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Improving the Morse Intercept Operator's Audio Display

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THESIS

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Jesse M. Washburn

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Abstract

This thesis improves the audio display for multiple Morse communications. Factors considered to improve the audio display are frequency of source, volume level of source, and methods of unmasking. The best frequency and volume level of a Morse source is 500 Hz at 70 dB sound pressure level (spl). Two types of masking are researched: frequency masking and expectation driven masking. Experiments showed by amplifying high pitched sources the effects of frequency masking are minimized. Other methods to compensate for frequency masking are 3-D sound and the placement of a source out of phase between the ears. Morse code recognition at 500 Hz is greatest when presented at the N0 Sπ condition. Greatest unmasking for broadband signals occurs at 3-D locations (between 60^o and 90^o) where the largest ITD (interaural time difference) exists. This thesis theorizes and confirms that greatest unmasking of a source tone in 3-D sound corresponds to the spatial location that gives an ITD equal to a 180^o phase shift for that tone. NASA/Ames Research Center has demonstrated that 3-D sound improves the performance of communication personnel who are required to monitor multiple speech communications. This thesis supports that result and further provides 3-D cues for simultaneous Morse sources. Research focuses on improving accuracy and reducing fatigue rather than increasing intelligibility. Fatigue is measured by subjects choice of which presentation option is easier to copy. The criteria for improving cues are minimal fatigue and the highest copy accuracy. The presentation options are 2-channel diotic (all sources in each ear) , monaural (each channel contains a unique source, information of a source is presented to only one ear) , 3-D angles of 0^o, 10^o, 32^o, 45^o, 58^o, 69^o, and 82^o. Experiments considered two and three simultaneous Morse signals. Results from four subjects showed that 3-D sound does not improve accuracy when multiple sources are at equal volume level for the tested signal to interference ratio (SIR). Reduction in fatigue occurs for 3-D sound presentation. These results are specific for Morse sources, but could provide insight for any multiple source audio display.

Improving the Morse Intercept Operator's Audio Display

I. Introduction

1.1 Background

Accurate copy of a Morse code interceptor's target is a necessity in the intelligence field. Accurate copy is often impossible because multiple sources are placed in the operator's ears simultaneously. The current Morse audio presentation leads to sources that temporally overlap and mask each other. Therefore, the operator can not determine what was sent, which target sent what, or misses changes in the source of interest (SOI). Not knowing who sent what, or what was sent makes analyses of such interceptions impossible, and during times of crisis, high level consumers would not be furnished with perishable intelligence. Sources not being copied can not be turned off because a complete picture of the situation must be maintained. Masking effects may be compensated for by using 3-D sound, or by amplifying masked signals.

Accuracy of Morse interceptions is also reduced by high fatigue levels. A Morse interceptor is often called to copy Morse for a full eight hours on rotating shifts. Rotating shift work makes any job relatively difficult compared to a straight shift. Copying Morse code for a full eight hours adds to the level of fatigue. By presenting Morse in a natural manner, using 3-D sound, the fatigue level will drop. With a decreasing fatigue level, accuracy increases.

Presentation of 3-D sound simulates delivery of natural sound. Unlike the eyes, which can only detect light from the space in front of the head, the ears are able to receive sound and localize from the entire space surrounding the head. 3-D sound gives the perception of placing sound in surrounding space. The ears and the brain, the human audio system, work together to process sound. The processing allows a listener to selectively focus on one sound, switch to another sound, and monitor for other important sounds, ultimately tracking multiple sounds. This ability to segregate sound is referred to as the "cocktail party effect." In a cocktail party, a person is able to focus on one conversation out of many. When a person becomes bored with a conversation, the person can easily locate and focus on a different conversation. By presenting sound in 3-D, an improvement in intelligibility over monaural or diotic sound occurs.

To transform the interceptor's current audio presentation to a 3-D audio presentation, auditory cues must be used. Auditory cues allow the brain to determine where a sound is located. The cues that allow for localization are interaural time difference (ITDs), interaural intensity difference (IIDs), and the head related transfer function (HRTF) [23]. The HRTF is a finite impulse response filter. The HRTF modifies the ITDs, and the IIDs to account for the shape of the head [14].

A method to reduce masking of Morse sources in noise is to exploit the equalization cancellation (EC) theory [5]. Ideally, the equalization process transforms the signal received in one ear in a way that the masking signal is the same as received in the other ear. In the C process (cancellation) the masking signal from the one ear is subtracted from the other ear and the masking signal is reduced [5]. The EC model indicates that if a source is presented with an interaural phase difference while noise is kept in phase, unmasking will be accomplished.

Two types of masking reduce Morse recognition: frequency masking and expectation driven masking. In frequency masking, low frequency tones reduce the perceived volume of higher frequency tones [6]. Frequency masking is caused when nerve fibers terminating in the basilar membrane fire due to a stimulating sound. The nerve fibers can no longer carry another message to the brain when stimulated by another sound source [6]. Thus, the other sound source is perceived to have a reduced volume. Frequency masking combined with expectation driven masking may cause missed changes in SOI.

In expectation, driven masking the audio system filters sound based on what it expects to hear [21]. Expectation driven masking allows an intercept operator to focus on a SOI, and mask out multiple sources not of interest (SNOI). The masking could be so effective that the interceptor does not hear a change in the SOI. Thus, the interceptor copies a SNOI instead of the new SOI.

1.2 Problem Statement

This thesis will investigate methods to improve the intercept operator's audio display by reducing masking. Methods considered to reduce masking are 3-D sound, frequency masking, and expectation driven masking. The methods are tested to determine which one best reduces fatigue and allows for highest copy accuracy.

1.3 Research Objectives

This thesis research is to improve the Morse display. Improvements of the Morse audio display could increase accuracy, and reduce fatigue. Accuracy and fatigue are determined for various presentation options for two and three simultaneous sources.

1.4 Assumptions

In this research, it is assumed that there is no noise, or man made interference corrupting the Morse code sources. Further, it is assumed that the head phones used attenuate outside noise below threshold levels.

All Morse code sources are assumed to send at a constant rate of 14 words per minute and that each Morse signal will transmit at a unique constant audio frequency.

1.5 Scope

The research will focus on improving Morse presentation for two and three simultaneous sources. Research will also develop techniques to copy a SOI while monitoring a SNOI. To determine improvements for a Morse presentation, a forced choice experiment design is used. The subject is given two different presentation options. For example, choosing between 3-D or diotic presentation. The subject is then asked which presentation is easiest to copy.

The HRTFs and ITDs used were furnished by the Armstrong Aerospace Medical Research Laboratories (AAMRL).

Masking experiments determine the conditions needed for an operator to detect a change in the source of interest (SOI). The masking experiments determine the effects of frequency, and expectation driven masking.

1.6 Overview of Thesis

Chapter II contains a literature review of the topics that improve audio displays. Chapter III describes the experiments conducted to find improvements for the Morse display. Chapter IV presents the results and discusses how these results affect the interceptor's display. Chapter V presents a summary, recommendations for improving the Morse audio display, recommendations for further research, and a conclusion of this research.

II. Background

2.1 Introduction

Improvements can be made in copying Morse code by considering the human factor issues associated with the Morse audio display. The four components considered for improving the Morse audio display are presentation options, listening levels, frequency of sources and unmasking. Presentation options include monaural, diotic, and 3-D. Diotic sound presents the identical sound to both ears. Monaural presentation presents a sound to one ear only. Copying Morse code at an improper listening level or frequency increases errors. Masking of Morse signals causes incorrect characters to be copied and changes in SOIs to be undetected. Frequency masking and expectation masking are two causes of mistakes in Morse interception. To decrease errors, compensation for masking must be accomplished. To compensate for masking, amplification of masked signals or 3-D sound may be used.

2.2 Morse Code

When copied by a human, Morse code is still considered the most reliable form of communications. Morse code requires the least amount of power and the simplest of transceivers. A human can copy a weak Morse code signal buried in noise, interference, or jamming. The signal to noise ratio (SNR) required for Morse communications is minimal compared to the SNR required for voice, or digital communications. Humans are successful in copying Morse code because of the brain's audio pattern recognition capabilities. The brain's pattern recognition capabilities dwarf those of the best pattern recognition system. Experiments have shown that man requires significantly less SNR compared to electronic Morse decoders [11].

Morse code contains short and long elements. The short elements are symbolized with a dot. The short element is pronounced "dĭ". The long elements are represented by a dash. The long element is pronounced dah. For example, "._" is the symbol for "A". The symbol for "A" is pronounced "di dah". The Morse code symbols for English letters are shown in Table 1.

Table 1. Morse Code

Letter	Symbol	Letter	Symbol	Letter	Symbol
A	·–	J	·–––	S	···
B	–···	K	–·–	T	–
C	–·–·	L	·–··	U	··–
D	–··	M	––	V	···–
E	·	N	–·	W	·––
F	··–·	O	–––	X	–··–
G	––·	P	·––·	Y	–·––
H	····	Q	––·–	Z	––··
I	··	R	·–·		

2.2.1 Timing of Morse Code. The basic unit for time in Morse code is the period. One unit is used for the pause between a di or a dah. A dah is three units. Pause between characters is three units. Seven units are used for the pause between words. The timing is illustrated in Figure 1. The average length of a random-letter groups is 60 units. For example, the word CODEX is 60 units. To send Morse code at 14 words per minute (wpm) keying speed is adjusted until CODEX is sent 14 times in one minute [1]. The above timing is expected only in machine transmitted code. Hand transmitted code will depart significantly from the timing. The idiosyncratic rhythm in the hand makes machine transcription of hand sent code extremely difficult.

2.2.2 Mental Process of Copying Morse Code. In order to improve the Morse audio presentation it is helpful to understand the mental process of copying telegraphy. Cases of aphasia indicate that copying Morse code is different than the mental process to copy speech or pure tones [12]. Two cases have been reported where speech was not affected but an aphasia for Morse code existed [2, 25]. A case for aphasia with speech but not for Morse has also been reported [15]. Cases of aphasia indicate that the center of telegraphy is not the same for speech. Further it has been suggested that those who are musically talented excel at copying Morse code. The suggestion that those who are musically talented are also talented Morse operators may show that Morse processing is similar to musical information processing.

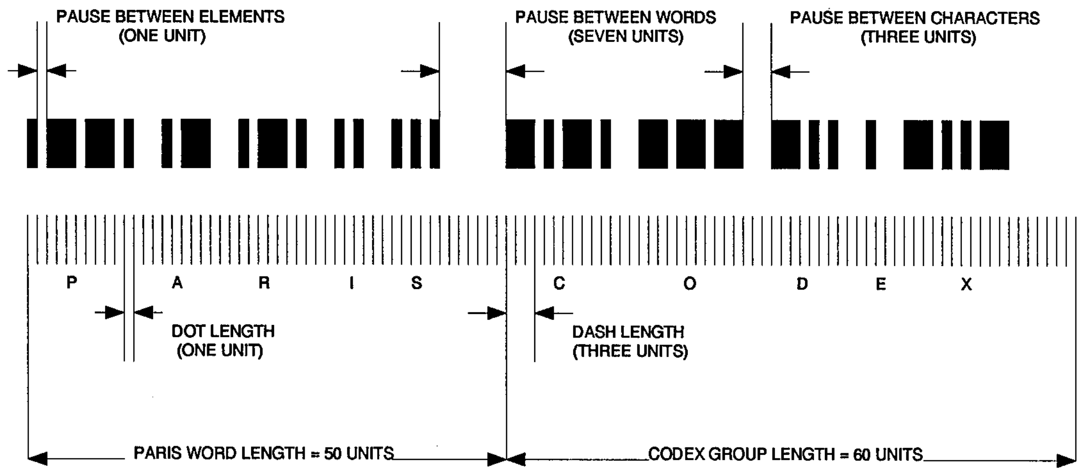

Figure 1. Timing of Morse code elements and spaces. The number of units in CODEX is typical of random-letter groups[1].

Further, research needs to be conducted to determine useful specifics in the mental process of copying Morse code.

2.3 Optimal Frequency and Listening Level

Source frequency and listening level adjustments must be made to increase copy accuracy. Recognition is highest when a source is presented at 500 Hz, with a spl (sound pressure level) of 70 dB [10]. For SNR above -7 dB, the frequency of the Morse source does not effect recognition. Figure 2 shows recognition rates for code presented at 16 wpm as a function of frequency. Figure 3 shows the median recognition values for 11 subjects as a function of spl.

2.4 Masking

In order to identify each Morse source, each source must be given a unique frequency. Unfortunately, the lower frequency source will mask the higher frequency sources. Masking occurs when simultaneous signals reduce the perceived volume of a SOI. Due to reduction in volume, intelligibility is also reduced. In frequency masking, low frequency tones mask high frequency tones [6, 7, 13, 19]. Pure tone masking is measured by a threshold shift. The threshold of a tone is the just detectable power level of that tone, the threshold of a tone is defined as 0 dB spl [16]. When a low tone and a high tone are played simultaneously, the

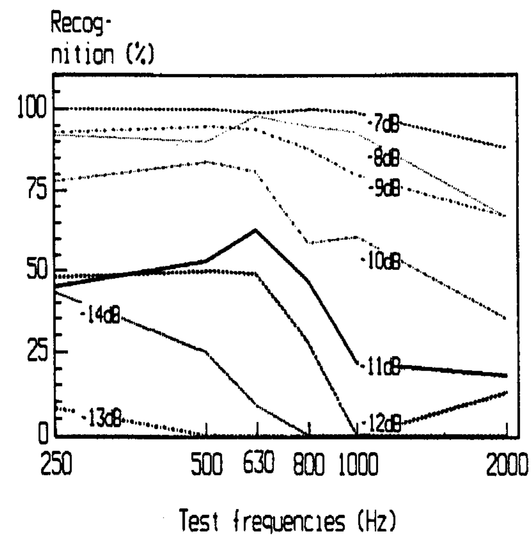

Figure 2. Median value of recognition for all subjects at different tone frequencies, different SNR (-7 to 14 dB), and 16 wpm telegraphy speed [10].

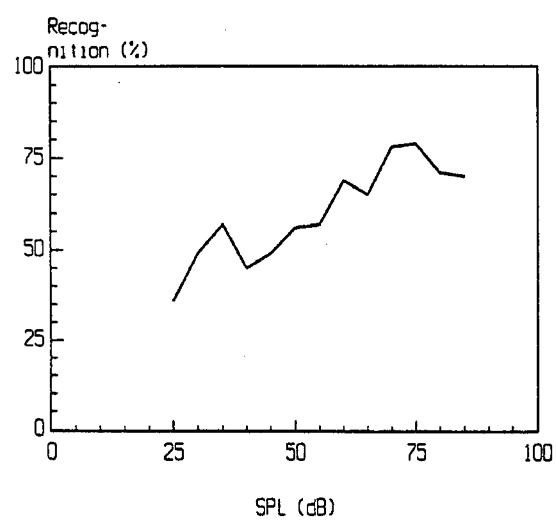

Figure 3. Median value of recognition for all subjects at different spl 16 wpm telegraphy speed, and +2 dB SNR [10].

threshold of the high tone increases. The increase in threshold is the threshold shift. The threshold shift is dependent on the spl of the masking tone and the frequencies between the SNOI and the SOI. Threshold shifts are illustrated in Figure 4. The frequency of the masker is at the top of each chart and its spl is by the number on each curve [6].

Changes in SOIs are often missed because a person desires and expects to copy only one source. Therefore, the operator considers the other sources as noise. Expectation masking occurs because one hears what one expects to hear [21]. Expectation masking demonstrates that pre-processing of sound occurs before becoming information in the brain. The pre-processing is based on what a person expects to hear. Expectation driven masking shows the process by which a familiar phrase is more pleasing than a random list of words. For example, "Four score and seven years ago..." has a higher quality than "ariel, markov, diet, cases, marty" [21]. Expectation driven masking also causes a person to filter out SNOIs, such as a fan or the better half's voice.

2.5 3-D Sound

3-D sound may be used to reduce the effects of masking on Morse sources. NASA communications personnel suffer from the same overlapping multiple source problem (with speech signals) as Morse code interceptors. During shuttle launches, communication personnel must be able to hear the conversation of interest despite overlapping communications. NASA has proposed a system to improve multiple speech communications. The Ames Spatial Auditory Display (ASAD) is similar to one necessary for a 3-D Morse audio presentation. The ASAD will aid the job of communication personnel during shuttle launches. In laboratory experiments, the advantage over two channel headsets was 6 to 7 dB for 3-D presentation angles between 60^o and 90^o [3].

For voice sources a 3-7dB improvement in intelligibility occurs when audio localization cues are used [4]. The experiments done with voice suggest a similar improvement may be made for Morse code.

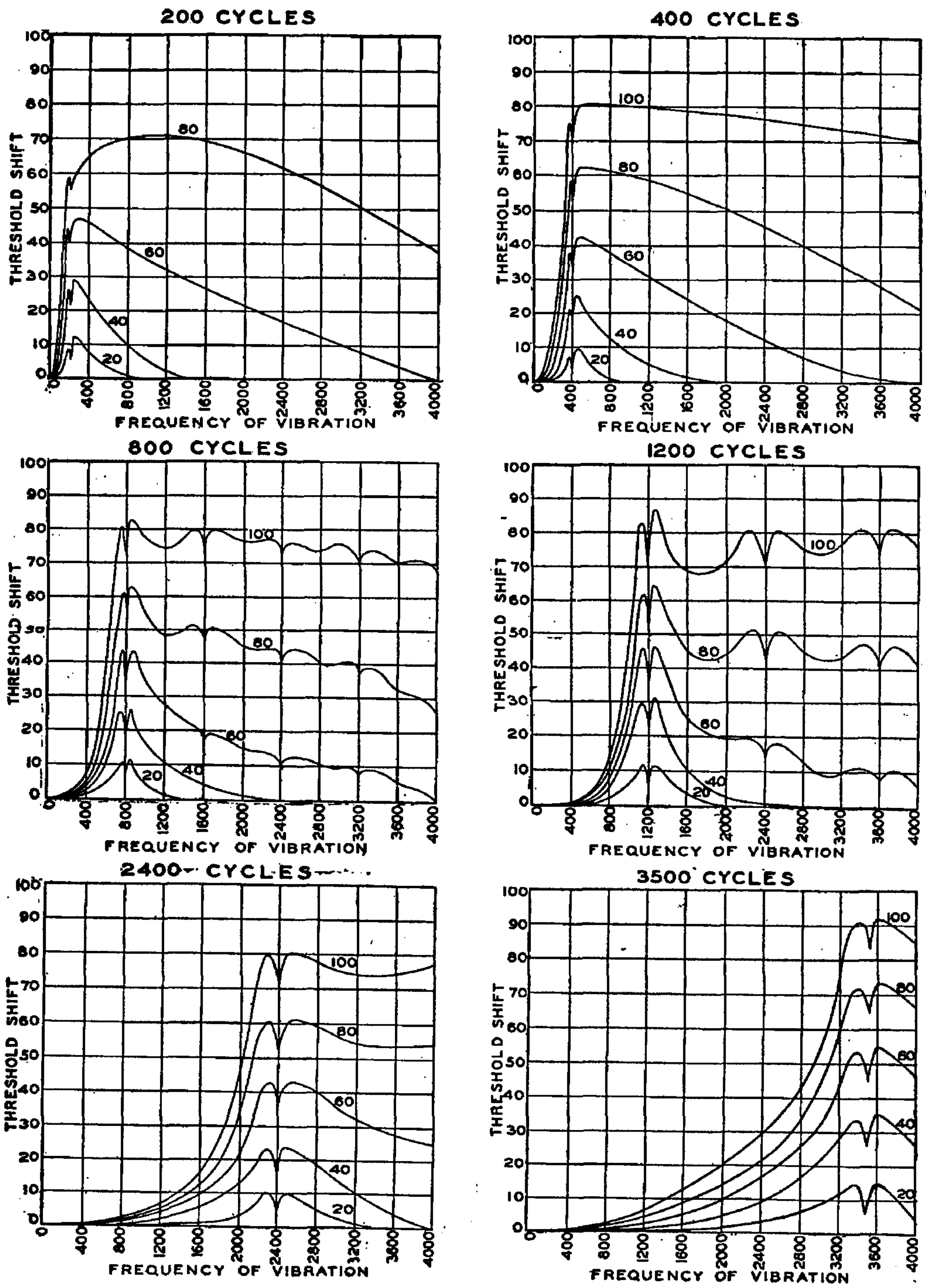

Figure 4. Pure Tone Masking Data for 200, 400, 800, 1200, 2400, and 3500 Hz [6]. The threshold shift created by the tone on the top at each graph is a function of frequency and spl.

2.6 *Auditory Cues for 3-D Sound*

To allow the user of an audio display to separate multiple Morse sources with 3-D sound, auditory cues must be presented. Auditory cues allow the brain to determine the direction from which a sound originated from. The cues that allow for localization are interaural time difference (ITDs), interaural intensity difference (IIDs), and the head related transfer function (HRTF). To present Morse naturally, all 3-D cues must be used. A combination of ITDs and IIDs is referred to as the duplex theory.

2.6.1 Interaural Time Difference. When a sound source is off to one side of the head, the time of arrival is different for each ear. A sound arrives first to the ear which is on the same side as the source. To locate a sound source, the brain determines the magnitude of the ITD [23]. The ITD is independent of frequency below 500 Hz and above 3000 Hz [20]. ITDs are an effective localization cue for frequencies below 3000 Hz. To present 3-D sound for frequencies above 3000 Hz, IIDs must be used [16]. Morse code is copied at frequencies below 2000 Hz. Therefore, the ITD is crucial for localizing Morse sources.

2.6.2 Interaural Intensity Difference. To aid in presenting Morse naturally the IID is used. The IID occurs because for frequencies above 3000 Hz, the head acts like an attenuator [16]. An IID occurs when a sound is off to one side of the head. The sound has the greatest amplitude at the ear facing the sound. The brain locates the sound source by determining the magnitude of the IID [23]. The shape of the torso, head, and ears also affect the IID [20].

2.6.3 Head Related Transfer Function. The HRTF is necessary to present high quality 3-D Morse code. When sound is presented as 3-D with IIDs and ITDs, the listener is able to satisfactorily determine the azimuth of a sound. However, a listener will state that the sound source originates inside the head. To simulate extracranialized 3-D sound and to improve localization, the HRTF must be used [23]. The HRTF takes into account how the shape of the head and torso filter sound. The filtering of the pinnae is the essential feature of the HRTF. The filtering of the face, nose, and body are also features used in the HRTF. When the effect of the head and the torso are taken into account, simulation of extracranialized 3-D sound is possible.

As shapes of the head vary from person to person, so do HRTFs. Therefore, the number of HRTFs equals the number of people in the world. HRTFs are a function of frequency and angle. Thus, for each angle there is a different filter response for each frequency. For example, the HRTF response for an angle of 60^o at 1000 Hz is different than the HRTF response for 62^o at 500 Hz. The responses make the filter data for the HRTF very large. The enormous size and number of HRTFs appears to make it an impractical audio localization cue. However, there are only a few shapes of the human head. Fortunately, like shirts, HRTFs need only to be made in off the rack style. HRTFs can be made in off the rack style because the shape of the head and torso are about the same for each person. Since most audio displays are moving towards voice, the number of possible frequencies will be reduced by 1/5 of the audio spectrum. Also since the number of practical sources presented to a user is no more than 10, the number of needed angles is only 10. The above reductions in the size and number of HRTFs allow for today's technology to produce 3-D sound.

2.6.3.1 Measurements of the Head Related Transfer Function. To determine HRTFs, an anatomically correct mannequin is placed in the center of an acoustically anechoic chamber. Armstrong Laboratory measured HRTFs with a geodesic sphere (Figure 5) in the anechoic chamber. To measure the HRTF, microphones are placed inside the ear canals [9].

Sine waves are produced by the speakers. The ear microphones then record the HRTF. The sine wave frequency is held constant until the HRTF is measured. The frequency is then incremented for the next HRTF sample. Azimuth and elevation information are contained in the speakers. Smith gives the location and elevation of 272 speaker used to determine the HRTFs [20]. When the HRTF is used with the IID and the ITD, sounds can then be simulated at distinct locations outside the head.

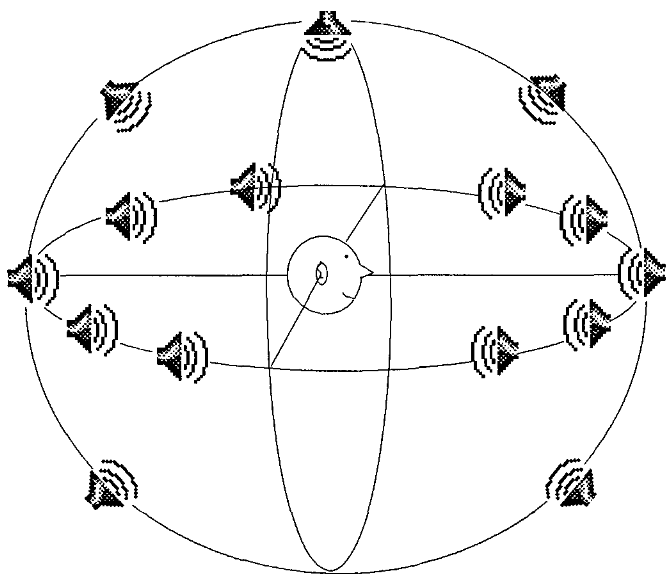

Figure 5. Geodesic sphere with sound sources at multiple locations[17:8]

2.6.4 Location of Sound Sources. 3-D sound should be used to increase recognition of Morse code and reduce fatigue. 3-D sound produces improvement in intelligibility over diotic sound presented over two channel headsets. It has been shown that a 6-7dB advantage over diotic playback for 50% intelligibility occurs when noise is presented at 0^o and a speech source is located between the angles of 60^o and 90^o and between 270^o and 300^o [3]. The results indicate that a signal may be presented four to five times weaker with 3-D sound than methods currently in use for equal intelligibility. These angles may work best because the ears are more sensitive at angles from 60^o to 90^o and 270^o to 300^o. It has also been proposed that the angles between 60^o and 90^o and between 270^o and 300^o may work best because maximum IIDs and ITDs occur between these angles [3]. The preceding reason supports the EC theory. Confusion in localization occurs at symmetric angles about the ears [23]. For example, a sound placed at 80^o may be confused with a sound placed at 100^o. Sounds at symmetric angles about the head have similar 3-D audio cues. The lack of difference in audio cues makes unmasking difficult.

2.7 N0 S0 versus N0 Sπ

A method to reduce masking of noise is to present the Morse source with a phase difference between the ears while keeping the noise in phase. By convention, N stands for noise and S for signal; the number after the letter stands for the phase difference between the ears. A 180^o phase difference between the ears is represented by π. For example, Nπ S10^o stands for the noise 180^o out of phase between the ears and the source 10^o out of phase between the ears [8].

The effects of phase difference when copying Morse code can be seen in Figures 6 and 7. Montnemery showed that with a 500 Hz Morse source with noise in the N0 Sπ condition, that the SNR can be 6 to 7 dB less than the N0 S0 presentation to achieve the same copy accuracy. Figure 6 also shows that where 0% copy recognition is available in the N0 S0 condition, 100% accuracy is available for the N0 Sπ. Montnemery further showed that maximum improvement for 50% intelligibility occurs when the source is approximately 180^o out of phase. The results for a 500 Hz source at various interaural phase shifts are shown in Figure 7.

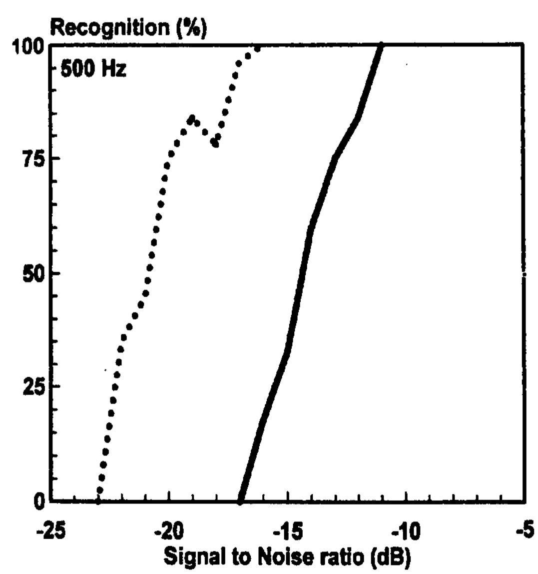

Figure 6. Recognition of telegraphy signs at different SNR when the signal was presented either in phase — or 180^o out of phase······ at 500 Hz tone frequency. The noise is in phase for both presentations; 8 wpm telegraphy speed, median of seven subjects[12].

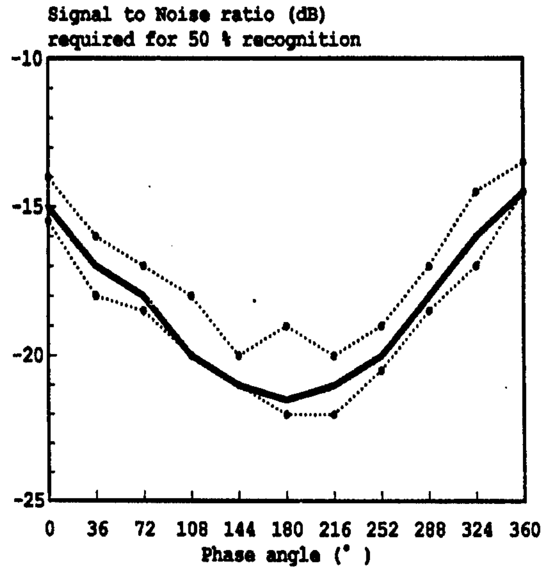

Figure 7. Recognition of telegraphy signs at different phase angles of the 3-D presented signal at 8 wpm telegraphy speed. 500 Hz tone frequency. The noise is in phase. Levels for 50% recognition. The min. and max. values are marked. Median of five subjects.[12].

2.8 Conclusion

Human copied Morse code is the most reliable form of communications to date. To improve the copy of a Morse code interceptor it is necessary to provide an audio display that works best with the human audio system. Morse code uses symbols composed of short and long elements to represent letters. The simplest methods to maximize accuracy is to present Morse code at the correct frequency and level. Results show that telegraphy should be copied at 500 Hz, with a spl of 70 dB [10]. For simultaneous Morse sources, the effects of masking must be considered.

Reducing masking effects is a large factor in improving the Morse display. Unmasking can be achieved by compensating for frequency masking [6] and expectation driven masking [21]. To compensate for frequency masking sources can be equalized so the perceived volume of each source is equal. To compensate for expectation masking a warning may be given before a change in the SOI occurs. However, warning an operator before a change in SOI is impractical. 3-D sound can also be used for increasing intelligibility.

3-D sound has been shown to improve simultaneous voice communications [3]. By providing the human audio system with audio cues(ITDs, IIDs, and HRTFs), the direction from which a sound originated can be simulated [23]. A 6-7 dB improvement in intelligibility can be realized by simulating a sounds direction between the angles of 60^o and 90^o.

By using the proper frequency and level to copy Morse code, copy errors will decrease. The combined effects of frequency unmasking, noise unmasking and 3-D sound presentation are shown to provide significant increases in an operator's accuracy.

III. Experiments

This chapter describes experiments used to determine and quantify which presentation options aid the human audio system in copying Morse code. Experiments with two and three simultaneous sources are discussed. The determination of threshold shift with two simultaneous Morse tones is presented. The average masking of a 1200 Hz tone by a 600 Hz, 900 Hz, and simultaneous 600 and 900 Hz tones is also determined. Morse experiments that compensate for masking are presented. Experiments also determine if maximum unmasking for 3-D sound occurs at the N0 Sπ condition.

The experiments determine the potential for improvement, using either a 3-D Morse audio presentation or a compensated masking display over a two channel headset presentation. Experiments determine if a 3-D Morse presentation with two sources will improve the accuracy of copy and reduce operator fatigue relative to a two channel headset presentation.

3.1 Approach/Methodology

This thesis has theoretical and experimental sections. The theoretical development will involve improving the audio presentation for Morse code interceptors. The potential for narrow band intelligibility improvement with 3-D sound will also be determined. The experiments will determine if a significant improvement is achieved using either a 3-D audio presentation or a masking compensated presentation versus the current Morse audio presentation.

3.1.1 Morse 3-D Audio Display. The Morse 3-D presentation must provide cues which the human audio system uses to segregate sound. The features which allow for maximum segregation are angular locations of Morse sources and location separation between sources. Since Morse code is a narrow band source, the ITD plays a key role in unmasking. The spatial location of the Morse source should be chosen which allows the audio system to completely exploit the ITD. The spatial separation between Morse sources must be significant enough to give the audio system different 3-D audio cues on which to focus.

3-D speech presentation experiments suggest the best locations for segregation are between 60^o and 90^o and between 270^o and 300^o [3]. The azimuth (θ) of the source is measured from directly in front of the face clockwise to the sound source (Figure 8).

The experiments also indicate that sound should not be placed at 0^o or 180^o. Further, sources to be segregated should not be placed at symmetric angles about the ears[23].

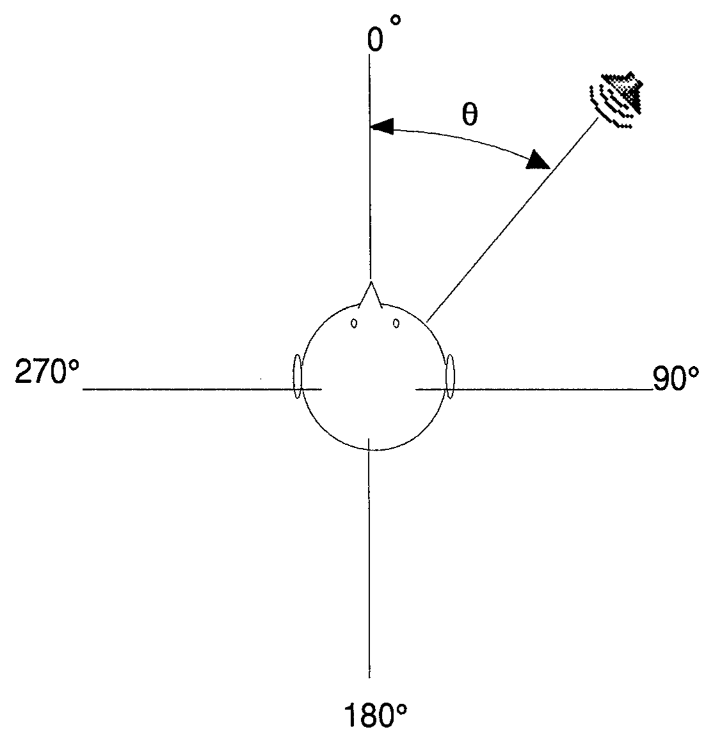

Figure 8. Azimuth, θ of sound source to directly in front of face

3.1.2 Analysis of Optimal Location of Sound Sources and N0 S0 versus N0 Sπ. Results for location of sound sources and the N0 $S\pi$ conditions suggest that the maximum unmasking available for a Morse source occurs at the maximum ITD for a Morse source. For a tone the maximum ITD corresponds to a 180^o phase shift. Also for 3-D sound maximum unmasking occurs at the location of maximum ITD. Thus, maximum unmasking occurs at the maximum ITD for a source.

Figure 9 shows an example using a 1000 Hz tone. The 1000 Hz tone has a maximum ITD of 500 μsec. A 500 μsec delay corresponds to an azimuth location of approximately

60^o. Therefore, a 1000 Hz tone should be placed at 60^o for maximum unmasking. Figure 10 shows where, in theory, various tones should be placed in 3-D sound for maximum unmasking. Experiments discussed below confirm this analysis.

Analysis of material in the literature review suggest that maximum unmasking for a Morse tone occurs at the maximum ITD. The result is consistent with the equalization cancellation model [5]. A 180^o phase shift corresponds to the maximum ITD for a tone. The largest ITD available for 3-D sound is 789 μsec [20]. Thus, the lowest frequency which can be unmasked by 3-D sound, using N0Sπ, is 633 Hz. This is calculated by:

$$2 \cdot ITD = \text{period} \qquad 2 \cdot 789\mu sec = 1.578 msec$$

$$\frac{1}{\text{period}} = \text{frequency} \qquad \frac{1}{1.578 \text{ msec}} = 633Hz$$

For frequencies below 633 Hz, 3-D sound can not provide maximum unmasking. Thus, for frequencies below 633 Hz, N0 Sπ presentation may be used to achieve maximum ITD.

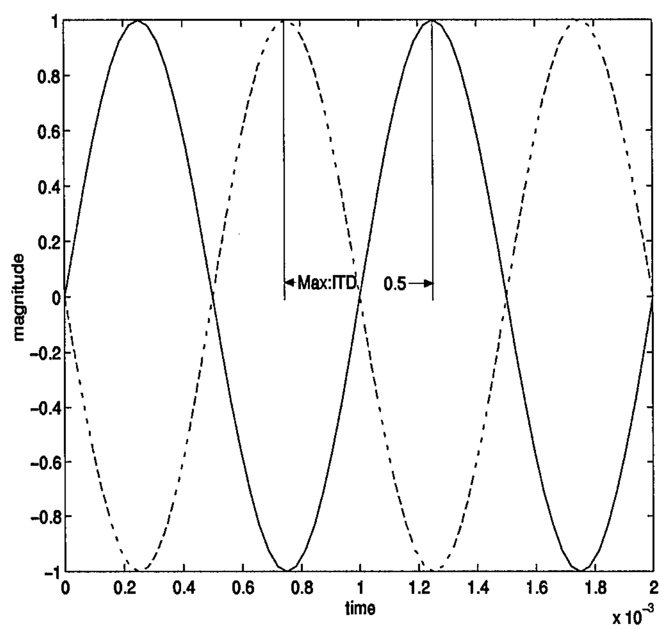

Figure 9. A 1000 Hz sine has a maximum phase shift of 0.5 msec. A 0.5 msec delay corresponds to a 180^o phase shift for 1000 Hz.

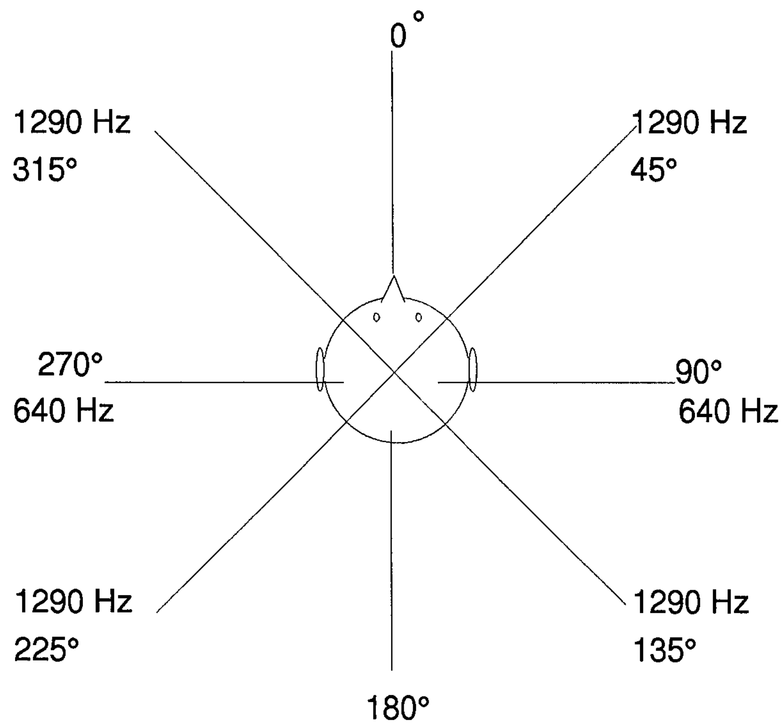

Figure 10. Hypothesized Location of Tones for Maximum Unmasking Around a Symmetric Head.

3.2 3-D versus Diotic versus Monaural Experiment with Two Simultaneous Morse Sources

The experiment with two simultaneous Morse signals determines which presentation option minimizes fatigue and maximizes accuracy. The symbols used to designate the type of presentation are similar to Jeffress [8]. The following symbols are used: SOI stands for source of interest, SNOI for source not of interest, "m" stands for monaural presentation, "d" for diotic presentation, a number stands for the 3-D simulated direction of a sound source. For example, SOIm SNOI72^o stands for the source of interest presented monaurally and the source not of interest 3-D placed at 72^o.

The first presentation option in Table 2 places a 600 Hz SOI at 82^o and a 900 Hz SNOI at 278^o. The next option presents a 600 Hz SOI and a 900 Hz SNOI diotically. Option two combines the SOI and the SNOI into one signal and presents it to both ears. The third option presents the SOI monaurally to the right ear and the SNOI monaurally to the left ear. Next the SOI was placed at 0^o and the SNOI was placed at 278^o and 82^o. The final option placed the SOI at 45^o and the SNOI at 278^o.

Table 2. Presentation Options for Two Simultaneous Sources

Option	600 Hz (SOI)	900 Hz (SNOI)
SOI82^o SNOI278^o	Right Ear 82^o	Left Ear 278^o
SOId SNOId	Diotic	Diotic
SOIm SNOIm	Monaural (Right Ear)	Monaural(Left Ear)
SOI0^o SNOI278^o,82^o	Center 0^o	Left and Right Ear 278^o and 82^o
SOI45^o, SNOI278^o	45^o	Left Ear 278^o

3.2.1 Procedure for 3-D versus Diotic versus Monaural Experiment with Two Simultaneous Morse Sources. Each session contains four tests. A test contained two of the presentation options in Table 2 played back to back. For example, the second test in Table 3 first played SOIm SNOIm and then played SOI82^o SNOI278^o. The first test determined which presentation option, monaural or diotic, produced the highest accuracy and minimum fatigue. Tests two through four determined if presentation options SOIm SNOIm; SOI0^o SNOI278^o,82^o; or SOI45^o SNOI278^o are better than SOI82^o SNOI278^o.

Table 3. Tests for Two Simultaneous Sources

Test	Option X vs. Option Y
1.	SOIm SNOIm vs SOId SNOId
2.	SOIm SNOIm vs SOI82^o SNOI278^o
3.	SOI0^o SNOI278^o,82^o vs SOI82^o SNOI278^o
4.	SOI45^o SNOI278^o vs SOI82^o SNOI278^o

To allow the subject to focus on the SOI, the SOI is preceded by nine v's and the attention character "BT", as shown in Figure 11. After "BT", a series of ten random character groups begins. Each group contains five characters. The format is shown in Figure 11. Each subject was given instructions (Appendix B), and the test was administered. The subjects were asked if the first or second presentation option was easier to copy. The test was then graded according to the procedure in Appendix B.

SOI: vvvvv vvvvBT vldfz vxtmb bqokl exoqw mvryy cvpss dfdrf xubat imlqz ccsha

SNOI: cnvpg dtwtc silgo fsztd spypz zqyxl psyqf yunnw aqmdd zhkft kagpe xozxi

Figure 11. Presentation of Random Character Groups

3.2.2 Creation of Morse Code Experiments. Morse code tests were generated using a computer. The computer created random Morse characters at specific frequencies. 3-D Morse sources were digitally filtered to add ITDs, IIDs, and HRTFs. The tests were then converted to analog with a 16-bit digital to analog converter. The analog output was recorded on a digital audio tape player.

3.3 Determination of Masking on a 1200 Hz Morse Source

These experiments determine the average masking created by single and simultaneous 600 and 900 Hz tones on a 1200 Hz tone. To compensate for frequency masking, it is necessary to know how much a low frequency tone masks a high frequency tone.

3.3.1 Determination of Masking on a 1200 Hz Tone by a 600 Hz Tone. Masking by a 600 Hz tone on a 1200 Hz tone was determined by finding the threshold shift. The apparatus included two frequency generators connected across resistors. A voltage meter was placed across the resistor for the 1200 Hz tone. Headsets were connected across the 600 and 1200 Hz generators (Figure 12).

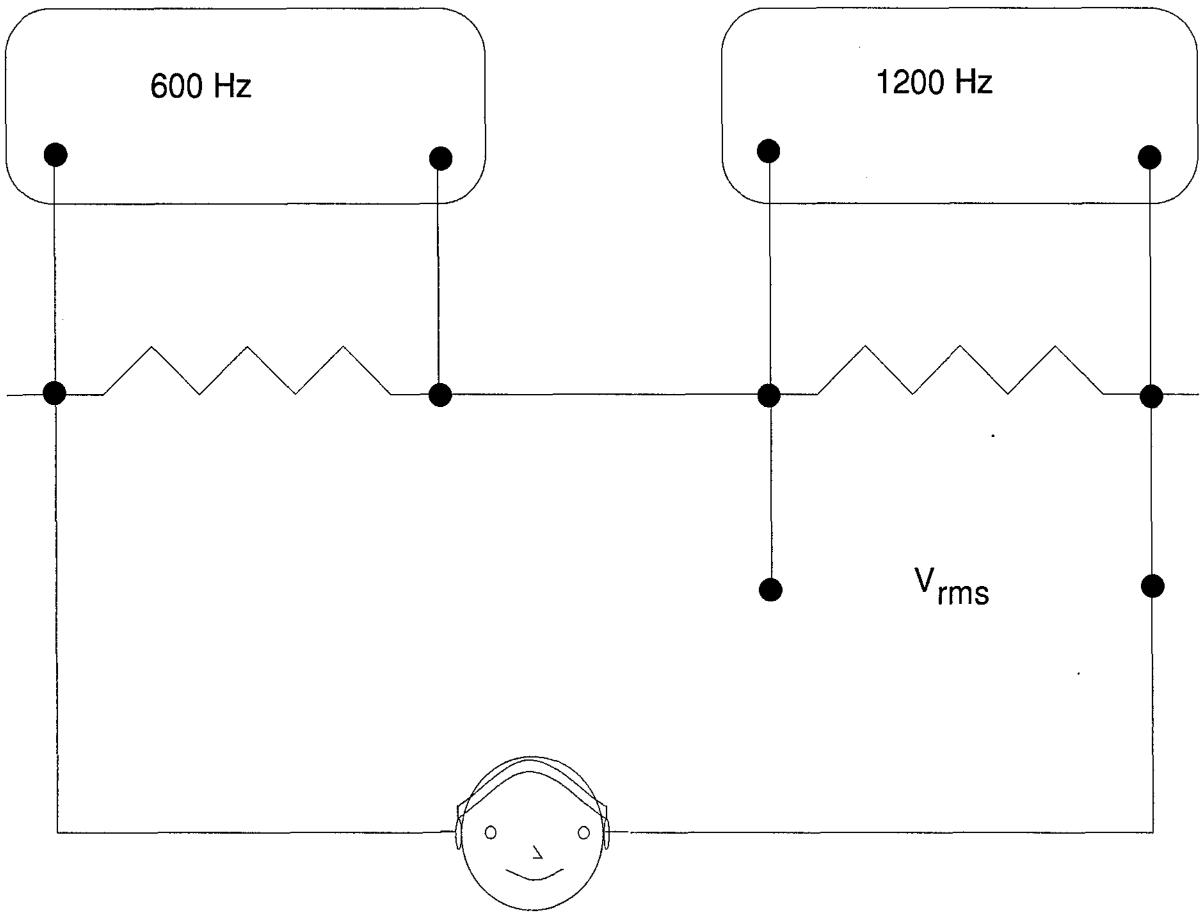

Figure 12. Apparatus for Determination of Masking on a 1200 Hz tone by a 600 Hz tone.

The 1200 Hz threshold was first determined. A 1200 Hz tone was played over headphones. The subject adjusted the volume until the tone was just noticeable. The volume, V_t, was measured, where V_t is the RMS voltage produced by the 1200 Hz generator.

The 600 Hz volume was set at normal speech volume. The 1200 Hz and 600 Hz tones were presented simultaneously. The subjects adjusted the volume of the 1200 Hz tone until the 1200 Hz tone was just noticeable. The volume, V_m, was then measured. Where V_m is the RMS voltage produced by the 1200 Hz generator. The threshold shift was calculated by:

$$S_{600} = 20 * log(V_m) - 20 * log(V_t)$$

This test was repeated four times, for six subjects. The average, and standard deviation of the threshold shift was calculated.

3.3.2 Masking of a 1200 Hz Tone by a 900 Hz Tone. The masking caused by a 900 Hz tone on a 1200 Hz tone was determined in the same manner as in the previous section. The generator producing 600 Hz was adjusted to produce 900 Hz.

3.3.3 Masking of a 1200 Hz Tone by Simultaneous 600 Hz and 900 Hz Tones. To find the masking caused by simultaneous 600 and 900 Hz tones an additional frequency generator was added to Figure 12. The volume of the 600 Hz and 900 Hz tones were set to one-half the comfort level. The total masking volume equaled the comfort level.

3.3.4 Verification of Frequency Masking Experiments. To verify the frequency masking experimental procedure, an experiment was conducted to determine if the shape of the masking curves in Figure 4 could be duplicated. This was done by setting the masking frequency to 800 Hz. The threshold for 900 Hz, 1000 Hz, 1100 Hz, and 1200 Hz was determined. The threshold shift for each of the four frequencies was determined using the same procedure as the previous experiments. The curve generated was the same shape as generated by Fletcher (Figure 13).

3.4 Determination of Average Masking of a SOI by Two SNOIs

To determine the average masking of a SOI two cases must be considered.

Case 1: The first case is the time the SOI is sending a di or a dah and simultaneously both of the SNOIs are sending a di or dah. To determine the amount of time in case 1 a

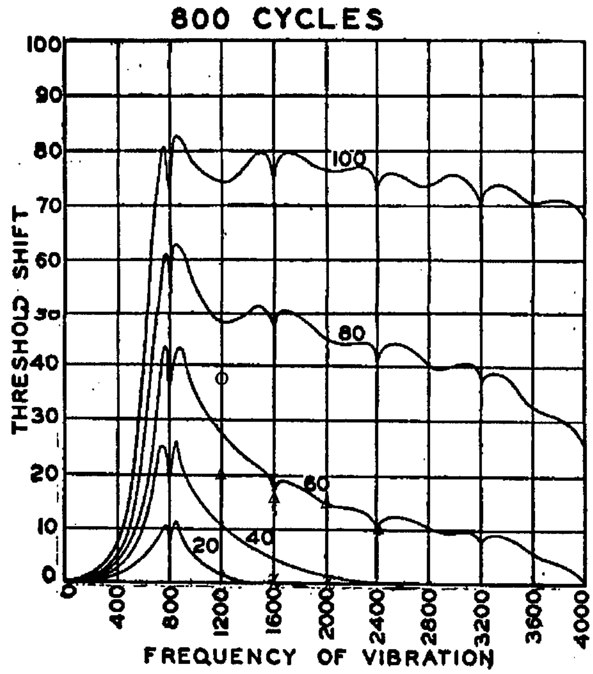

Figure 13. Verification of Masking Experiments. Δ test at comfort level. χ test at 20dB below comfort level. *o* test at 20 dB above comfort level.

computer simulation was used. A di was represented by a one. A dah was represented by a series of three ones. Pauses were represented as zeros. For example, the symbol for "A" was represented by 1 0 1 1 1. The computer simulation generated three Morse code vectors. Each vector contained 3000 words. Each word contained five characters. Two of the vectors were point multiplied together. The resulting product was multiplied to the remaining vector. The resulting vector contained a 1 when case 1 occurred. The sum of the elements was calculated. The sum was then divided by the total number of elements. The quotient gave the percentage of time all three sources are sending a di or a dah.

Case 2: The second case determined the amount of time the SOI is sending a di or a dah and simultaneously only one of the SNOIs is sending a di or a dah. To determine the amount of time in case 2 a computer simulation is used. The simulation was similar to the one used for case 1. To begin, two of the vectors were point multiplied together. The resulting vector contained a 1 where case 1 or case 2 existed. The sum of the elements was calculated. The sum was then divided by the total number of elements. The quotient gave the percentage of time two or three sources were sending a di or a dah. The quotient was then subtracted by the time found for case 1. The preceding step eliminated from the result the time case 1 existed. The result was the average time two sources were sending a di or a dah simultaneously. A sample calculation is shown in Figure 14.

```
10111011101000101110001011101000101000101010000000101   B
```

Figure 14. Determination of Average Masking of a SOI, by two SNOIs. Case 1: the ratio of time the SOI is sending a di or a dah and simultaneously both of the SNOIs are sending a di or dah. Case 2: the ratio of time the SOI is sending a di or a dah and only one of the SNOIs is sending a di or a dah.

3.5 3-D versus Diotic Experiment with Three Simultaneous Morse Sources

This experiment determined the accuracy and fatigue improvement using 3-D Morse sources over diotic Morse sources. The Morse sources where at 600, 900, and 1200 Hz. A Morse code test was designed similar to Figure 11, with an additional SNOI. The initial frequency of the SOI was randomly selected for each subject. In each test, the SOI was randomly changed to a SNOI after every ten groups. The tests were given diotically and 3-D. The order of presentation options was randomized. The presentation options are shown in Table 4.

Table 4. Presentation Options for Three Simultaneous Sources

Option	600 Hz	900 Hz	1200 Hz
1.	Diotic	Diotic	Diotic
2.	Left Ear 278^o	Right Ear 82^o	Center 0^o

3.5.1 Determination of Expectation Driven Masking or Frequency Masking. To determine if the inability to detect a change in the SOI was caused by expectation driven masking or frequency masking two experiments were conducted.

3.5.1.1 Experiment with a Warning Before a Change in the SOI. In this experiment expectation driven masking was eliminated by warning the subjects just prior to a change in the SOI. The subjects were warned by giving them a form to copy Morse code (Figure 15).

The form contained three columns with 10 rows. The rows were numbered one through 10. After the subjects copied the tenth row they knew the SOI was changing. Each subject was tested to determine if they could detect a change in the SOI. The order of SOIs is shown in Table 5.

Table 5. Order of SOI for Experiment with a Warning Before a Change in the SOI

Test	Order of SOI (Hz)		
1.	600	900	1200
2.	900	1200	600
3.	1200	900	600

3.5.1.2 Experiment with Frequency Masking Compensation. This experiment determined if compensating for frequency masking eliminated missed changes in SOI. Frequency masking was compensated for by amplifying the 1200 Hz source by the average masking found in previous experiments. Each subject was given three tests in random order to determine if they could detect a change in SOI. The order of SOIs is shown in Table 6.

1. ________	1. ________	1. ________
2. ________	2. ________	2. ________
3. ________	3. ________	3. ________
4. ________	4. ________	4. ________
5. ________	5. ________	5. ________
6. ________	6. ________	6. ________
7. ________	7. ________	7. ________
8. ________	8. ________	8. ________
9. ________	9. ________	9. ________
10. ________	10. ________	10. ________

Figure 15. Morse code copy form used to warn subjects of a change in SOI

Table 6. Order of SOI for Experiment with Frequency Masking Compensation

Test	Order of SOI (Hz)		
1.	600	1200	900
2.	900	600	1200
3.	900	1200	600

3.6 Experiments Confirming Analysis of Optimal Location of Sound Sources and N0 S0 versus N0 Sπ

These experiments indicate the best method of listening to a SOI while monitoring idle SNOIs. These experiments also determined which source phase shift gives maximum unmasking while the noise is in phase. Also determined was if the same source phase shift gives maximum unmasking in 3-D sound. The results will indicate where a tone should be spatially located to achieve maximum unmasking.

3.6.1 Maximum Unmasking of a 1064 Hz Tone With a Source Phase Shift. The first experiment determined which phase shift gives maximum unmasking for a 1064 Hz tone. This frequency was chosen because the 180^o phase shift corresponded to the ITD, 470 μ sec, for a spatial location of 58^o. Thus, the results can be compared to the results of the experiment with 3-D sound. The experiment compared perceived loudness levels of the tone for the following conditions: N0 S0, N0 S34.74^o, N0 S80.41^o, N0 S127.51^o, N0 Sπ, N0 S218.33^o, and N0 S252.04^o. Each presentation was tested at SNRs of -10 dB, -10.41 dB, and -10.79 dB. Table 7 shows the tests presented to each subject.

3.6.1.1 Experiment Procedure. Each session consisted of 21 tests. The session tested the seven presentation methods at the three different SNRs shown in Table 7. The order of the tests were randomized. Each test lasted a total of four seconds. The tone in noise was presented for one second and three seconds was given for response time. Six subjects were used. The subjects were asked to give a subjective anchored volume level one through seven. With one being the quietest and seven being the loudest. The subjects were

Table 7. Tests given to each subject to determine which phase shift gives maximum unmasking for a 1064 Hz tone.

Test	Presentation	SNR (dB)
1.	N0 S0	-10, -10.41, -10.79
2.	N0 S34.74^o	-10, -10.41, -10.79
3.	N0 S80.41^o	-10, -10.41, -10.79
4.	N0 S127.51^o	-10, -10.41, -10.79
5.	N0 Sπ	-10, -10.41, -10.79
6.	N0 S218.33^o	-10, -10.41, -10.79
7.	N0 S252.04^o	-10, -10.41, -10.79

first played the 1064 Hz without noise. A presentation with just noise and no tone was played for level one. Test 5 in Table 7 with a SNR of -10 dB was played to demonstrate volume level seven.

3.6.2 Maximum Unmasking with 3-D sound. This experiment determines if the source phase shift in 3-D sound that gives maximum unmasking is the same source phase shift as the previous experiment. The same phase shifts as in the previous experiment were used in this test. Phase shifts of 0^o, 34.74^o, 80.41^o, 127.51^o, π, 218.33^o, and 252.04^o correspond to spatial locations of 0^o, 10^o, 32^o, 45^o, 58^o, 69^o, and 82^o respectively. IIDs modified by HRTFs were added to the phase shifts to simulate 3-D sound. Tests were given at the same dB levels as in the previous experiment. In each test, the noise was presented at a spatial location of 0^o. Table 8 shows the tests given. The experimental procedure used for this experiment was the same as the previous experiment.

Table 8. Tests given to each subject to determine which spatial location gives maximum unmasking for a 1064 Hz tone

Test	Spatial Location of Tone (degrees)	SNR (dB)
1.	0	-10, -10.41, -10.79
2.	10	-10, -10.41, -10.79
3.	32	-10, -10.41, -10.79
4.	45	-10, -10.41, -10.79
5.	58	-10, -10.41, -10.79
6.	69	-10, -10.41, -10.79
7.	82	-10, -10.41, -10.79

IV. Results and Discussion

4.1 Results of Two Simultaneous Morse Sources

Results of two simultaneous Morse sources indicated that none of the presentation options in Table 2 improved accuracy. All subjects reported that 3-D presentation was easier to copy than monaural or diotic presentations. The subjects' views on which 3-D presentation option was more comfortable varied greatly. Therefore, no determination of which 3-D presentation minimized fatigue could be made.

4.2 3-D versus Diotic Experiment with Three Simultaneous Morse Sources

The accuracy of copy for 3-D or diotic presentation was the same. All subjects stated that 3-D presentation was easier to copy than the diotic presentation. For 3-D and diotic, none of the subjects were able to determine a change in the SOI. Each subject was able to copy the initial SOI, despite frequency, for the entire test. These results suggest that expectation driven masking is a large cause of missed SOI changes. The subjects also stated that the 900 Hz and the 1200 Hz sources were quieter than the 600 Hz source.

4.3 Results of Masking Experiments

The masking experiments showed that a 1200 Hz Morse source is significantly masked by 900 and 600 Hz sources. The masking of the 1200 Hz source by the 600 Hz tone is 7 dB less than the 900 Hz tone. These results are consistent with Fletcher's results on pure tone masking [6]. The results of two simultaneous maskers on a 1200 Hz tone only increased by two dB over a single 900 Hz masker. This is to be expected since the volume of the 600 and 900 Hz tones were each reduced by 6 dB for the three tone simultaneous experiment. Table 9 gives the results of the masking experiments.

4.3.1 Discussion on Results of Masking Experiments. The results of two simultaneous maskers on a 1200 Hz source suggest that the masking effects of two simultaneous

Table 9. Threshold Shift of Masking on a 1200 Hz tone

Masker (s) Frequency (Hz)	Average of Threshold Shift (dBW)	Standard Deviation of Threshold Threshold Shift (dBW)
600	9.77	2.99
900	16.76	9.59
600 & 900	18.26	4.32

tones are not additive. Assuming the threshold shift is reduced by the amount of decrease in volume of the masker, the threshold shift would be 3.77 dB and 10.76 dB for 600 Hz and 900 Hz tones respectively. If the total masking was additive, the masking of two simultaneous sources would be 14.53 dB. Instead the masking is 18.26 dB.

4.3.2 Average Masking on a 1200 Hz Morse Source. From computer simulation, it was found that 12.63% of the time the 1200 Hz source is sending a di or a dah at the same time both the SNOIs were sending a di, or a dah . It was also found that 12.46% of the time the 1200 Hz source sent a di or a dah simultaneously with only one of the SNOIs. The average masking was calculated as shown.

$$Mask_{1200} = (0.1263) * (18.26) + (0.1246) * (9.77) + (0.1246) * (16.76)$$

$$Mask_{1200} = 5.61 dBW$$

4.3.3 Detection of a Change in the SOI with a Warning and Frequency Masking Compensation. All of the subjects were able to detect a change in the SOI when warned just prior to the change. All of the subjects stated that they desired to continue copying the initial SOI, but forced themselves to change sources after the warning. Compensating for frequency masking by amplifying the 1200 Hz source by 5.61 dB allowed all subjects to detect a change in the SOI. The results indicate that a combination of frequency masking and expectation masking causes missed changes in SOI.

4.3.3.1 Frequency Compensating. To compensate for frequency masking only the 1200 Hz source was amplified. If the 900 Hz source was amplified to compensate for the 600 Hz source, the masking on the 1200 Hz source would increase. In order to minimize masking on the 900 Hz tone, one should reduce the volume on the 600 Hz tone. By doing this the masking on the 900 Hz tone would be reduced without adversely affecting the 1200 Hz source. These results also demonstrate the great amount of situational awareness the intercept operator must have. The operator must be able to determine how much to decrease the volume of a lower frequency source and how much to increase the higher frequency signal to maintain awareness of all three sources. The results also indicate that when copying Morse and monitoring channels with man-made interference, operators should tune the radio so the frequency of the Morse is lower than the interference. By having the Morse source a lower frequency than the interference, the Morse source will attenuate the interference. The effects of frequency masking can be overcome by training the operators on the effects of frequency masking and by providing a volume control for each receiver.

4.3.3.2 Compensation For Expectation Driven Masking. By warning the subjects before a change in the SOI all the subjects were able to detect a change of SOI. This indicates that expectation driven masking can be overcome by warning an operator before a change in SOI. However, this is impossible because it is unknown when a change in SOI will occur. It would be extremely difficult to create a device that detects a change in the SOI. The cues would be difficult to detect and are continuously changing. The results from frequency compensation indicate that the effects caused by frequency masking and expectation driven masking can be overcome by amplifying the higher frequency signals.

4.4 Discussion of 3-D Presentation

Results presented in this chapter, along with those found by Begault [3], support the use of 3-D sound in Morse displays. 3-D sound is easier for a human to copy because sound is presented in a natural manner. The situation is analogous to a picture versus a painting. A photograph of a scene is more realistic than a painting. Thus, it is easier for the visual system to interpret information from a picture than a painting.

It is not surprising that 3-D sound did not improve accuracy. Considering that the SNOIs were at the same volume as the SOI, the SIR (Signal to Interference ratio) is 0 dB for two simultaneous sources and -3 dB for three simultaneous sources. In contrast, the improvement in accuracy shown by Montnemery [12] are for SNRs less than -15 dB.

The results from this thesis, and from Montnemery [12], support the use of presenting audio cues to Morse interceptors. Where 0% copy recognition is available with no audio cues below -17 dB SNR, 100% recognition is available using an interaural phase shift. The auditory cues in 3-D sound reduce fatigue in Morse interceptors. Fatigue is a key problem. Morse operators work rotating shifts and copy code for a full eight hours. The working conditions create a requirement to minimize fatigue. 3-D sound is less taxing on the audio system because it presents sound in a manner which the audio system is prepared to receive.

4.5 Results of Maximum Unmasking of a 1064 Hz Tone Without IID

Results show that the perceived volume level increases as the phase shift approached π. The volume levels for -10, -10.40, and -10.79 dB were averaged because of their small difference. The results are shown in Figure 16. In the polar plot (Figure 17) it can be clearly seen that as the phase shift moves away from π, unmasking decreases.

4.6 Results of Spatial Location Experiment

The spatial location experiment indicated that as the ITD approached the 180^o phase shift for a tone, unmasking is at its highest. Statistical analysis of the results show that the average volume level at spatial locations 45^o and 58^o are statistically equal. The two-sampled pooled t-test was used to show that the results of 45^o and 58^o are equal. A complete description of the two-sample pooled t-test can be found in many statistical texts. It is assumed that both distributions are normal and that $\sigma_1 = \sigma_2 = \sigma$. The equations used are:

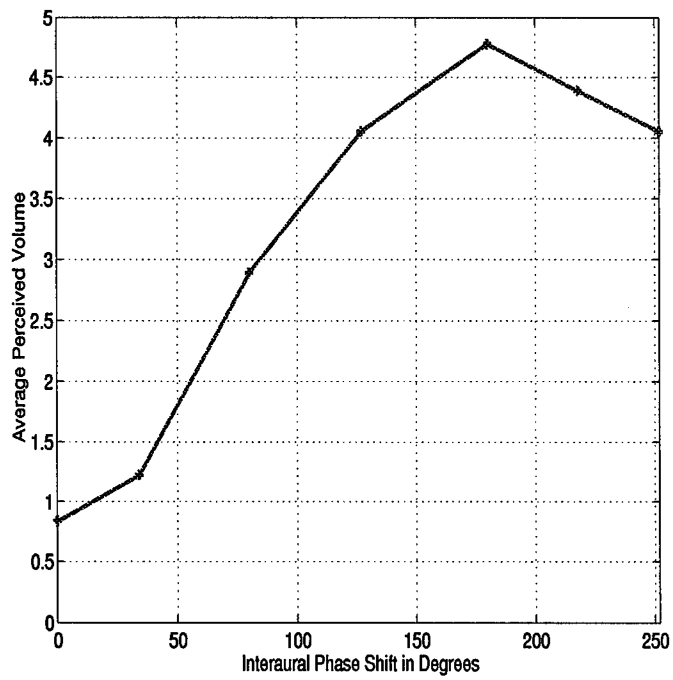

Figure 16. Average Volume levels of a 1064 Hz tone with a mean SNR of -10.40 dB. The noise was kept in phase and the interaural phase shift for the tone was changed.

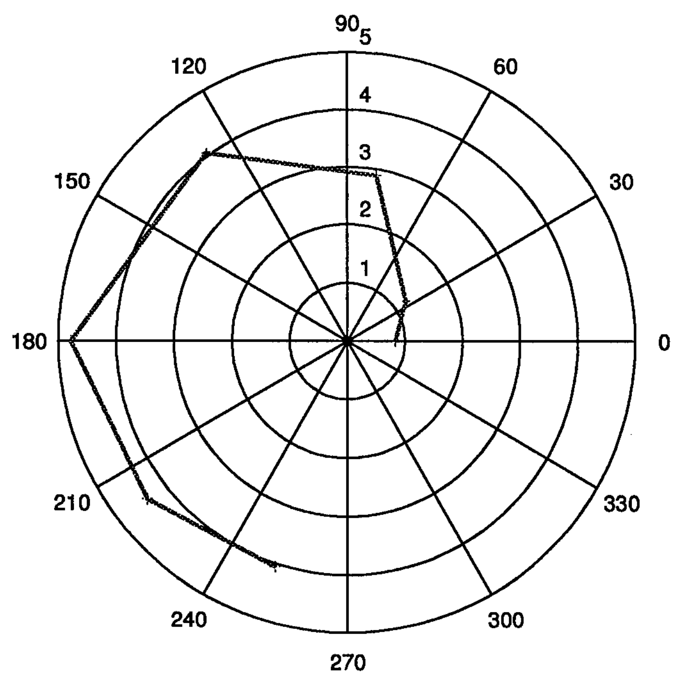

Figure 17. Polar plot of the results shown in Figure 16; Average volume levels of a 1064 Hz tone with a -10.40 dB mean SNR. The noise was kept in phase and the interaural phase shift for the tone was changed.

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - d_0}{s_p\sqrt{1/n_1 + 1/n_2}},$$

where

$$s_p^2 = \frac{s_1^2(n_1 - 1) + s_2^2(n_2 - 1)}{n_1 + n_2 - 2}.$$

The t-distribution is involved and the two-sided hypothesis is not rejected when [22]

$$-t_{\alpha/2,n_1+n_2-2} < t < t_{\alpha/2,n_1+n_2-2}.$$

To show that the results at 45^o and 58^o are equal d_0 is set equal to zero. t was found to be 0.60 and $t_{\alpha/2,n_1+n_2-2}$ was found to be 2.228. Since, 0.60 is between $\pm$ 2.228 the results at 45^o and 58^o are equal. Figure 18 shows the average volume levels of six subjects at various locations, along with the corresponding ITD and phase shift.

4.7 Discussion of Experiments Confirming Analysis of Optimal Location of Sound Sources and N0 S0 Versus N0 Sπ

The experiments indicate that when copying a SOI, while monitoring idle SNOIs, the SOI should be placed at a spatial location that gives the SOI a phase shift of 180^o and the SNOIs have an interaural phase shift of 0^o. From the results of the previous experiments it is clear that as phase shift reaches 180^o unmasking is at its highest. The result is also true for 3-D sound. Generalizing the results of the experiments with the 1064 Hz tone the greatest unmasking using 3-D sound can be obtained when the tone is spatially located where the ITD matches the 180^o phase shift. Figure 19, shows the location tones should be placed to achieve maximum unmasking.

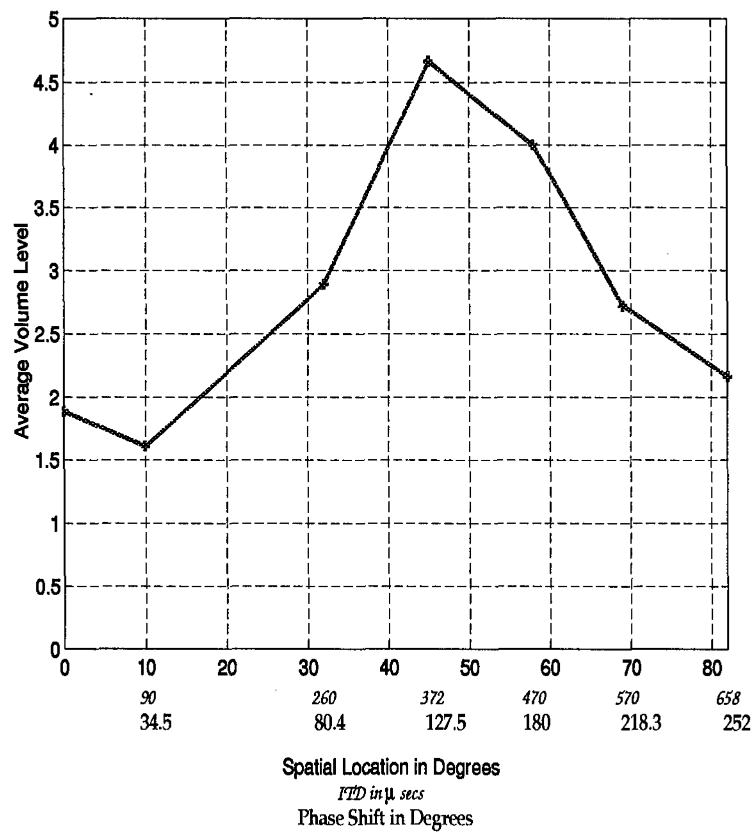

Figure 18. Average Volume levels of a 1064 Hz tone, average SNR -10.40 dB while the noise was kept at zero degrees.

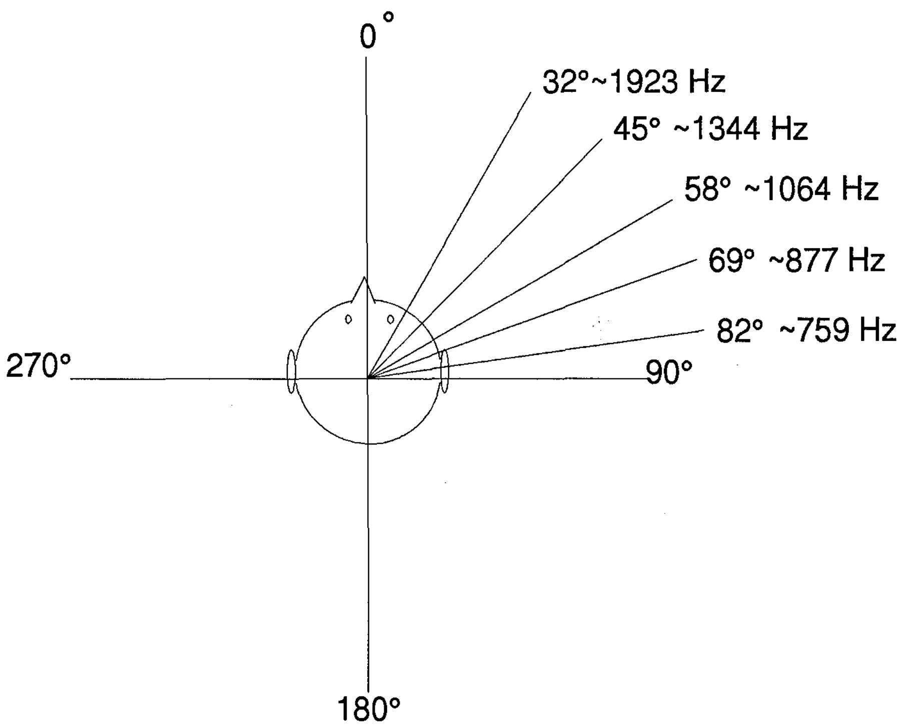

Figure 19. Spatial Location of Tones for Maximum Unmasking in Noise.

V. Recommendations and Conclusion

5.1 Summary

The objective of this thesis was to develop methods to improve the Morse code interceptors audio display. The factors considered to improve the audio display where presentation options, frequency of sources, level of sources, and methods of unmasking. The literature revealed the best frequency and level for intercepting Morse code in noise is 500 Hz at 70 dB spl [10]. Experiments revealed that to reduce the effects of frequency and expectation driven masking, the perceived volume of all sources must be equalized. By equalizing the volume detection of SOI changes occur. None of the presentation options provided increase of Morse accuracy. By using 3-D sound, fatigue levels for multiple sound sources decreases, while using N0 $S\pi$ to copy code, improves accuracy [12].

The experiments also showed the effects of frequency masking in simultaneous Morse sources. In frequency masking lower frequency sources mask higher frequency sources [6]. The results of a single masker on a 1200 Hz tone were consistent with Fletcher's results. The experiments suggest that the effects of two simultaneous maskers are not additive. With three simultaneous sources at 600, 900, and 1200 Hz, the masking on the 1200 Hz signal is greater than the sum of the masking caused by a single 600 and 900 Hz tones.

Expectation driven masking was also demonstrated in the monitoring of three simultaneous Morse sources. Expectation driven masking causes one to hear what one expects to hear [21]. In experiments where the SOI changed and no compensation for masking existed, subjects could copy the initial SOI, but always missed the changes in SOI. This demonstrates that once a person focuses on a source, one expects to continue copying the SOI and considers other sources as noise. When subjects where warned just prior to a change in the SOI, they could detect the change. All subjects stated that despite the warning, it was still difficult to switch. The combined results of the experiments without a warning, and with a warning support the existence of expectation driven masking in simultaneous Morse signals.

Analysis of the material in the literature review suggests that the best unmasking for a Morse tone occurs at the ITD corresponding to the 180^o phase shift. The result is consistent with the equalization cancellation model [5]. A 180^o phase shift corresponds to the largest ITD for a tone. The largest ITD available for 3-D sound is 789 μsecs. Thus, the lowest frequency which can be best unmasked by 3-D sound is 633 Hz. Experiments showed that to achieve the largest unmasking using 3-D sound a tone should be spatially located where the ITD matches the 180^o phase shift. This result should be applied when an operator is copying a SOI and monitoring idle SNOIs.

5.2 Recommendations for Optimizing the Morse Audio Display

The results from this thesis support the following recommendations to improve the copy accuracy of the Morse intercept operator. 3-D sound should be used to copy Morse code. Further, while copying a SOI, and monitoring SNOIs, the SOI should be placed at a spatial location that produces a 180^o interaural phase shift, while the SNOIs have a 0^o phase shift. The use of 3-D sound is supported by this thesis and the results from Begault [3]. Along with the use of 3-D sound, the operator should be taught the effects of frequency masking. During training the intercept operator should be taught that accuracy is highest when the copy frequency is from 500 to 600 Hz [1, 10]. Given this knowledge, the interceptor can make intelligent decisions, on the best frequency and volume level for each of the simultaneous Morse sources. To allow the operator to implement decisions the operator must be given control of the audio display. The controls should include a volume control for each of the receivers in use. By using 3-D sound, education, and adding controls the accuracy of copy will substantially increase. Such an increase in accuracy will undoubtedly provide the material necessary to produce a quality intelligence product to high level consumers.

5.3 Recommendations for Further Research

Experiments should be done that combine 3-D sound and frequency masking compensation to determine accuracy, gain, and comfort improvement. Currently it is known that for one source, 500 Hz is the frequency that has the largest recognition rates. Experiments should be conducted to determine which frequencies should be used for multiple sound sources. Research in the mental process of copying code will give clues to other methods that may improve the Morse audio display. By understanding the mental process, a device may eventually be created that will greatly improve the copy accuracy of Morse code.

5.4 Conclusion

This thesis determined methods to improve the Morse intercept operators audio display. To determine improvement methods, a literature review and experiments were conducted. Both supported using 3-D sound to improve an audio display with noise [3]. It was also found that the best frequency and listening level for copying Morse code is 500 Hz at 70 dB spl. [10].

The experiments conducted determined how to improve a Morse audio display with simultaneous Morse sources. Experiments were conducted for two and three simultaneous Morse sources. Experiments compared presentation options to determine improvement in accuracy and fatigue. The experiments found that 3-D sound greatly reduces fatigue. 3-D sound does not directly improve accuracy for SIRs of 0 or -3 dB; however, since it reduces fatigue, it may indirectly improve accuracy. Experiments determined the effects of simultaneous tone frequency masking. It was found that a 600 and 900 Hz tone with a total volume equal to normal speech level caused a 18.26 dB threshold shift on a 1200 Hz tone. The average masking on a 1200 Hz tone was found by finding the ratio of time the SOI and the SNOIs were simultaneously sending a di or a dah, and the time the SOI and only one of the SNOIs was sending a di or a dah. It was also found that it was difficult to detect a change in SOI. The missed changes where caused by frequency masking and expectation driven masking. By amplifying the 1200 Hz tone, the effects of frequency masking and expectation driven masking are minimized. Thus, changes in SOIs could be detected. Experiments also showed that maximum unmasking for a Morse tone in 3-D sound occurs at the spatial location that gives a 180^o phase shift.

Appendix A. Definitions

Definitions of key terms used in this thesis are presented.

3-D Sound. Sound presented to one ear is modified and presented to the other ear. The modifications include phase differences, IID, ITD, and HRTF.

Diotic Sound. presents the identical sound to both ears

Extracranialized Sound. 3-D sound presented to a listener through headphones that is perceived as coming some distance outside the head [9].

Pinna(e) is(are) the human outer ear(s). The design of each person's pinnae is unique and each set of pinnae will uniquely filter sounds. The human head and ears form an antenna system for every individual [18]. Experiments show that spectral shaping by the pinnae is dependent on direction and cues provided by the pinnae. The spectral shaping is critical in extracranilizing sound [14].

Head Related Transfer Function (HRTF) is the transfer function which models the filtering of the pinnae. Because the filtering of sound by the pinnae is dependent upon direction, there is a different HRTF for each angle of azimuth and elevation. HRTF's are unique to each person; however, these differences are relatively small. Because differences in HRTF's are small HRTF's can be made in off the rack style and still allow for accurate localization [24].

Monaural Sound Monaural presentation presents a sound to one ear only. No information, from the sound, presented to one ear is presented to the other ear.

Appendix B. Methods for Morse Code Experiments

This appendix covers methods for minimizing human variance, instructions to the subjects, and grading of Morse code tests.

B.0.1 Minimizing Human Variance. To minimize the effects of human learning, illnesses, and variations of concentration during the test, the order of combinations presented is randomized.

B.0.2 Instructions to the Subjects. The following instructions were given to the subjects.

1. You will be given a Morse code test containing two simultaneous Morse signals.
2. The signal to be copied will be preceded by a series of v's followed by the character "BT".
3. After "BT"the test will begin.
4. You may copy the series of v's.
5. You may adjust the volume to a comfortable level during the first set of v's
6. After the first set of v's no adjustment may be done.
7. Would you like to copy with a pencil, or type?
8. Are there any questions?

B.0.2.1 Instructions to the Subjects With a Warning Before a Change in the SOI. The instructions to the subjects were the same as in the experiment with two simultaneous signals with the following added.

1. After a few groups the SOI will change to one of the SNOIs.
2. The SOI will change to a SNOI after the warning.
3. The new SOI will send a series of v's followed by the character "BT".

B.0.3 Grading. In grading a test, a mistake is counted when the wrong character was copied or a character was not copied. Format errors are not counted as mistakes. An example of a format error are six characters in a group instead of five.

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Vita

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This thesis improves the audio display for multiple Morse communications. Factors considered to improve the audio display are frequency of source, volume level of source, and methods of unmasking. It has been shown that the best frequency and volume level of a Morse source is 500 Hz at 70 dBs sound pressure level(spl). Two types of masking are researched: frequency masking, and expectation driven masking. Experiments showed by amplifying high pitched sources the effects of frequency masking are minimized. Other methods to compensate for frequency masking are 3-D sound and placing a source out of phase between the ears. Morse code recognition at 500 Hz is maximized when presented at the N0 $S\pi$ condition. It has been shown that maximum unmasking for broadband signals occurs at 3-D locations were the maximum ITD(interaural time difference) exists. This thesis theorizes and confirms that maximum unmasking of a source tone in 3-D sound corresponds to the spatial location that gives an ITD equal to a 180^o phase shift for that tone. Fatigue is measured by subjects choice of which presentation option is easier to copy. The criteria for improving cues are minimal fatigue and the highest copy accuracy. The presentation options are 2-channel diotic(each channel contains a unique source, information of a source is presented to only one ear), monaural(all sources in each ear), 3-D angles of $0^o, 10^o, 32^o, 45^o, 58^o, 69^o$, and 82^o. Experiments considered two and three simultaneous Morse signals. Results from 4 subjects showed that 3-D sound does not improve accuracy when multiple sources are at equal volume level for the tested signal to interference ratio(SIR). Minimum fatigue occurs for 3-D sound presentation.

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