Journal of Human Performance in Extreme Environments

Volume 7 | Issue 2 Article 10

Published online: 10-1-2003

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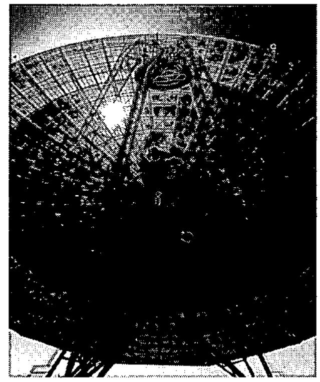

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Testing to date indicates there is a significant potential for adverse interference from the digital system to the analog system, especially for General Aviation (GA) aircraft. This type of interference can be described as short, random bursts of noise capable of completely obliterating parts of the voice communication. The subsequent degrading effects on voice radio communication could jeopardize flight safety. To address this issue, the goal of the present study was to examine the degree to which such noise impacts voice radio communication intelligibility. Intelligibility was assessed employing a classic, well-established psycho-acoustic method, which uses human beings, rather than electronic test instruments, to assess speech communication systems. The discussion centers on the importance of understanding how interference with speech can degrade human performance directly, by disturbing normal social and work-related activities, and indirectly, by causing annoyance and stress.

Introduction

Pilots have many tasks in a very complex environment in flight and on the ground. Part of the complexity of this environment can be attributed to the airborne radio communications equipment. Because the results of miscommunication can be catastrophic, voice communication is such a vital aspect of the aviation system. Several factors may influence the effectiveness of the communication process, including human characteristics and environmental factors, as will be described in more detail in the following sections.

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The Federal Aviation Administration (FAA), in conjunction with airlines and avionics manufacturers, is undertaking the development and deployment of a set of datalink services to enhance air/ground communications in the en route environment. In this globally coordinated effort, digital data communication between controllers and flight crews is being introduced. Out of necessity there will be a transition period when digital data and conventional analog voice radios must coexist.

Problem Statement

Digital Very High Frequency (VHF) data radio transmissions interfere with analog VHF AM receiving equipment used for voice communications. The potential for this type of interference represents a critical issue because of the inability to separate antennas enough, especially for general aviation (GA) aircraft. Pilots perceive digital data transmission interference as short noise-like bursts capable of distorting parts of the incoming speech. The subsequent degrading effects on voice communications could jeopardize flight safety. The partial obliteration of important information would result in distracted attention, debilitated cognitive performance, high levels of annoyance, and stress.

Communication System

Generally, communication involves implicitly the transmission of information from one point to another through a progression of processes:

http://dx.doi.org/10.7771/2327-2937.1035

- Generation of a message in the mind of an originator
- Description of that message by a set of symbols (aural, visual, etc.)
- Encoding of these symbols in a form that is appropriate for transmission over a physical medium
- Transmission of the encoded symbols to the desired destination
- Decoding and reproduction of the original symbols
- Recreation of the original message, with a determinable degradation in quality caused by imperfections in the system, in the mind of the recipient.

The communication process is of a probabilistic nature and to appreciate this fundamental property, we merely have to recognize that if the receiver of a communication system were to know the composition of a message exactly, there would be no point in having the system transmit that message (Shannon & Weaver, 1947). Sources of "uncertainty" in the operation of a communication system include noise that originates naturally at the front end of the receiver, interference due to undesirable sources or external effects, and the source of information itself. The result is that the received signal is random like in appearance; in other words, we cannot predict the exact value of the received signal (Haykin, 1994). The received signal, however, can be described in terms of its statistical properties.

In the field of communication theory, noise means signals that bear no information and its intensity vary randomly in time (Kryter, 1994). The Federal Communications Commission (FCC) defines harmful interference (CFR 47) as interference which endangers the functioning of a radio navigation service or other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio communication service operating in accordance with the Radio Regulations. For the purpose of this experimental study, however, the focus is on noise as "audible acoustic energy (or sound) that is unwanted because it has adverse auditory and non-auditory physiological or psychological effects on people" (Kryter, 1994).

The transition of air/ground communications, from its present analog structure to new digital communications architecture, will span a ten-year time frame. Testing to date indicates that the potential for interference from the digital system to the analog system would be significant, especially for GA aircraft. This type of interference can be described as short, random bursts of noise capable of completely obliterating parts of the voice communication. In the case of digital radio data communication induced interference with voice communication, the pilot perceives the VHF data transmission that interferes with the VHF AM (Amplitude Modulation) receiving equipment used for Voice Communication as a short burst of noise. The source of this interference is the so-called co-site interference from on-board or same site digital radio data transmitters, operating simultaneously with the reception of VHF signals virtually anywhere within the 118-137 MHz band.

Human Characteristics Influencing Speech Communication Systems

Speech communication is the primary method for human communication and it is a process involving the transfer of information from a speaker to a listener, which takes place in three stages: production, propagation, and perception. The human vocal and auditory organs form a very complex communication system. Speech sounds are produced when breath is blown from the lungs and causes either a vibration of the vocal cords (for vowels) or turbulence at some point of constriction in the vocal tract (for consonants). For voiced sounds like the vowels, the vocal tract acts as a resonant cavity. This resonance produces large peaks in the resulting speech spectrum. These peaks are known as formants. The formants of the speech contain almost all the information contained in the signal. Nasals are produced when the oral cavity is blocked and the velum is lowered to couple the nasal cavity with the vocal tract. They are also voiced in nature, but the coupling of the oral and nasal cavities introduces anti-resonances or nulls instead of resonances so the formants disappear. Unvoiced hiss-like sounds like "s," "f," and "sh" are generated by constricting the vocal tract close to the lips (Goldstein, 1999).

The sound power in speech is carried by the vowels, which average from 30 to 300 milliseconds in duration. Intelligibility is imparted chiefly by the consonants, which average from 10 to 100 milliseconds in duration and may be as much as 27 dB lower in amplitude than the vowels. The strength of the speech signal varies as a whole, and the strength of individual frequency ranges varies with respect to the others as the formants change (Haykin, 1994).

The sense of hearing provides a unique source of information. Auditory function is the process by which the stimulation of receptors in the inner ear is followed by transduction of the mechanical stimulus into neural energy, which upon reaching the brain gives us the sensation of hearing. Recognizable tonal quality, however, requires some minimal duration of the sound. If a tone of an audible frequency and intensity is presented for only a few milliseconds, it will lose its tonal character and will either be inaudible or be heard as a click. According to Gulick et al. (1989), the length of time a given frequency must last in order to produce the perception of a stable and recognizable pitch is 250msec. Loudness is also affected by the duration of the sound. As the duration of a sound becomes progressively briefer than 200msec, intensity must be increased to maintain a constant level of loudness.

The perception of continuous speech does not depend only on the fixed acoustic stimulation that occurs at any given moment. It also depends on anticipations and expectations of what the stimulation should be based on the cognitive framework created by preceding and following speech sounds, in other words on the context. People sometimes "hear" phonemes that are not there. In the 1970 study, Warren (1970) presented participants with recording of a sentence in which a 120 ms portion had been replaced with a coughing sound. Nineteen out of twenty listeners demonstrated phoneme restoration effect, so called because listeners apparently "restore" the missing phonemes predicted by other linguistic information during the course of perception. The context directs the listener's perception of a sound - typically without the listener even being aware of this influence. The phoneme restoration effect demonstrates that people effortlessly "fill in" the gaps created in a stream of speech.

The role of context may also reduce inaccuracies in the perception of fluent conversational speech. This occurs especially when the acoustic input is ambiguous or the same articulation has readily accessible alternative perceptions (Goldstein, 1999). That is when the same acoustic input, received phonetically in the same manner, may be perceived differently, depending on the context in which that occurs.

Speech perception is based on the interaction of an enormous number of complex psychological factors. It requires us to make very fine discriminations between sounds. A spoken word consists of a short pattern of sounds lasting less than a second. The perception of speech persists even when the sounds comprising words change greatly. Words retain their identity and are perceived accurately under many distorting conditions. Even when most physical characteristics of speech sounds have been changed to some degree, the sounds may still be intelligible.

A complex cognitive integrative mechanism is required to perceive speech, but we appear to come specially equipped to perceive speech in very efficient ways. We continue to perceive intelligible speech even when the flow of speech is reduced or distorted (Sanders & McCormick, 1993).

Environmental Factors Influencing Speech Communication Systems

Intruding noises can interfere with human activities by distracting attention and by making activities more difficult to perform, especially when concentration is needed. Interference from noise can even make some activities (such as communication) virtually impossible. The effects of noise are seldom catastrophic, and are often only transitory, but adverse effects can be cumulative with prolonged or repeated exposure. There is some evidence that it can affect general health and well being in the same manner as chronic stress (Broadbent, 1979).

Noise is considered a nonspecific biological stressor, gaining a response that prepares the body for action response. The physiological mechanism thought to be responsible for this reaction is the stimulation by noise (via the auditory system) of the brain's reticular activating system (Cohen & Theinstein, 1981). Neural impulses spread from the reticular system to the higher cortex and throughout the central nervous system. Therefore, noise can influence perceptual, motor, and cognitive behavior, and also trigger glandular, cardiovascular, and gastrointestinal changes. Noise can adversely affect task performance in a variety of circumstances (Broadbent, 1983). For example, noise can mask important sounds and disrupt communication between individuals in a variety of settings. This process can cause anything from a slight irritation to a serious safety hazard involving an accident or even a fatality because of the failure to hear important piece of information. Numerous accident reports have many "say again" exchanges between pilots and controllers, although neither side reports anything wrong with the radios. Interference with speech communication and other sounds is one of the most salient components of noise-induced annoyance. The resulting disruption can constitute anything from an annoyance to a serious safety hazard, depending on the circumstance (Gardner, 1998).

Speech Intelligibility

Intelligibility is defined as to the degree to which speech can be understood (French & Steinberg, 1947). With specific reference to speech/voice radio communication system testing, intelligibility denotes the extent to which trained listeners can correctly identify words or phrases that are spoken by trained talkers and transmitted to the listeners via the communication system.

The research literature on speech intelligibility is extensive and dates back well before the World War II (Campbell, 1910; Fletcher, 1929). The effects found with the intelligibility paradigm include: word length (Egan, 1948); word frequency and familiarity (Rosenzweig & Postman, 1957; Owens, 1961; Broadbent, 1967); context (Miller et al., 1951; Miller, 1962; Warren, 1970; Kalikow et al., 1977); differential masking of consonants and vowels (Miller, 1947; Licklider and Miller, 1951); speaker voice (Bigler et al, 1955; Peters, 1955; Mullennix, Pisoni and Martin, 1989); and stimulus set size (Miller et al, 1951).

In summary, intelligibility is:

- Highest for sentences, less for isolated words, and lowest for nonsense syllables
- Higher for sentences than for isolated words because the context supplies information
- Higher for long words than for short words, because with short words there is less opportunity to pick up pieces of the word
- Higher for familiar words than for unfamiliar words

The effects of noise on speech intelligibility were also extensively investigated by researchers. Miller et al. (1951) demonstrated that the intelligibility of speech in noise is a strong function of the probability of occurrence of a given speech sound, word, or phrase. They demonstrated that the larger the message size, the lower the probability of occurrence of a particular word from the message set and the more susceptible is the communication system to interference from noise.

One form of masking of speech by noise is partially filtering out whole ranges of frequencies from the speech signal. In a classic study by French and Steinberg (1947), subjects heard a series of recorded words from which whole bands of frequencies either above or below 1900 Hz were completely removed. When frequencies above 1900 Hz were filtered out, about 70% of the words were still intelligible. The same result was obtained with the elimination of all frequencies below 1900 Hz. This means that as much of the total intelligibility is carried by frequencies below 1900 Hz as is carried by frequencies above 1900 Hz. Thus, the critical stimulus information for speech perception is not confined to any frequency range. This procedure is known as frequency cutoff.

A result similar to the perceptual filling-in-effect of context occurs when seconds of speech are eliminated by periodically turning the speech on and off or by systematically blanking out sections of speech flow by turning a masking noise on and off. This form of speech disruption is called speech blanking (Miller, 1947). When conversation was blanked out for 50% of the time (at a rate of nine blinks per second), speech intelligibility altered, but only about 15% of the words were lost.

Speech perception is remarkably resistant to degradation. Speech remains reasonably intelligible even with background noise and even when chunks of linguistic elements, including phonemes and whole frequency bands, are far from ideal (Warren, 1970).

Measures of Speech Intelligibility

In general, two different methods may be employed to assess speech intelligibility: *subjective* intelligibility measurements using human beings, rather than electronic test instruments, to assess speech communication systems; and *objective, based on physical parameters of the communication channel (Herman, 2002).* First proposed in 1910 and refined with the introduction of the telephone and the advent of electronic communication systems in World War II, subjective tests are still considered to be the most accurate and reliable measures of intelligibility.

Speech elements frequently used for testing include phonemes, words (meaningful words, or nonsense CVC-words (Consonant-Vowel-Consonant), and sentences. A sentence that is used to present test words in subjective intelligibility tests is called carrier sentence. The test word is spoken without emphasis, and the sentence is the same for each test word. The score is given by the percentage correctly recalled items. The recall procedure can be based on a given *limited* set of responses or on an *open response* design where all possible alternatives are allowed as a response. Limited response set is used with the so-called rhyme tests. These types of tests are easy to administer and do not require extensive training by the listeners in order to arrive at stable scores. Open response tests, however, make use of nonsense words, and require an extensive training of the listeners. This experiment deals most directly with the American National Standards Institute's approved procedure (ANSI S3.2-1989).

A number of specialized word lists are in common use for testing various aspects of speech communication. The ANSI standard specifies three:

1. Modified Rhyme Test (MRT)
Test materials consist of six 50 rhyming monosyllable word sets (i.e. pin, sin, tin, fin, din, win) that were selected with half to differ in the initial consonant and the other half in the final consonant. The listener's task is to respond to the stimulus by indicating which of the six rhyming words presented before him was spoken.
2. Diagnostic Rhyme Test (DRT)
Test materials consist of 96 rhyming monosyllable word pairs (i.e. veal-feel) that were selected to differ in only their initial consonant. These differences are categorized into six distinctive features and scores in each of these categories provide information on diagnosing system deficiencies. These six scores are averaged together to provide an overall measure of system intelligibility. The listener's task is to respond to the stimulus by indicating which of the two rhyming words presented before him was spoken.
3. Phonetically Balanced Word Lists (PB)
The oldest of the three tests is the set of 20 phonetically balanced (PB) lists, each of

which contains 50 monosyllabic English words. The words are presented in a pseudo-open set, and listeners write down their responses. The words are included in the same carrier sentence, "*Would you write <word> now*" which all speakers use for all words [1]. In each list of words the frequency or occurrences of types of speech sounds are proportional to those in everyday life. Pre-recorded test material can be used. At a minimum, each participant is given three PB or MRT word lists. A set of percentage scores is calculated showing the number of times words were identified correctly by each listener. Taking an average of these can produce a single overall score. If either the DRT or MRT is used, the results are adjusted mathematically to account for guessing (no adjustment is required for the PB test). The three tests are highly intercorrelated with each other and with other tests of speech intelligibility. With appropriate control of extraneous factors, all three tests yield highly self-consistent and repeatable results.

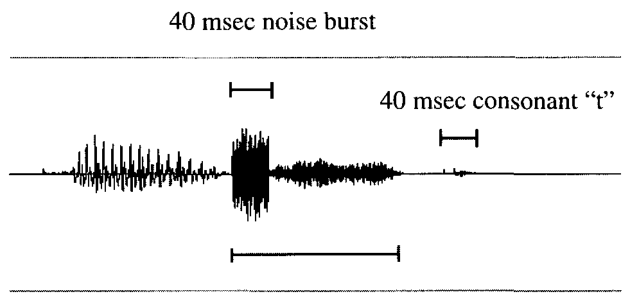

Figure 1. *The waveform of the word "FEAST" with the burst of white noise pasted over the leading 40msec of the consonant "s"*

Experiment

The goal of the proposed experiment was to examine the degree to which simulated digital data radio transmission induced interference impacts voice radio communications intelligibility.

Hypothesis

Voice radio communication intelligibility decreases as the ratio between the length of the noise-like burst and the length of the affected consonant (LR) increases.

Method

Participants

Twenty-seven pilots were used as participants. All participation was on a volunteer basis. All participants were English-fluent and held a valid second-class medical certificate, which includes a hearing test. Pilots were considered as highly trained listeners because they have received on-the-job training and have extensive experience in voice radio communications.

Instruments

The experiment consisted of one condition with each participant. A set of three prerecorded (Intelligibility and Measurement Test Discs 1 & 2, produced by PROSONUS in association with INTEREC Publishing, 1991) PB word lists (50 words each), were used with each participant, as a minimum requirement by the standard [1]. The PB test was chosen for this experiment because in each list of words the frequency or occurrences of types of speech sounds are proportional to those in everyday life. PB tests have also demonstrated sensitivity to degraded speech and have been very successful with human participants. All three PB word lists were edited using SOUND FORGE XP 4.5 sound editor.

A sample of white noise, 40msec - long, was used to simulate the digital data radio transmissions. One of the consonants of each word in the second and the third word lists was obliterated by the burst as shown in Figure 1.

The burst location in each word was assigned over one of the consonants because consonantal sounds are difficult to transmit successfully, and are, thus, more important than vowels to speech intelligibility. The words from the second and the third word lists were divided into two groups of 50-word each. The first group of words contained a long (lasting 80-200msec) consonant. The second group of words contained a short (lasting 30-80msec) consonant. In both groups, consonants (one per word) were edited using SOUND FORGE XP 4.5 sound editor in a way so that the leading 40msec of each consonant was cut off and then a 40msec burst of white noise was pasted in its place. The test sequence of words was saved as 150 separate files. The files were then randomized using a table of random numbers. The test was computer based and self-paced. All participants wore headsets (Optimus PRO-50MX). They were given paper to write on.

Task

Words were presented one at a time. Participants then wrote down the word they heard. Words were not repeated.

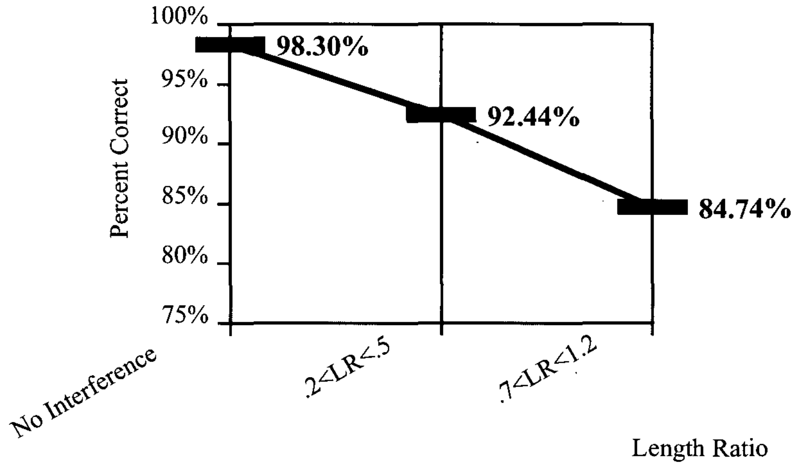

Figure 2. Percent correctly identified words as a function of the LR

Design

A within-subjects design was used for the study. A within-subject design was chosen because it allows the variation among participants to be removed prior to the assessment of factor effects. The independent variable (IV) was the ratio between the length of the burst and the length of the affected consonant (LR). The dependent variable (DV) was the speech intelligibility or percentage correctly recalled items out of 150. In this experiment there were three levels of the factor (interference) defining the conditions - no interference, low interference (.2 < LR < .5), and high interference (.7 < LR < 1.2). Scores were obtained from each participant for each of the conditions.

Procedure

Participants were given verbal instructions. The participants then became thoroughly familiar with all the perception-discrimination tasks required to recognize the test words under the conditions of the actual test. An equipment familiarization trial of three words (each in a carrier sentence) with no interference was conducted. The participants were thoroughly familiar with the motor demands of the test and were briefed on the specific kinds of degraded communication that were investigated. In both familiarization and testing no visual cues were allowed. In order to prevent them to get any visual cues the participants were asked not to write anything down during the familiarization nor were they allowed to see printed copies or of the actual test sequence of words.

Results

The evaluation of the data from this experiment consisted of a set of percentage scores and a statistical analysis and summary. The generally accepted method for measuring performance on intelligibility tests is to compute the arithmetic mean of percent of words correctly identified by the participants. The mean test scores for no interference, low interference (2 < LR < .5), and high interference (7 < LR < 1.2) group were 98%, 92% and 84% correct, respectively (Figure 2).

These means do differ significantly using One-Way ANOVA, F (2, 52) = 117.59. Thus, different Length Ratios significantly influence the percent of words correctly identified by the participants. Specifically those words treated with higher LR were more difficult to identify that those treated with lower LR or with no interference at all. The number of items correct was used as a measure of intelligibility. The data was subject to a one-way within-subjects analysis of variance (ANOVA), the results of which are shown in Table1.

Table 1 Summary Table of One-Way Within-Subjects Measures ANOVA

	Sum of squares	*df*	Mean square	*F*
Factor A (interference)	0.249	2	0.125	117.591
Subjects	0.081	26	0.003	
Interaction A x S	0.055	52	0.001	
Total	0.386	80		

* $p<.001$, $F_{crit} = 3.23$

From looking at the graphed means (Figure 2) it appears that when there was no interference introduced, the scores are higher, while the percent of correctly identified items, where different levels of interference were present, was lower. Thus, when the LR was higher the scores were lower.

These apparent differences were examined using a Tukey HSD post hoc procedure, HSD (2, 40) = .0215 (Table 2.)

Table 2 Tukey HSD Post Hocs

Tukey HSD	No	Low	High	
0.022	No	0		
	Low	0.058	0	
	High	0.136	0.077	0

$^*p < .05$

In fact the percent correctly identified items for the no interference group of words was significantly higher than the low interference or high interference groups. However the percent correctly identified words from the low interference group was significantly higher than the percent correct from the high interference group.

In summary different levels of interference or no interference at all produce significant effect on the percent correctly identified words.

Discussion and Recommendations

Of primary concern for this study were the effects of digital data radio communication induced interference on voice radio communication intelligibility. It was anticipated that the digital data radio communication interference would influence voice communication intelligibility and the length ratio (LR) would be critical for voice communication intelligibility. Based upon the results of the statistical analysis that was exactly what happened. Those words treated with higher LR were more difficult to identify that those treated with lower LR or with no interference at all. In general, as the interfering burst obliterates a larger proportion of a consonant, the intelligibility decreases.

To investigate the effect of this type of interference specifically the study was conducted in a very conservative environment. No other form of noise, distortion or interference was introduced in the experimental setting. All context factors, particularly aviation context factors, were intentionally eliminated from the experimental study design, because earlier research [23] demonstrated that speech could be severely distorted without becoming unintelligible. The normal stream of speech contains many more discriminative clues than are necessary. If interference removes or confuses some of these clues others carry the message. If the speech stimulus contains many more clues than the listener needs, distortions in the stimulus must be extreme in order to obliterate all traces of the message.

Even the context of each word itself was enough for some of the participants in this study to correctly identify most of the words, especially when a longer consonant was obliterated.

There were recognizable shortcomings in this study. First, the conservative environment used in the experiment reduced the ecological validity of the study. Given what we know about the influence of context on speech intelligibility, research similar to this should be conducted in a higher fidelity environment. It could well be the context of a live cockpit that reduces the negative effect of this type of interference to a negligible level. But, it also could be that the typically very noisy environment in the live cockpit makes the negative effect of the burst even stronger.

It should be noted that scores were negatively influenced not only by the higher LR, but also by the location of the burst. Specifically scores worsen when the burst occurred over the first consonant.

Future research on the impact of the use of English as a second language on voice radio communication intelligibility would bring some insights about the way we should approach the growing diversity of cultural backgrounds in today's "busy" skies.

Interference caused by digital data radio transmission may affect intelligibility differently over the various phases of flight. This may be influenced by the specific terminology/phraseology commonly used by controllers. A better understanding of the intellectual strategies pilots use to cope with the already noisy environment of the live cockpit may be required.

Communication is an essential element of human society, and speech is its most convenient form of expression. Interference with speech can degrade living directly, by disturbing normal social and work-related activities, and indirectly, by causing annoyance and stress. Sometimes the communications, disturbed by noise are of vital importance, especially in the aviation environment.

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