Tactile Auditory Sensory Substitution

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Abstract

High frequency hearing loss is a problem common among people of all age groups. People who suffer from this type of hearing loss often lose the ability to hear certain consonant sounds. 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. 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. 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.

Product Design Specifications Summary

The final design should expand upon the prototype from the previous semester and meet requirements in the areas of performance, safety, cost, and ergonomics. It should help to substitute for high frequency hearing loss to the extent of helping the user with everyday communication. The system should be able to detect speech spoken at the normal 60 dB level and separate it into four frequency bands above 1000 Hz. It should also be able to transmit vibrations at a frequency of 250 Hz resulting in a skin displacement of 1 mm. Aesthetically and ergonomically, the device should be comfortable to the user and be hidden behind the ear. The device should be safe such that the transducer terminals are insulated from the skin and the electronics powering the system should be isolated from the user. The product design specifications can be viewed in its entirety in Appendix I.

Background

High Frequency Hearing Loss

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 (ASHA, 1997-2006). It not only affects the elderly however, 1.4 million children under the age of 18 also have a hearing condition (BHI, 2005-2006). The two most common types of hearing loss are conductive and sensorineural. Conductive hearing loss is defined as the condition when sound is not transmitted correctly through the middle ear and into the inner ear. Some describe it as like having the ears plugged all day. It can be caused by wax buildup or even infection. This type of hearing loss can often be medically cured.

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, as seen in Figure 1. 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.

Most elderly Americans suffer from some form of high frequency hearing loss, along with 14.9 percent of children (ASHA, 1997-2006). High frequency hearing loss is not easily medically fixed. Hearing aids do not do an adequate job of fixing this problem because they only amplify the sound. Consider a piano with no strings. No matter how hard the keys are hit, there is still not going to be any sound. Similarly, no matter how loud the hearing aid makes the sound, a person with high frequency hearing loss cannot hear sounds in those frequencies. Obviously, something more than hearing aids needs to be considered in order to help the rising number of people with high frequency hearing loss.

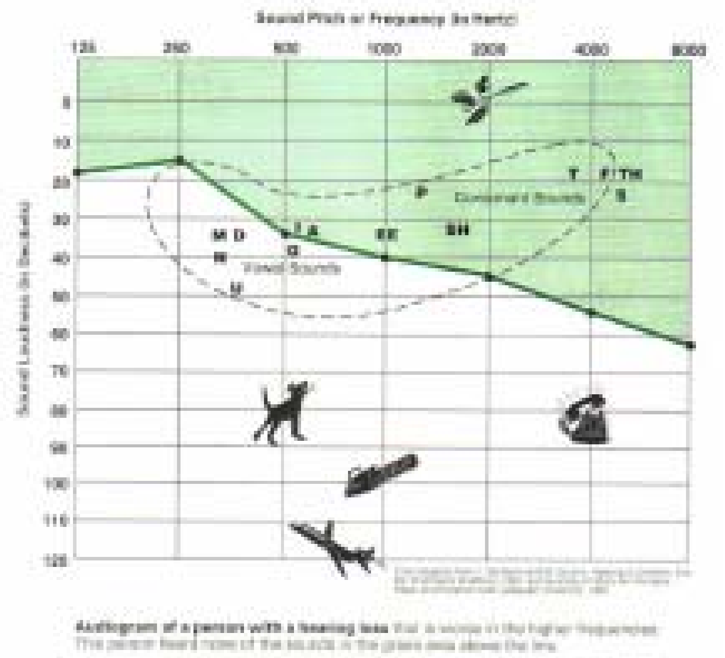

Figure 1: Audiogram of missing consonant frequencies

Sensory Substitution

Sensory substitution is presenting environmental information absent in one sensory modality to another. Sensory substitution can be seen in many actions people perform throughout their everyday lives. For example, a person substitutes the sense of touch for sight when reaching into their pocket to retrieve an object. Other common examples are the use of sign language to substitute vision for hearing and Braille which substitutes the sense of touch for sight. In this project, the device will substitute missing high frequency hearing with vibrotactile stimulation.

Existing Sensory Substitution Products

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 (Galvin, 1999). 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 (Lynch, 1992). This device also covers the whole spectrum of hearing and has a steep learning curve. In similar ways, the Tactaid VII, seen in Figure 2, uses vibrations covering the entire range of human hearing (Lynch, 1992). The vibrators are attached to the user's sternum, each corresponding to a certain frequency range.

Figure 2: The Tactaid VII (Audiological Engineering Corp)

Placement of Transducers

The skin is the largest organ in the human body. It is composed of three layers, the epidermis, dermis, and hypodermis, and is loaded with sensory nerves. These sensory nerves can detect temperature, pressure, pain, and touch. The nerves that sense pressure, vibration, and touch are called mechanoreceptors. Specifically, the Pacinian corpuscle senses slight pressure and vibrations.

The tactors must be able to stimulate the Pacinian corpuscles, which are of different prevalence in different parts of the body. Three areas of placement, inside the ear (ITE), behind the ear (BTE), and the back of the neck, were considered. Each considered area was on the head for the easiest and least conspicuous placement. The key advantage for placement of the transducers in the ear is that it allows for almost complete concealment of the tactile element of the device. However, because the device is being placed in such a small area the construction would be much more complicated than for the other areas. Also, with multiple stimulators, it would be difficult to space the stimulators far enough apart to reach the two-point discrimination threshold. Another disadvantage to this placement would be the adverse conditions of the inner ear, which might cause damage to the device due to build up of ear wax or moisture. Placement of the transducers behind the ear allows for the device to be mostly concealed from outsiders. Another advantage is that if vibrotactile stimulation is used, bone conduction would help with propagation of the signal. One of the few disadvantages of this placement is that its attachment may be impeded by the hair of the user.

The final area considered for placement of the transducers was on the back of the neck. This area allows for the most space for the tactile layout, which would help in surpassing the two point minimum discrimination distances. This large amount of space also would allow for the easiest construction of the transducer layout. However, placement on the neck allows for the most visibility to outsiders, which is a major drawback to the designs aesthetics.

Based on the predicted advantages and disadvantages of each location, it was determined the tactors will be placed behind the ear. Thus, the sensitivity of this region was tested to find the optimal place to put the tactors. Through the two point discrimination test, it was found that there will be two tactors on the mastoid process and two on the skin below it. The distance between the tactors, if they are stimulated at similar frequencies, was also found. The results of the two point discrimination of the skin behind the ear are shown in Table 1. It was determined that stimulations similar in frequency 25 mm apart on the mastoid process and tactors on the skin below the mastoid process must be 25 mm apart. The last tactor on the mastoid process and the first one on the skin below it must only be 20 mm apart. This is due to increased sensitivity of detecting different stimulations if one is on the bone and one is on the skin below it. This can be seen in the results in Table 1. In the table, under the placement heading A means both stimulations occurred on mastoid process, B means both were presented on the skin below the mastoid process, and C means that one was on bone, and one was on the skin. As can be seen from the results, there was increased sensitivity at placement C.

The study also showed a learning curve involved with the sensitivity of the skin. Each subject became more sensitive in that region as the testing progressed. This could mean that after having the tactors on the skin for a long period of time, the user would become more accurate in discerning the stimulations, and thus make a better substitution for the hearing loss.

Subject	Stimulation	Distance apart (mm)	Placement A = both stimulations on mastoid process B = both on skin below C = one on bone, one on skin	Number of times the subject recognized two distinct stimulations
1	1 - 3	15	A, B, and C	0/2 at each site
	4	25	A	0/3
	5		B	2/3
	6		C	2/3
	7	35	B	3/3
	8		C	3/3
	9	19	A	0/2
	10		B	2/3
	11		C	1/2
	12	20	A	0/2
	13		B	1/2
2	1	10	B	0/3
	2	16	B	0/3
	3	36	B	0/1
	4	50	B	2/2
	5	36	B	2/2
	6	35	B	2/2
	7	16	B	0/2
	8	25	A	0/2
	9		B	2/3
	10		C	3/3
3	1-3	15	A, B, and C	0/2 at each site
	4-6	20	A, B, and C	0/2 at each site

	7	25	A	0/3
	8		B	2/3
	9		C	0/3
	10	30	A	0/2
	11		B	2/3
	12		C	0/2
	13	39	B	2/2
	14		C	3/3
	15	35	B	2/2
	16		C	2/2
	17	30	A	1/3
	18		B	2/3
	19		C	3/3
	20	25	A	0/4
	21		B	3/4
	22		C	0/4
	23	20	A	2/3
	24		B	0/3
	25		C	0/3

Table 1: Results of two point discrimination test

Vibrotactile Transducers

Vibrotactile stimulation involves generating vibrations that activate mechanoreceptors in the skin. This form of sensory substitution by using mechanical vibrations to replace hearing loss can be achieved by integrating several vibrotactile transducers into the prototype developed in the previous semester. The prototype is currently able to distinguish and separate high frequency speech into four channels, and as a result, the next step would be to correlate the data in each channel with an appropriate amount of vibration in each transducer.

The amount of vibration that is appropriate for the user is determined by the characteristics of mechanoreceptors known as Pacinian corpuscles. These mechanoreceptors are sensitive to gross pressure changes and higher frequency vibrations applied to the skin. They are also classified as fast afferent type II (FA II), referring to their ability to adapt after sending an action potential (Physiology of Receptors). It has been shown that the minimum threshold amplitude needed to stimulate these receptors varies with the frequency of vibration. In one study, the minimum threshold for the average subject was measured to be 1 mm at 5 Hz and 1 μm at 200 Hz. These values are indicative of a trend that at higher frequencies, less amplitude of skin displacement is needed to activate Pacinian corpuscles. The optimal range of sensitivity, however, was discovered to be in the range of 60 Hz to 250 Hz (Konyo *et al*).

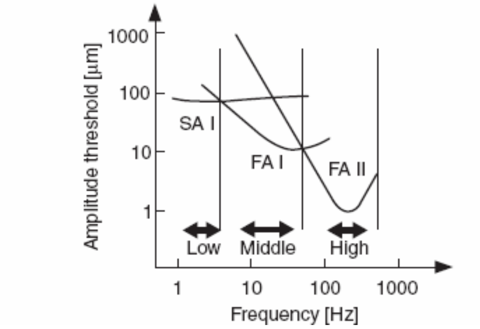

Figure 3: Frequency and amplitude required for Pacinian corpuscle activation

The vibrotactile transducers that are currently being pursued are constructed from piezoelectric film. The transducers measure 13 cm by 25 cm with negligible thickness and comprise of two terminals that can be used as an input or output.

Figure 4 and 5: Piezoelectric transducers (www.digkey.com)

The piezoelectric transducer operates by changing the voltages of its faces which cause molecules of its crystalline structure to realign back and forth with the changing voltage and thus results in vibration (NDT). The deflection in the transducer is proportional to the frequency of the voltage input. Therefore, each channel of data in the prototype might need to be modulated in order to yield an appropriate vibration. When used as a vibration sensor, the transducers exhibit a deflection to voltage relationship as shown in Figure 6, but the relationship has yet to be established when used as a transducer.

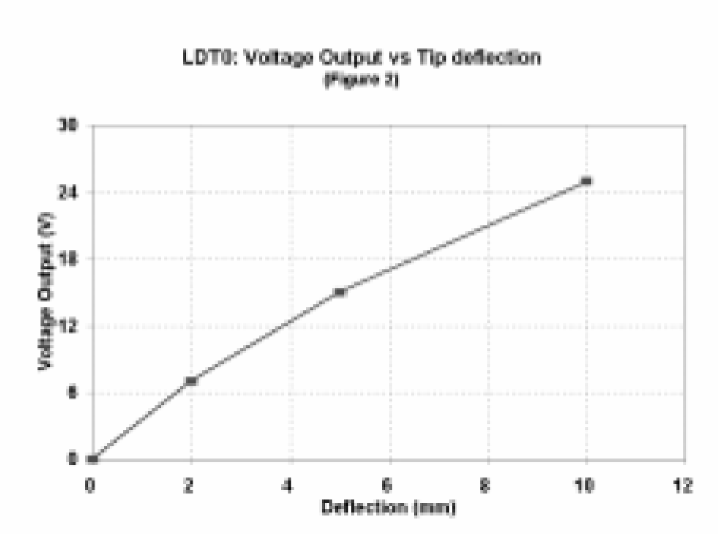

Figure 6: Voltage versus deflection plot for piezoelectric transducers in sensor mode.

There are several distinct benefits to using vibrotactile transducers in this manner when compared to an electrotactile stimulus. The sensation that the user perceives is more consistent with a mechanical stimulus because the transducer is only displacing the skin as opposed to sending currents through the skin. This displacement can be strictly controlled with the voltage applied to the transducer. Another advantage is that the piezoelectric transducers are cost effective at $1.20. Furthermore, vibrotactile transducers can be more easily implemented into the current prototype, requiring a less complex circuit.

The major disadvantage of vibrotactile transducers is their high power requirement when in actuating mode. Though not specified for this exact model of transducer, similar transducers have been shown to require 168 mW for a 4 mm transducer, more than 10 times the power consumption of a similarly sized electro-transducers (Kaczmarek).

Electrotactile Stimulation

The other option for providing tactile feedback to the user is electrotactile stimulation. Electrotactile stimulation creates a vibrating sensation by passing small amounts of current from electrodes through the skin. Current is passed through the skin by creating large voltage differences at the skin-electrode interface. Perceptible and comfortable tactile sensations can be created with between 1 mA – 20 mA of current (Kaczmarek & Webster). In order to create this level of current, large voltage differences, between 200 V – 500 V, are necessary to overcome the high resistance levels of the skin. Typical skin resistances are around 2 kΩ while the skin-electrode interface can be represented by a resistor in parallel with a small capacitance, with values of 10 kΩ – 320 kΩ and 0.42 nF respectively, as can be seen in Figure 7 (Poletto). Common variables in electrotactile waveform are the pulse repetition rate (PRR), number of pulses per burst (NPB), phase width, frequency, current and interphase

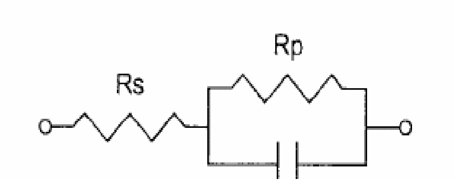

Figure 7 – First order electrical model of the skin

interval (IPI). According to one study by Kaczmarek et al. the maximal current without discomfort was found for waveforms with NPB of 6, PRR of 350 Hz, phase width of 150 μs, and frequency of 15 Hz. Typical electrodes used are gold or silver plated and several millimeters in diameter. The electrodes can be made smaller or larger in order to increase or decrease the sense of localization.

The main advantage of electrotactile stimulation over vibrotactile is its much smaller power consumption. A 3 mm electrotactile electrode has a power consumption of 1.2 mW as opposed to 138 mW for a 4 mm vibro-tactor, a more than 100 fold difference (Kaczmarek and Webster). When creating a portable device this is a key consideration. Also, electrotactile electrodes can be made smaller and more discrete than their vibrotactile counterparts.

One of the disadvantages of using electrotactile stimulation is the high voltage that is necessary to overcome the high skin-electrode interface resistance. Using voltages on the order of 200 V – 500 V introduces more safety concerns than the smaller voltages necessary for vibrotactile stimulation. Also, because skin resistance varies from day to day and from person to person, there can be a greater degree of variance in the perceived sensation. For this reason electrotactile simulation is often described as less comfortable than vibrotactile.

Signal Processing / Consonant Determination

In order to stimulate the right tactors, once the acoustic signal is recorded and digitized, it must be analyzed to determine which high-frequency consonants it contains. The current design does this by separating the high-frequency consonant range into four smaller frequency ranges, each containing several specific consonants. This method is easy to implement by analyzing the signal with a Fourier Transform to determine the various frequencies present and their respective amplitudes. When the amplitude of sounds within a given range reaches an appropriate amplitude, one of the transducers is activated. For a more sophisticated system, there must be a method to determine more specifically which consonant sounds are present in the recorded speech signal.

The most obvious method is to use more specific frequency ranges, with each range corresponding to one or two consonants sounds. The cutoff frequencies for each range as well as the number of channels included could be determined through experimentation and the use of Audiogram charts. This method would be fairly easy to implement using the current Cool Edit Software, provided a method of outputting more than 5 channels can be found. The downfall of this method is that it does not take into account some subtleties of the English language that influence the way consonant sounds are produced. These consonant sounds do vary somewhat in frequency from speaker to speaker, although this variation is rather small since the sounds are created by moving air through the vocal tract and are rarely influenced by the speaker’s natural voice tone. Also, the nature of consonant sounds can be influenced by the other speech sounds that they are surrounded by. One solution to this problem is to incorporate a voice recognition system to determine which consonant sounds are present.

Voice recognition is a fairly complex process that takes into account many aspects of an audio signal in order to determine what words it contains. These systems use not only frequency but strength and order of the sounds present. Using probability models, the system then determines which specific speech sounds are produced (Zue, et al.). A system such as this would also perform better in noisy environments since they employ various methods to determine which portions of the input signal actually represent the human voice. Although a system of this type may perform with greater accuracy, it does have some limiting aspects. First of all, this system would be much more difficult to implement. A program would have to be found that could be integrated into portions of the current design. This would most likely require a computer and increase the size of the device. Also, with the additional processing necessary, the system may not perform fast enough in real life situations.

Design Matrix

We constructed a design matrix to evaluate our design options. This can be found in Appendix II. The first design matrix compared the two stimulation types: vibrotactile and electrotactile. We compared these stimuli by evaluating power consumption, safety, ease of implementation, patient comfort, and aesthetics. Ultimately, we chose vibrotactile as our stimulation method even though electrotactile stimulation would require a smaller power supply and require less skin surface area for stimulation. Vibrotactile is more comfortable to patients because of the preference of the vibratory sensation over a controlled electrical stimulus. Vibrotactile transducers are easier to integrate into our circuit design, where as the use of electrotactile stimulation would require significant modification to our existing circuit.

The type of frequency analysis utilized by out device was also chosen using a design matrix (Appendix II). Frequency and linguistical analysis were compared on the basis of accuracy, ease of implementation, noise adaptability, processing time, and cost.

Even though linguistic analysis is more accurate at recognizing fricative sounds and distinguishing noise from speech sounds, we decided to use frequency analysis in our final device design. Frequency analysis is easier to implement into the system than linguistical due to the difference in complexity of the system. Frequency analysis also has a much faster processing time and is significantly more economical to implement into the device design.

Proposed Design

The proposed design consists of vibrotactile transducers placed behind the ear and frequency analysis for speech and consonant recognition. Speech will be recorded onto a personal computer and filtered by specific frequency range to isolate certain consonant sounds. Each specific frequency range will correspond to one channel which will be outputted from the Roadie soundcard to the multi-channel amplifier/comparator. The amplifier/comparator will amplify the outputted voltage from the soundcard and then measure it against a baseline voltage. If the voltage signal has a large enough amplitude it will be sent to the vibrotactile transducers and they will vibrate, communicating the missing high frequency information to the user.

Future Work

Our first objective is to integrate the vibrotactile transducers with the circuit constructed during last semesters work on the project. This will involve changing the voltage amplification of the circuit. Further research will be done on the frequency ranges that should be used for each channel, to best isolate the fricative sounds of interest. Continued research will also be put into device locations on the body. This will be especially important if we find that more than four tactors need to be used.

By the end of this semester, we would like to be at the point in device development where we could begin testing the efficacy of the device on its ability to aid patients with high frequency hearing loss on daily communications. While also developing methods and techniques to miniaturize our device to make it more aesthetically pleasing and portable.

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Appendix I: Product Design Specifications

Tactile Auditory Sensory Substitution

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

Function:

High frequency hearing loss is the most common form of hearing loss experienced. It is caused by damaged nerve ends on the hairs in the cochlea. People with high frequency hearing loss cannot hear high frequency sounds such as ‘s’, ‘f’, ‘sh’, ‘ch’, ‘t’, and ‘p’ sounds. Since these sounds are some of the most used in the English language, high frequency hearing loss immensely inhibits communication.

Individuals with high frequency hearing loss tend to rely on hearing aids, which amplify sounds. However, the hearing loss cannot be fixed with amplification of these high frequency consonants because the person simply cannot hear in that frequency range, the volume does not make a difference. Instead of amplification, these missing consonants can be communicated by sensory substitution. In other words, a sense other than hearing can be used to send the auditory information to the brain. The goal is to design and develop an auditory substitution device that through the use of vibro-tactile stimulation can substitute for regional frequency hearing loss. Individual vibrators will represent certain frequency ranges, and when the user feels the specific vibration attributed to certain frequency range, the user will be able to identify the sound.

After using the device for an extended period of time, the user will no longer have to concentrate on the vibrations but will be able to “hear” the high frequency sounds. Due to the plasticity of the brain, the brain will interpret the vibrations as sounds and fill in the gaps for the user, and communication will be restored.

Client Requirements:

- The device will substitute for high frequency hearing loss to the extent of helping the user in everyday communication.
- The device will use vibro-tactile stimulation.
- The device should be self contained, portable, and discrete.
- Complete a testable prototype for analysis of frequency range and wear-ability.

Design Requirements:

1. Physical and operational characteristics

a. Performance requirements

- It will increase the user’s quality of communication by allowing the user to recognize high frequency consonants and incorporate them into word recognition through vibro-tactile stimulation.
- This device should use the programmable functions of computer software to recognize and separate certain high frequency sounds and communicate them to the vibro-tactile stimulator.

b. Safety

- A current of more than 5 mA should not pass through the device and into the user.
- The device should not heat to over 43° C (110° F) while in use.

c. Accuracy and Reliability

- Be able to pick up and transmit sound that is detected at normal speaking level of 60 dB
- Be able to process and substitute for the consonants T, F, S, Th, Sh, and P when coming from a variety of different vocal tones enough to improve scores on standard speech recognition evaluation tests, Word Intelligibility by Picture Identification (WIPI), sentence level Bamford-Kewal-Bench test (BKB), and PLOTT test for vowel and consonant discrimination.
- Human Hearing Frequency Range: 20 – 20,000 Hz
- Speech Frequency Range: 125 – 8,000 Hz
- High Frequency Hearing Loss: above 1,000 Hz

Sound	Frequency (Hertz)
T	3500
F	4000
S	4000
Th	4000
Sh	2000
P	1500

d. Life in Service

- The transducers should last at least 3 years.
- The sound processing unit, along with its microphone, should last 10 years.
- Adhesive should last at least through an entire day.
- On a single battery charge the device should last approximately 5 days, similar to that of a common hearing aid so they can be charged at the same time.
- Common hearing aid batteries have an output voltage of 1.4 V and have power ratings between 140 and 640 mAh. With daily use of the device being about 14 hours the device should draw from 2 - 10 mA of current from the battery.

e. Operating Environment

- The device will be located near the ear.
- Elements such as wind, rain, sun and sweat should not cause the device to vibrate for non-spoken noises, output dangerous levels of current or distort outgoing signals.
- Eventually test the prototype on human subjects in a lab setting.

f. Ergonomics

- The device should not move during normal physical activity.
- Transducer unit should be hidden by the ear.

- Device should be comfortable to the user.
- The controls of the processing unit should be small enough to keep them discrete yet still be able to be manipulated.
- Attach vibro-tactile device with adhesive that will not cause irritation.
- The location of the transducer should be easily repeatable.

g. Size

- The transducer unit should be no more than 5 cm in length, 1.75 cm wide, and 1.25 cm thick.
- The processing unit should be no more than 10 cm in length, 5 cm wide, and 2 cm thick.

h. Weight

- The weight of the processing unit should be no more than 8 oz.

i. Materials

- Adhesive which holds the transducer unit in place should not irritate skin, leave large amounts of residue, or be painful to remove.
- Soft, durable plastic such as vinyl

j. Aesthetics, Appearance, and Finish

- Unit should be flesh-colored and not overtly noticeable to others.
- Adhesive attachment used for transducer unit should not leave large amounts of residue and should not be painful to remove.

2. Production Characteristics

a. *Quantity*: The device should be able to be produced in mass quantities.

b. *Target Product Cost*: The device should cost between $300 and $500, which is approximately 5-10% of the total cost of a hearing aid.

3. Miscellaneous

a. Standards and Specifications: FDA approval of a class II device. Must follow regulation code 21 CFR 812 and 21 CFR 50 for testing.

b. Customer: Adjustable frequency ranges depending on what the user needs most

c. Patient-related concerns: Device should not cause discomfort and should not be overly noticeable.

d. Competition:

- Tickle Talker
- Tacticon 1600
- Tactaid 7 – http://www.tactaid.com/tactaid71.html

Appendix II: Design Matrices

Speech Analysis	**Frequency**	**Linguistic**
Accuracy (10)	7	8
Ease of Implementation (10)	9	1
Noise Adaptability (5)	2	4
Processing Time (5)	4	2
Cost (5)	5	2
Total	**27**	**17**

Stimulation	**Vibro**	**Electro**
Power Consumption (10)	5	9
Safety (5)	4	4
Ease of Implementation (10)	9	2
Patient Comfort (5)	4	2
Aesthetics (5)	2	4
Total	**24**	**21**