects using the device being slightly higher than the baseline scores.

	BASELINE	WITH DEVICE
AVG	69.60	73.20
STD DEV	7.80	7.29
VARIANCE	60.80	53.20
MIN	62	70
MAX	82	84
q1	66	70
q3	72	74

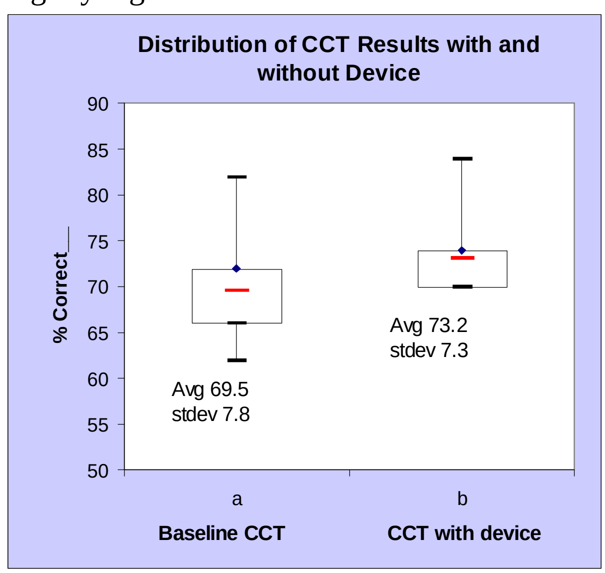

Figure 2: Distribution of CCT scores and variance statistics

The result of the Student's t-test at a 95% confidence interval on the CCT scores show:

$$p = 0.23$$
$$H_0 \text{ is accepted at 95\% confidence } \mu_0 = \mu_A$$

With this limited sample size, even though the majority of the subjects improved on the CCT with the device, the Student's t-test concludes that it is not significant at a 95% confidence interval. The performance on the consonant training for each subject compared to the performance on the CCT is shown in Figure 3.

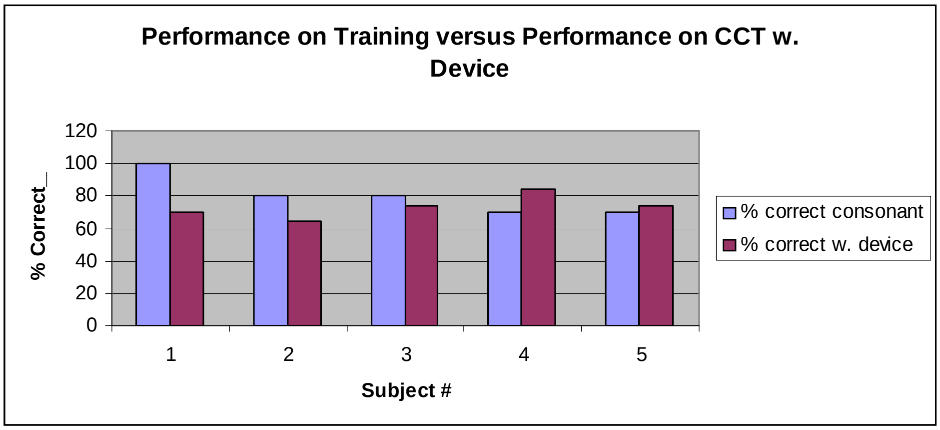

Figure 3: Distribution of consonant training performance against CCT performance with device

For the non-parametric Spearman's rank correlation coefficient r_s to conclude that a correlation exists for n = 5, r_s must be greater or equal to 0.9. The results of this test show:

$$r_s = -0.703 < 0.9$$

There does not exist a correlation between higher training score and a higher CCT with device score. Furthermore, the trend shows that data trend toward a lower training score relating to a higher CCT with device score.

DISCUSSION

The purpose of this study was to test whether tactile auditory sensory substitution could be used to increase the word recognition ability of subjects with high-frequency hearing loss. The subject's ability to identify the location of the vibration and their ability to learn the specific patterns of vibration associated with certain consonants was also tested to look for a correlation between the subject's learning capability and their word recognition scores. With a p-value of 0.23 the study pertaining to increased word recognition ability was inconclusive. Also, it was expected that higher scores on the subject's vibration location and consonant training (learning capabilities) would correlate with a greater increase in word recognition ability. However, as exposed in the Spearman rank correlation, the study did not show this. The inconclusive results can be explained partially due to factors of variance including the small sample size, varying range of subject's hearing loss and perceptual skills, and short device training period.

While the gathered evidence for the improvement in word recognition ability was inconclusive among the five high-frequency hearing impaired individuals tested, the information and experience gain resulted in valuable insight. The lack of a positive correlation between training test scores and overall word recognition ability with the substitution device points to a possible deficit in the training procedure used for testing. In planning the study the learning curve for using the device was unknown, but appears to be higher than initially thought. The lack of correlation in the results also points to a need for stricter guidelines for subject recruitment, as the five subjects tested varied quite significantly in age as well as in degree of hearing loss.

Future testing with this device and in the auditory substitution subject area in general can benefit greatly from the insight gained in this study. The next series of tests with this device should incorporate multiple testing sessions for each individual subject, focusing much more time on training with use of the device. Specifically, spending more time teaching the subject to recognize the individual consonant sounds one at a time could lead to significant improvements. Also, narrowing the required range of hearing loss for prospective subjects would decrease the amount of variability in the test.

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LITERATURE CITED

[1] American Speech-Language Hearing Association (ASHA). The Prevalence and Incidence of Hearing Loss in Children. 1997-2006. http://www.asha.org/public/hearing/disorders/children.htm

[2] Better Hearing Institute (BHI). Hearing Loss- The Prevalence of Hearing Loss. 2005-2006. http://www.betterhearing.org/hearing_loss/prevalence.cfmC. J. Poletto and C. L.

[3] Galvin, K. et al (Aug 1999). Acquisition of a tactile-alone vocabulary by normally hearing users of the Tickle Talker™. *The Journal of the Acoustical Society of America*, Vol. 106, Issue 2, pp. 1084-1089.

[4] Lynch, M., Eilers, R., (April 1992). Open Set Word Identification by an Adult with Profound Hearing Impairments: Integration of Touch, Aided Hearing, and Speech Reading. *Journal of Speech & Hearing Research*, April 1, 1992, Vol. 35, Issue 2.

[5] Owens, E, Schubert, E.D. (1977). Development of the California Consonant Test. *Journal of Speech and Hearing Research*, 20, 463-474.