Using Two Channel Communication To Study Selective Auditory Attention Using Air And Bone Conducted Interfaces.

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering

By

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BY KUTBI NURUDDIN KALIYAKUWAWALA ENTITLED Using Two Channel Communication To Study
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The purpose of this study was to evaluate the human capability to use selective auditory attention across the two different hearing pathways, air conduction and bone conduction. Four two channel communication systems were used as a basis for comparison: (1) both channels presented via headphones (left ear and right ear each represent a different channel), (2) two channels presented via loudspeakers placed at $135^\circ$ and $225^\circ$, (3) one channel presented via headphones (both ears) and one channel to bone vibrator (placed at the condyle), and (4) one channel presented via bone vibrator and one channel via loud speakers (placed at $135^\circ$ and $225^\circ$). The SATASK sentence database was used as auditory stimuli. For the four systems chosen, each channel presented a different sentence, in a different voice, simultaneously. Listeners were assigned a target sentence and asked to record various elements of the SATASK sentence for the target presentation.

The results showed that when bone conduction is used as a channel in the communication systems chosen, the speech intelligibility scores were slightly decreased, but the differences were not statistically significant. The only systems where the differences in the scores were significant were the loudspeakers and the system that combined bone conduction and air conduction.
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1

Introduction

The general functionality of the human auditory system is to sense, identify, and understand any auditory stimuli in the environment, as well as assist with localization. In everyday life, information is processed by all human senses. The auditory system can aide the operator in several different ways that the other sensual systems may be limited. It has a number of advantages to over the visual sense. Mainly, the human vision system is limited to a particular field of view. The auditory sense is omni-directional meaning that humans can hear from all directions and there are no such limits for auditory means of communication.

As with all other senses, the auditory stimuli that is being sent needs to be done so in a manner in which it can be easily interpreted, or else it is considered useless. Auditory information may be audible but this does not necessarily make it intelligible (easily understood). On the other hand for materials to intelligible, they must be audible. For example, in military operation, effective auditory communication is considered essential to successful missions which requires a high level of intelligibility. In military combat operation communication takes place in the presence of many different noises in the background such as noise from equipment, weapons firing, and overhead aviations. These background sounds could be considered irrelevant based on the task at hand. During such operations the relevant messages must be intelligible in respect to the unwanted stimuli or stimuli that are considered noise. Also, there are many communication systems where the listener needs to pay attention
1.1. RESEARCH OBJECTIVES AND SCOPE

to more than one auditory stream or channel at a time, (for example, those used in teleconferencing, aviation, emergency telephone services, and in military operations). These types of systems have more than one relevant stream of auditory information being presented to the operator. This selective/divided attention situation can reduce the overall performance of the system, which on the surface can look as if the speech signals have low intelligibility. This observation may be misleading. Reduced system performance can be a function of higher cognitive workload. In many environments and situations, we do not respond to some of the auditory stimuli that are present. In these instances, selective attention is in use. Here, the most relevant information dominates the irrelevant information for further processing. The presence of the irrelevant information can reduce human performance with the system.

In traditional communication systems, air conducted interfaces with earphones or loudspeakers are utilized. Recently, the military has been interested in systems that utilize bone conducted technology. The problem with earphones is that they occlude the ear and isolate the listener from environmental and ambient sound which is important for situation awareness. Communication with loudspeakers is not appropriate for most military scenarios because of issues with privacy. Thus, bone conduction has become an attractive option for military communication systems. Communication through bone conduction is in today’s focus because it is light weight, can be easily placed under the helmet, it does not occlude the ear, and also because of the latency it provides to reveal the properties of the inner ear as it excludes the outer and middle ear in transmitting sound to the inner ear. Chapter 2 provides more information about how we hear via bone conduction.

1.1 Research Objectives and Scope

This research uses four different two channel communication systems to test the human capability to use auditory selective attention when the competing sources of information come from a different auditory pathway. The objective of this study is to find out the possibility of combining air with bone conduction technology in order
to utilize the advantages of both. Bone conducted communication does not occlude the ear, thus users are able to maintain situation awareness. The technology however has not matured to the point where it provides similar speech intelligibility as with air conducted technologies.

If we can prove that you do not lose any performance abilities when a bone conducted interface is implemented, then we can proceed with a multi mode, two channel communication system. This would be useful especially in military applications where soldiers attend to multiple sources of auditory information at once, but currently with both ears covered.

1.2 **Key Research Questions**

In an attempt to find out if performance on auditory selection tasks is degraded when we introduce one auditory channel as bone conduction following questions must be answered.

1. Are there any differences in selective auditory attention performance for the two channel systems that are more traditional and those that introduce bone conduction as a channel?

2. Does performance increase or decrease when one channel is presented via Bone conduction?

The following section will provide a brief overview and importance of above two research questions.

1.3 **Importance of Research Questions**

1. The two channel systems chosen represent both traditional forms of communication systems (air conducted interfaces) as well as a potentially new communication system that utilizes both the bone and air conducted interfaces. For communication systems that utilize more than one channel it would be useful to have one
channel presented via bone conduction. This supports the situation awareness of the user, but the system will still have the intelligibility criterion of air conduction. This multi-modal type of interface draws on the advantages of both hearing pathways. The only problem is that there is a need to understand the human capability to use selective attention across these two hearing pathways. For this reason, the research here was designed to compare traditional communication systems (headphone, loudspeakers) with those that utilize bone conduction technology. The purpose is to evaluate if the system that combines bone and air conduction degrades performance on the selective attention task.

2. This is important to know because it will inform potential communication systems. If it is known that a system that uses bone conduction has higher performance scores, this may imply that bone conduction can enhance overall communication system performance. In addition, this can inform information allocation i.e. which information to be delivered via air mode and which information via bone conduction mode in air and bone interface communication system. If the results show that the performance on the systems that use bone conduction is higher, with further research, this could lend itself to the theory that the most relevant information should be presented via bone. Obviously, it is the desire that the overall performance is enhanced or increased with the use of bone conduction (at least the same or similar). If this is not the case, there is not as much potential to move forward with a communication system that utilizes both bone and air conduction.

1.4 Organization of the Thesis

This research in the next sections will provide an overview of human hearing including the two different hearing pathways; air conduction and bone conduction (Chapter 2). This is followed by a brief discussion on auditory attention and its theoretical backgrounds (Chapter 3). The final chapters (4 and 5) describe the research methodology,
data collection, data analysis and final results and conclusions. In addition, a brief description of potential future work is presented in the final chapter.
2

Hearing

The purpose of this chapter is to discuss the two pathways of sound to the inner ear. A brief discussion on the anatomical structures of the ear as well as how sound travels through the auditory mechanism will be given as a background for the discussion of the history and utilization of bone conduction.

2.1 Pathway of Sound

The human ear is comprised of three main parts: the outer ear, the middle ear, and the inner ear (See Figure 2.1). The outer ear is the part of the ear that can be seen outside the head. It includes the pinna and external auditory canal. The middle ear is an air filled cavity that consists of the tympanic membrane and the ossicular chain (malleus, incus, and stapes; the three smallest bones in the human body). The inner ear is a fluid filled cavity that houses the organ of corti, cochlea and the basilar membrane. Organ of corti contains the sensory cells which transmit the auditory signal to the brain via cochlea.

For typical sound transmission, all three parts of the human ear are involved in the process. The function of outer ear is to collects sound energy from the environment and to divert the sound waves towards tympanic membrane. Once the sound waves pass through the outer ear, the sound pressure causes the tympanic membrane to vibrate. At this point, the sound energy is transformed to mechanical energy. As the tympanic membrane vibrates, this causes the ossicular chain to move. The foot
plate of the stapes rest on the oval window which attaches to the inner ear. The ossicular chain and the tympanic membrane vibrate in synchrony and transport the sound energy to the cochlea of the inner ear. The basilar membrane is stimulated by the energy which activates the sensory cells (hair cells of the Organ of Corti). The sensory cells generate the nerve impulse, which electrically stimulates the auditory nerve. This electrically stimulated wave hits the auditory cortex which denotes the stimulus is heard at the human brain.

The pathway to the inner ear that was described in the previous paragraph is an air conducted pathway. It is how we listen naturally. Most of the communication systems currently in use utilize the air conducted pathway with the use of either earphones or loudspeakers as a sound source. The technology for air conducted communication systems is very mature and the speech intelligibility of these systems can be very high in many different environments.
2.2 Bone Conduction

Generally bone conduction is the transmission of sound waves to the inner ear through vibration of the bones of the jaw and skull, bypassing the outer and middle ear. The pathway of sound through the human ear starts from the outer ear and then passes through the middle ear before reaching the inner ear, from auditory nerve it is sent to the brain for processing. In mid 18th century it was found that sound could be passed through solid materials. This led to the conclusions that there had to be more than one pathway of sound transmission to the inner ear. In the middle of the 19th century there were two basic theories. One school of thought was that sound could pass directly to the inner ear by vibrating the middle ear walls. The second theory was based on the utilization of the osseous route. Here, it was believed that sound could be passed to the inner ear by vibrating the human skull. This became known as osseotympanic route (Tonndorf, 1968). Later, it was proven that sound can be passed to the inner ear by vibrating the osseous region with a bone conduction vibrator (Stenfelt et al., 2001). This was a first step in the direction of bone conduction becoming an official mode of communication. Since then, research has been initiated to understand the phenomenon behind the bone conduction mechanism and its pathway.

The technical portion of a bone conducted communication system is a small electromechanical transmitter known as a bone conduction vibrator. There are several factors that influence the effectiveness and reliability of bone conduction measurements including the type of bone vibrator, the amount of force applied by the vibrator to the skull, and where the vibrator is placed on the skull. It should be placed on the thinnest bony area of the jaw or skull. The issue is that the thinnest bony area varies from person to person human (Studebaker, 1962). The human skull contains different mechanical parts where the bone vibrator can be placed, but in the scheme of a communication system, all possible locations are not feasible. The listener’s ability of hearing and understanding the speech material rely upon the placement of the bone conduction vibrator. There have been several studies to investigate the placement of
2.3. UTILIZATION OF BONE CONDUCTION

Bone conduction vibrators. Most research in this area looks at hearing thresholds for the different locations of the skull. A lower the threshold, indicates that the location may be a better choice for the placement of the bone conduction vibrator. Watson evaluated hearing thresholds determined with bone conduction at the following locations: upper front teeth, mastoid, and the center of the forehead. His results showed that the thresholds found at the upper teeth location were 7 dB less than those on the mastoid and 10 dB more sensitive than the thresholds at forehead (Watson, 1938). Though it is found that the center of forehead location results in less sensitivity if we place the bone vibrator at forehead, the forehead location would be preferred over the mastoid for bone conduction vibrator placement because it is relatively easier to position the vibrator there, there is an equal distribution of the audio stimuli to both of the ears, a uniform structure of the frontal bone, this position is far enough from the ear to assure that stimuli is heard by only bone conduction and no air conduction is involved (Watson, 1938; Studebaker, 1962; Weston et al., 1967). Though it is far from the ear and hearing by air conduction is thought to be negligible, at higher frequencies, hearing level thresholds are better when the bone vibrator is placed on forehead than mastoid because of low resistivity to the vibrator at forehead site. At lower frequency hearing threshold is better when the vibrator is placed at mastoid than on the forehead (Kelly et al., 1937).

McBride, et al (2005) investigated 11 different locations for bone conduction vibrator placement. The results showed the condyle as the best location among those tested. The second best location was the jaw angle followed by the vertex (top of the head). The feasibility of placing a vibrator on the jaw angle is somewhat low because as a person talks, it will shift in position.

2.3 Utilization of Bone Conduction

Over time, bone conduction has proven to have several utilities including testing various forms and levels of hearing impairment, hearing aids, and also in some military operations. Since 1920 bone conduction has been used to test the hearing level of
2.3. **UTILIZATION OF BONE CONDUCTION**

It is used by audiologists to determine whether the hearing loss is due to conductive or sensorineural impairment. Here, if an air conduction hearing threshold suggests hearing loss and bone conduction threshold suggests normal hearing range then it is inferred that the hearing loss is due to the outer or middle ear disorder.

Since 1970, nearly 15,000 hearing impaired patients have been implanted by Osseointegrated bone conduction hearing aid (Janas, 2004). Bone conduction hearing aids are a great benefit to those who suffer from outer and middle ear malfunctions. Bone Anchored Hearing Aids (BAHA) is the surgical implant system that allows the hearing impaired to listen by stimulating the inner ear with the bone conducted hearing aid. The pictorial representation of BAHA System is as shown in figure 2.2. It is useful for those who suffer from chronic outer and middle ear disorders and has been in use since 1977. It has three stages of implementation (1) titanium implant which is implanted behind the pinna inside the temporal bone, (2) external projecting part, and (3) the sound processor.

![Figure 2.2: BAHA system (Honigblum, 2008)](image)

In addition, bone conduction has recently been used in cell phones and mp3 players.
According to the Ryan Watson (the Sanyo spokesperson) one can hear clearly on the cell phone in noisy environment with the bone conduction, as bone conduction goes directly to the inner ear excluding the air conduction function (Weir, 2004). It is also used in mp3 players that can be used under water. For this application, the bone conduction transmitter is placed on the cheek bone and sound is transmitted from here (cheek bone) to the inner ear (Janas, 2004).
3

Auditory Attention

Attention is the cognitive process where the listener concentrates on one particular aspect of their environment while ignoring others. Study on attention started back in the 1800’s with William James (1890) who looked at self inspection of the human thoughts and their perception. There are so many different things going on around us and typically, we select only certain stimuli to focus on. How this is done, is very difficult to explain, and the explanations rely on the psychological functioning of human brain. Research on attention is concerned with selective processing of incoming sensory information.

From an auditory sense, speech that is heard may not always be intelligible. For example, it is common for people to complain that speech is not understandable when there is background noise present; such as birds singing, computer noise, cars, various forms of machinery, and other people speaking at the same time. There is a mental processing limitation, thus, it is not possible for the human to fully process all the different sound stimuli simultaneously. To get the relevant message from the various auditory stimuli, it is necessary to filter them before reaching the brain. The process of filtering auditory stimuli is called selective listening. The performance of the auditory system depends on how sounds interact and interfere with each other, as well as the sound’s perceptibility to the listener (Shinn-Cunningham et al., 2004). There are several theories about how the brain filters auditory stimuli.

According to Broadbent (1958) when multiple stimuli are presented to a listener,
early filtering process takes place as a part of information processing. Theory states that only the target auditory stimulus, or those with which the listener is biased, can pass through the filter for further analysis by the central nervous system while all others are excluded at the filter stage. At the end attended stimulus reach a stage of Dictionary unit (a structure of nodes in the human brain) where the process of semantic meaning analysis is done. The stimulus is tested for its relevancy content. This is known as early filter or early selection theory. Figure 3.1 shows the graphical representation of the early filter theory proposed by Broadbent.

![Figure 3.1: Early filter theory flow diagram](image)

This theory was the first attempt at understanding auditory selective attention. According to this theory information is filtered out at an early stage before processing. The idea was that this early filtering would prevent the human auditory system from becoming overloaded. Here, stimuli are filtered based on their physical characteristics such as the location of the sound source and difference in pitch of the various stimuli. Later on this theory was challenged by Treisman (1960). He found that when the name of the subject is detected in the unattended channel attention is diverted to the unattended channel. This finding was similar to the well documented cocktail party effect. It has been documented that some words such as a person own name has a lower hearing threshold (Moray, 1959). This is one common explanation of the cocktail party effect.

Later Treisman challenged the early filter theory. Treisman (1960) introduced his attenuator theory. Instead of blocking, as was envisaged in the early filter the-
ory, Treisman proposed that the unattended stimuli are attenuated as graphically presented in Figure 3.2.

![Figure 3.2: Attenuating filter theory flow diagram](image)

This theory states that the unattended stimuli are passed on to the central auditory system for processing as well, but in a weakened version. It is difficult to extract the meaning and identity of the weaken stimulus except for those who has lower threshold for identification. The attenuation of the unattended channel depends on the physical characteristics of the words such as location, quality of voice, and its contents. Not all but only few words which have lower threshold activates lexical units in memory.

The Late filter theory was proposed by Deutsch and Deutsch (1963) and refined by Norman (1968). This theory goes one step beyond the physical characteristics and filters based on more complex psychological properties such as meaning analysis of the speech stimuli. According to this theory all auditory stimuli are processed simultaneously but response is given only to the relevant auditory channel. The response depends on the meaning of the message played in the channel. The filter will be activated after the meaning is analyzed. Implication of this theory leads to the concept of auditory divided attention task. Figure 3.3 represents pictorial view of how late selection theory works.

Broadbent also proposed that computer technology dominates the human due to higher processing limit of computers than human central auditory system. Two or more than two auditory channels at a same time decrease the intelligibility of the system which is affected by so many different factors. One of the contributing factors
is location of two different speakers. Relevant message is omitted or misheard when the irrelevant message is more analogous to the relevant message (Poulton, 1953). The model prepared by Broadbent (1958) suggests that the selection of a message from multi channel speech communication is done by a filter that is present in the central stage of reception and response. If one is not sure about the relevant message and in which channel it is going to be delivered then selective filter in advance is of no use. Broadbent’s stimulus filter theory has given a search light in the area of selective attention, this theory purport that attention is diverted to the relevant stimulus ignoring the irrelevant stimulus (Hagen et al., 1973). According to Hagen and Hale, selective attention that differentiates a relevant stimulus from irrelevant a stimulus is thought to be a two-stage process. Stage one consists of separation of relevant aspects of stimulus from irrelevant aspects of stimulus and stage two consist of maintaining attention on that particular relevant stimulus (Hagen et al., 1973).

The process of organizing sound into its elements with respect to their individual source from the mixture of sound is called auditory scene analysis (ASA) (Bregman, 1990). As humans, we have the ability to select a particular speech that is important to us among the cacophony of others. This phenomenon of hearing selectively is known as cocktail party effect. For example, if you are at a party listening to one person and suddenly somebody calls your name from another room, which draws your
attention. This happens because a person’s own name can have a higher priority in terms of intelligibility (Cherry, 1953; Moray, 1959; Wood & Cowan, 1995). A study conducted in a well controlled room on people who were in deep sleep showed that the participants were able to listen selectively and recall someone calling their name (Oswald et al., 1960). Also other results from experiments conducted on selective auditory attention show that selective listening depends on its common characteristics, such as its frequency range (Egan et al., 1954) and spatial location of the stimuli (Hirsh, 1950; Poulton, 1953; Webster et al., 1954).

There are so many operations going on in real life where listeners have to listen either selectively or divided. In the past, a number of studies have been conducted to find out the performance of selective attention in various environments using bone conduction, air conduction, and free field sound sources. During the 1950’s the air traffic controllers faced the problem of listening to messages from multiple pilots over the loudspeakers. Simultaneous messages from different pilots over the single loudspeaker made the hearing task extremely difficult for the air traffic controller (Kantowitz et al., 1983). Since then and today we are on the verge of increasing interaction between psychology and neuroscience. Research to better understand the attention phenomena and to explain the psychological and neurological processes behind it continues.

3.1 Selective Attention

Operationally, selective attention is defined as the recall of information that is relevant to the given task from other presented irrelevant information (Hallahan et al., 1978). It is the ability of the human to attend the stimulus that has relevant information while ignoring the irrelevant stimulus. The phenomena that make certain stimuli more salient than others are physical differences such as differences in their source location, diotic / dichotic listening, and voice differences with respect to gender (high pitch female voice or low pitch male voice). All of these factors will help to differentiate, and select the relevant stimulus among present stimuli.
3.1. SELECTIVE ATTENTION

Shinn-Cunningham (2004) found in the study of selective and divided attention at varying target to masker energy ratio that spatial separation of two or more than two channels improves the effectiveness of selective listening, if the listener has to respond to only particular channel among all of the rest. But if the listener is unaware about the channel to be focused on, then the spatial separation will not aid into the selective attention performance (Shinn-Cunningham et al., 2004). The listener reported more correctly when the target stimulus is presented from the front direction than side of the listener i.e. at 0° in the task of listening selectively where the target is randomized to any of the two channels (Shinn-Cunningham et al., 2004).

Various experiments were conducted to increase the performance of selective listening by selecting different cues such as frequency, location and combination of both, and varying its difference. Frequency and combination of both frequency and location are much more effective in selecting important message from the played sentences if the separation frequency of high rate tone is more than 1 octave (Woods et al., 2001). If time difference between the two stimuli is more than 2 sec than location cues plays an important role. The results of this study suggested that frequency plays a same role in auditory selective attention as spatial separation does in visual attention.

More difficult task in listening selectively is the identification of relevant message from two or more irrelevant messages (Treisman, 1964). It is easier for the listener to reject two irrelevant messages when it is played to the one channel than to two different channels (Treisman, 1964). Two irrelevant messages do not reduce intelligibility if played in the same channel but reduces when it is played in two different channels. Three channels system overloads the system at certain point, reduces the shadowing effects that may be thought of in separating the different channels, filtering the irrelevant message followed by understanding and gathering the relevant message information. Also, Lisa J Stifelman (1994) has taken two tasks in her studies: (1) listening comprehensively and (2) monitor the target in all audio streams and she found that performance decreases as number of audio channels increases. She concluded that the human has the ability to focus the attention on one audio stream,
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while over hearing the targeted information in the irrelevant audio stream. Messages which are received by the ear are thought to be stored in short term memory storage of nervous system and then it is withdrawn from the storage if recall immediately or it may goes to the long term memory. Norman (1976) found that the ignored message goes into short term memory i.e. between 0 to 5 seconds, so if the listener is interrupted during this period message can be recall.

Difference in any of the cues phase (location), intensity and frequency will make the relevant message more intelligible to the listener which is found from the previous experiments done by Hirsh (1950). Licklider (1948) on masking of pure tones and speech found that speech is more intelligible when they come from different locations. Cherry (1953) in his diotic and dichotic studies, found that the human has an ability to shadow the primary message while ignoring the other irrelevant audio stream, irrespective of the language changed. Later on Treisman (1964) found that efficiency of ignoring irrelevant audio stream increases when it is played diotically. Norman was not satisfied with Cherry’s findings. He said that a subject can listen and remember the words played in the ignored stream which depends on the stress induced by the shadowing the audio stream, time to recall the ignored message from the audio stream, and time period of message played. Norman (1976) suggests that there is also a chance that message which is shadowed can be ignored.

Listening comprehensively rather than shadowing will increase the chance of identifying the relevant information even though it is played in ignored channel. Auditory monitoring is increased where as recognition score decreases when subject listen comprehensively rather than shadowing i.e. subjects face difficulties in understanding the meaning of the presented auditory stimuli. Separation of the audio channels increases the speech perception by making it easily identifiable with respect to the source audio channel; the effect is known as spatial unmasking (Cherry, 1953). From the performed experiment dichotically Treisman and Geffen (1967) found that percentage of targeted word heard from primary audio signal is more than the percentage which is heard from rejected audio signal. Lawson did a similar experiment as Treisman but with
3.2. FACTORS AFFECTING PERFORMANCE OF SELECTIVE ATTENTION

3.2 Factors Affecting Performance of Selective Attention

There are a number of factors that can affect human performance on selective attention tasks. For instance, differences in various cues such as frequency, location, and intensity all can affect the performance on selective listening tasks. Also, as discussed previously, the number of channels of information being presented can affect performance. As the number of input channels increases, the performance decreases (Treisman, 1964). Treisman (1964) also discussed how the type of information, degree of synchrony between the channels, length of the message and the degree of the difference between interaural intensity also affect the efficiency of selective listening as well. Also, according to Spieth et al. (1954), selective attention improves when the two voices in which the speech is presented differ in terms of pitch. Varying the source location from trial to trial of a particular channel will reduce the effectiveness of listening selectively but will not affect the divided attention efficiency much (Shinn-Cunningham et al., 2004).

Selective attention studies can be done with different modalities such as visual, auditory or sometimes combining both. For this research only one mode of commu-
3.3 Divided Attention

The process by which one can allocate his/her attention to two or more messages and recall all of them simultaneously is known as divided attention. Recalling two or more message at a same time will double up the processing requirement in comparison with selective attention. More messages are omitted if the listener has told to hear two or more than two channels simultaneously and remember all of the messages conveyed to the listener (Poulton, 1953). In divided attention task knowledge of relevant stimulus location does not help much as the listener has to listen to all stimuli. If the listener has to divide his/her attention to all of the sound stimuli then it is easier to listen to the louder stimulus then the quiet one (Shinn-Cunningham et al., 2004). There are cases where the effectiveness of divided attention improves in which listeners focus their attention to the quiet stimuli, recall and report it. They can always recall and report the louder stimuli later. The location awareness of the quiet sound stimuli will aid in the performance of divided attention task.
Methodology and Experimental Design

There are a number of communication systems available to the military. We are working towards proposing a new system that can potentially incorporate both bone and air conducted interfaces into one communication system. Prior to developing a prototype of any kind we need to inform the basis for the design. There is a need to understand the human capability to use selective attention across the two pathways of hearing: air conduction and bone conduction. The purpose of this research study is to evaluate the human ability to perform a selective auditory attention task using a two-channel communication system when the competing source of information comes from a different auditory pathway. The results will inform future research into the potential of a new communication system.

The hypothesis here is that for two-channel communication systems, when a bone conducted mechanism is employed as one channel, the speech intelligibility of that system will be at least the same as a system where all channels are air conducted. If this is observed, the potential for a communication system with both air and bone conducted interfaces increases.
4.1 Participants

After approval from the Institutional Review Board of Wright State University, the data was collected as outlined in following paragraphs. A total of 20 normal hearing listeners between the ages of 20 and 26 years participated in the study. Normal hearing for this test was considered to be those having hearing thresholds less than or equal to 20dBHL at frequencies between 250 Hz and 8000 Hz. Only those meeting this criterion were able to participate. All participants were recruited from the student body population of Wright State University. There were (16) males and (04) females who participated in the effort.

4.2 Instrumentation and Software

The instrumentation used for this research were a personal computer with CD ROM drive, a pair of TDH-39 P headphone, two loud speakers placed at the 4 feet from the left and right ear, acoustically treated sound proof audiometric booth, a Radioear B-71 bone vibrator with its standard headband, and an equinox AC440 two channel clinical audiometer to test the hearing level of the participants. Soundforge-9 software was used to create and deliver the speech files.

4.3 Stimulus Materials

The SATASK materials, developed by the United States Army Research Laboratory Human Research and Engineering Directorate (USARL-HRED) are a database of speech samples developed for measuring speech intelligibility in multi-channel communication systems. The testing materials consist of spoken sentences in the following arrangement: “(NAME), write the number (NUMBER) on the (COLOR) (OBJECT)”. Table 4.1 shows the words used for the sentences. These materials were chosen for this research because it represents basic communication and so the results can be generalized for day to day conversations.
Table 4.1: SATASK wordlist

<table>
<thead>
<tr>
<th>Name</th>
<th>Number</th>
<th>Color</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mike</td>
<td>1</td>
<td>Black</td>
<td>Ball</td>
</tr>
<tr>
<td>Nate</td>
<td>2</td>
<td>Blue</td>
<td>Cup</td>
</tr>
<tr>
<td>Troy</td>
<td>3</td>
<td>Brown</td>
<td>Fork</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Gray</td>
<td>Key</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Green</td>
<td>Kite</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Pink</td>
<td>Spoon</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Red</td>
<td>Square</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>White</td>
<td>Stair</td>
</tr>
</tbody>
</table>

Typically, listeners will be given a name from Table 4.1 to identify as a target sentence and all other presentation will be considered masker sentences. Listeners will record all or parts of the target sentence. For example, the target name is Mike. If one of the presentations is “Mike, write the number five on the blue cup”, and the listener is asked to report all parts of the sentence, the correct response would be “five”, “blue”, and “cup”.

4.4 Communication Systems

Four two-channel systems were used to present the SATASK materials. Each channel presented a different sentence in a different voice. The systems used are listed below. From this point, the systems will be spoken of in terms of their system number as associated below.

1. **System 1**

   Both channels presented under headphones. One channel was presented in the left ear and one channel was presented in the right ear.

2. **System 2**

   Both channels presented via the loud speakers which are placed at $135^\circ$ and $225^\circ$. 
4.5 Procedure and Methodology

Each speaker represents a different channel.

3. System 3

Channels presented via headphones and one bone vibrator. One channel is presented to bone vibrator that is placed at the condyle (see Figure 4.1), and channel two is presented to the both ears via headphones.

![Bone vibrator on Condyle]

Figure 4.1: Placement of bone vibrator on condyle bone (R & J Public Relations, 2005)

4. System 4

Channels presented via bone vibrator and loud speakers. One channel was presented to the bone vibrator which is placed at the condyle bone (see Figure 4.1), and channel two was presented to the two loud speakers, which are placed at 135° and 225°.

4.5 Procedure and Methodology

Participants were seated at a small table in the center of an audiometric booth facing the computer monitor. The two loud speakers were placed at the back side of the listener, spatially separated 45° one to the left and other to the right of the listener. For all tests, listeners were wearing one of the communication systems specified above.

All participants were asked to record the number, color, and object from the target sentence for 50 sentence presentations. The target to masker ratio between target
4.6. EXPERIMENTAL DESIGN

and masker sentence was 0dB. Both target and masker sentences were played at 0 ITD (Interaural Time Difference), thus the presentations were simultaneous between channels. Each participant completed 50 sentence presentations using all four systems mentioned above to complete the study.

All of the systems were verified for similar perceptual sound intensity. Thus, all presentations whether they came from the loudspeakers, bone vibrator, or headphones perceptually sounded the same in terms of loudness or intensity. The final sounds from the loudspeaker were around 60dB which is close to the level of normal conversation. When measuring the output from the loudspeaker, the sound level meter was placed where the listener was going to be seated.

4.6 Experimental Design

The research design was a within subjects design, as all participants completed trials with all four communication systems. There was one independent variable, communication system (4 levels) and one dependent variable, word recognition scores. The different communication systems were counterbalanced using the Latin Square shown below in Table 4.2 was generated to avoid any effects of learning or fatigue. The Table was repeated for every set of four participants. All data was transformed using the arcsine transform and analyzed using a single factor analysis of variance, and Tukey analysis. The results are discussed in the following chapter.

<table>
<thead>
<tr>
<th></th>
<th>System1</th>
<th>System2</th>
<th>System3</th>
<th>System4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listener1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Listener2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Listener3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Listener4</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.2: Latin square
5
Data Analysis and Conclusions

5.1 Data Analysis

Performance data was collected on a total of twenty listeners. The analysis begins with exploratory analysis on the means. Next, Comparisons were done among the four different communication systems with respect to each of the different parts of the SATASK sentences (number, color, and object) as well as the sentence as a whole (either everything is correct or not). A single factor analysis of variance (ANOVA) was used for this part of the analysis. Tukey tests were completed when the ANOVA found differences between the scores between the systems. Arcsine transformation of all percentage scores (number, color, object, and totally correct sentence) was done prior to the statistical analysis. This transformation consists of taking the arcsine root of the response variable value which stabilizes the variance and produces a variable with an approximate normal distribution (Studebaker, 1985). Generally it is applied to transform the data which are in the form of either proportion or percentage.

5.2 Exploratory Analysis

The mean scores for each of the communication systems are shown in the table 5.1 below. Figure 5.1 is a graphical representation of the mean data for each system. Each system provided similar percentage correct scores (within 10%) with system 2 having slightly higher scores for the different parts of the sentences as well as the
5.3. STATISTICAL ANALYSIS

Further analysis is conducted with single factor ANOVA’s to find out statistical significance between the participants scores on the different systems. One way within subject ANOVA’s were done for each of the different parts of the sentence and the entire sentence being correct.

<table>
<thead>
<tr>
<th>System</th>
<th>System Description</th>
<th>Number</th>
<th>Color</th>
<th>Object</th>
<th>Sentence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Both channels under headphones</td>
<td>89.30</td>
<td>85.10</td>
<td>89.20</td>
<td>80.00</td>
</tr>
<tr>
<td>2</td>
<td>Both channels under loudspeakers</td>
<td>93.40</td>
<td>89.70</td>
<td>93.90</td>
<td>85.90</td>
</tr>
<tr>
<td>3</td>
<td>Bone vibrator &amp; headphones</td>
<td>84.40</td>
<td>81.25</td>
<td>88.90</td>
<td>72.20</td>
</tr>
<tr>
<td>4</td>
<td>Bone vibrator &amp; loudspeakers</td>
<td>86.80</td>
<td>85.40</td>
<td>91.90</td>
<td>79.90</td>
</tr>
</tbody>
</table>

Table 5.1: Mean percentage score correct for each communication system

Figure 5.1: Mean percentage correct scores per communication system

5.3 Statistical Analysis

Further analysis is conducted with single factor ANOVA’s to find out statistical significance between the participants scores on the different systems. One way within subject ANOVA’s were done for each of the different parts of the sentence and the entire sentence being correct.
5.3. **STATISTICAL ANALYSIS**

The results from this analysis are shown in Table 5.2. For the number (F = 7.3815, p = 0.0003), color (F = 4.6305, p = 0.0058), and entire sentence (F = 7.3482, p = 0.0003), there is sufficient evidence to conclude that there are differences between the scores on the different communication systems. Thus, there is at least one system on which the performance is significantly different from the other systems for these conditions. There were no significant differences for the object portion of the sentence (F = 1.3850, p = 0.2566) among all four communication systems. Since this is the last word in the sentence, it could be a function of a learning effect for the trials.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NUMBER</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems</td>
<td>3</td>
<td>1855.298</td>
<td>618.433</td>
<td>7.3815</td>
<td>0.0003</td>
</tr>
<tr>
<td>Listeners</td>
<td>19</td>
<td>4703.154</td>
<td>247.534</td>
<td>2.9545</td>
<td>0.0008</td>
</tr>
<tr>
<td>Error</td>
<td>57</td>
<td>4775.519</td>
<td>83.781</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>79</td>
<td>11333.971</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COLOR</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems</td>
<td>3</td>
<td>1414.811</td>
<td>471.604</td>
<td>4.6305</td>
<td>0.0058</td>
</tr>
<tr>
<td>Listeners</td>
<td>19</td>
<td>3208.474</td>
<td>168.867</td>
<td>1.6580</td>
<td>0.0729</td>
</tr>
<tr>
<td>Error</td>
<td>57</td>
<td>5805.277</td>
<td>101.847</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>79</td>
<td>10428.562</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>OBJECT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems</td>
<td>3</td>
<td>488.2010</td>
<td>162.734</td>
<td>1.3850</td>
<td>0.2566</td>
</tr>
<tr>
<td>Listeners</td>
<td>19</td>
<td>2618.4141</td>
<td>137.811</td>
<td>1.1729</td>
<td>0.3188</td>
</tr>
<tr>
<td>Error</td>
<td>57</td>
<td>6697.3453</td>
<td>117.497</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>79</td>
<td>9803.9604</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENTIRE SENTENCE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems</td>
<td>3</td>
<td>2546.194</td>
<td>848.731</td>
<td>7.3482</td>
<td>0.0003</td>
</tr>
<tr>
<td>Listeners</td>
<td>19</td>
<td>4612.591</td>
<td>242.768</td>
<td>2.1019</td>
<td>0.0162</td>
</tr>
<tr>
<td>Error</td>
<td>57</td>
<td>6583.574</td>
<td>115.501</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>79</td>
<td>13742.359</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: One way ANOVA results for the different parts of the SATASK sentence and the entire sentence
The ANOVA shows significant differences between the scores on the four systems for the color, number, and entire sentence. In order to investigate where the differences are among the four systems, Tukey-Kramer HSD tests were completed. Figure’s 5.2 - 5.4 show the results from these pair-wise comparisons. The results show that for the number, color, and entire sentence, system 2 (both channels coming from loudspeaker) is significantly different from system 3 (one signal going to both ears via headphone and one signal going to the bone vibrator). In addition to this for the number, system 2 (both channels coming from loudspeaker) is significantly different from system 4 (one signal going to bone vibrator and one channel coming from both loudspeakers).

<table>
<thead>
<tr>
<th>Means Comparisons</th>
<th>Comparisons for all pairs using Tukey-Kramer HSD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>q* Alpha</td>
</tr>
<tr>
<td></td>
<td>2.84847 0.05</td>
</tr>
<tr>
<td>Diff=Mean[1]-Mean[2]</td>
<td>2  1  4  3</td>
</tr>
<tr>
<td>2</td>
<td>0.000  7.626  8.404  13.479</td>
</tr>
<tr>
<td>1</td>
<td>-7.626  0.000  0.778  5.853</td>
</tr>
<tr>
<td>4</td>
<td>-8.404  -0.778  0.000  5.075</td>
</tr>
<tr>
<td>3</td>
<td>-13.479 -5.853 -5.075  0.000</td>
</tr>
<tr>
<td>Abs(Diff)LSD</td>
<td>2  1  4  3</td>
</tr>
<tr>
<td>2</td>
<td>-7.66021 -0.03471 0.743794 5.818294</td>
</tr>
<tr>
<td>1</td>
<td>-0.03471 -7.66021 6.88171 1.80721</td>
</tr>
<tr>
<td>4</td>
<td>0.743794 -6.88171 -7.66021 -2.58571</td>
</tr>
<tr>
<td>3</td>
<td>5.818294 -1.80721 -2.58571 -7.66021</td>
</tr>
</tbody>
</table>

Positive values show pairs of means that are significantly different.

<table>
<thead>
<tr>
<th>Level</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>A  99.829500</td>
</tr>
<tr>
<td>1</td>
<td>A+B  92.204000</td>
</tr>
<tr>
<td>4</td>
<td>B  81.425500</td>
</tr>
<tr>
<td>3</td>
<td>B  86.351000</td>
</tr>
</tbody>
</table>

Levels not connected by same letter are significantly different.

Figure 5.2: Tukey-Kramer HSD for percentage correct number
### 5.3. STATISTICAL ANALYSIS

#### Figure 5.3: Tukey-Kramer HSD for percentage correct color

<table>
<thead>
<tr>
<th>Level</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>93.161000</td>
</tr>
<tr>
<td>1</td>
<td>87.078000</td>
</tr>
<tr>
<td>4</td>
<td>86.665500</td>
</tr>
<tr>
<td>3</td>
<td>81.282000</td>
</tr>
</tbody>
</table>

Levels not connected by the same letter are significantly different.
5.4 Conclusion

Comparing all four systems with respect to the different parts of the SATASK sentences showed significant differences between systems two and three for the color and number, and significant difference between systems two and four for the number. There were no significant differences in the performance scores for the object portion of the sentence among the four different systems. In terms of the entire sentence being correct, there were significant differences between the performance scores for systems two and three again.

When the system that combines bone conduction and air conduction (system 3) is compared to the system where both channels are under the headphones (system 1),
the differences were not significant. Thus, it can be concluded that performance on selective listening tasks (where a communication system is employed), is not significantly different if we include one channel as a bone conducted interface. The performance for system three (bone conduction and earphones) was slightly lower than the others, but this is in agreement with previous studies where bone conduction was not superior to air conduction.
The efficiency of listening selectively in two-channel auditory communication was evaluated among four different communication systems using the SATASK sentence test. This test is structured in the following format: “NAME” mark the number “NUMBER” on the “COLOR” “OBJECT”. The two-channel systems evaluated were: (1) both channels under headphones, one sentence to the left ear, one sentence to the right ear, (2) Both channels presented via the loud speakers which are placed at 135° and 225°, each loudspeaker presented a different sentence, (3) one channels presented via headphones (both ears) and one channel presented to the bone vibrator, and (4) one channels presented via bone vibrator at the conoyle and one channel presented to both loud speakers. The percentage of correct responses for the number, color, and object, were computed as well as the percentage correct responses for the entire sentence.

The goal of this experiment was to find out the human capabilities to use selective attention to identify information that is presented with competing information coming from a different hearing pathway (air conducted and bone conducted). The purpose was to inform the potential for a communication system that will leverage the advantages of both bone and air conducted interfaces. Air conduction provides good speech intelligibility but bone conduction allows for better situation awareness. A system that combines the two would be beneficial in situations where neither speech intelligibility nor situation awareness can be compromised. The answers to the proposed
6.1 Are there significant differences in performance for the four communication systems evaluated?

The performance of listening selectively was compared among the four different systems with respect to the different parts of the sentence as well as the entire sentence. The ANOVA and Tukey test showed that there were significant differences in the scores for the combined bone and air conduction system and the loudspeakers condition. This is not unexpected as the loudspeaker condition represents the most common and natural way of listening. There were no significant differences between the system that combined the air conduction and bone conduction and the headphones and the system that used the loudspeakers and the bone conduction headset. Thus, statistically, the performance on the combined system was not significantly different from the system where both channels were presented under the headphones (more traditional communication system) or the system where bone conduction and the loudspeakers were used. The conditions where an actual communication system was used all provided scores that were not statistically different. This lends itself to the possibility of a communication system that will combine bone and air conduction as you do not lose any significant performance when one channel is presented via the bone conduction.

6.2 Does performance increase or decrease when one channel is presented via bone conduction?

For all portions of the SATASK sentences, the performance for the system that combined bone and air conduction was slightly lower than the other systems, but from the statistical analysis, these differences were not significant. Since the statistical analysis showed no significant differences between the systems that used only head-
6.3. **THE PRACTICAL IMPLICATIONS OF THESE RESULTS MAY BE SUMMARIZED AS FOLLOWS**

phones, and headphones and bone vibrator, we can conclude that performance is not significantly degraded when bone conduction is added as a channel to present stimuli.

6.3 **The practical implications of these results may be summarized as follows**

The result of percentage correct score of number, color, and totally corrected sentence among four different systems shows that system three (bone vibrator and headphone) has lower percentage correct score among all four systems which suggest that some degree of spatial separation may be required if the individual is listening to two or more different channels. Again the scores were lower but the difference was not significant which lends itself to the potential of a new communication system.

6.4 **Future Work**

Even though bone conduction slightly reduces the performance of selective listening compare to air conduction, this decrease is statistically not significant. The bone conduction mode of communication is in today’s focus as it enhances the situation awareness of the listener. Performance of bone conduction depends on the how sensitive the bone vibrator is. Researchers are working on improving the sensitivity of the current bone conduction vibrators. This work should continue as we progress towards a multi modal communication system.

Future research should also be done to consider which mode of communication (bone or air) the most relevant message should delivered to. For example if the operator is in need of hearing protection, then the most relevant information possibly should be presented to the bone. Other situations and contexts should be defined in which allocation of information should go to the different pathways.

Many communication systems use more than two audio channels at the same time so it is necessary to continue this research with three audio channels to see the affect of multiple channels on efficiency of listening selectively. This might include two
bone conduction vibrators instead of one and three loud speaker instead of two. For example we may use one channel as bone conduction and one channel as air conduction through earphone, where the earphone is placed on one ear and keeping one ear unoccluded which increase the surrounding awareness of the listener. Thus different configurations of communication systems including both bone and air conduction should be investigated.

While selecting the system that consists of bone vibrator, location of the bone vibrator placement should be considered as one of the contributing factor in increasing the performance of selective attention. Here, the bone vibrator was placed on the condyle bone as it is easy to place under helmet and is one of the thinnest bone on the human skull. Experiment may be conducted by placing the bone vibrator on the forehead or other bony locations of the body. Comparison studies can be done by placing bone vibrators at different places on the human skull such as mastoid, forehead and teeth to find out the optimal point of placing the bone vibrator.


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