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16. Abstract

Laboratory studies have shown that the human binaural auditory system can extract signals from noise more effectively when the signals (or the noise) are presented in one of several interaurally disparate configurations. Questions arise as to whether these laboratory studies in anechoic or semi-anechoic spaces can be generalized to more reverberant listening conditions. In the current study, tests were conducted in the cabin of a light airplane, in flight. For symmetrical signal sources, loudspeaker transmissions of intelligibility-test materials produce higher intelligibility scores for speakers out-of-phase than for speakers in-phase.

17. Key Words

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Aircraft, Light
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BINAURAL PROCESSING OF SPEECH IN LIGHT AIRCRAFT

I. Introduction.

Pilots of large jet aircraft do not often face noise levels that will interfere significantly with speech reception, but those who fly light planes frequently do. The noisiest times can be the most critical; for example, during takeoff, a tower transmission may be heard but not understood. Perhaps it is a message to someone else, but the pilot cannot always be sure.

For most flyers, the use of earplugs or other hearing protection would increase the speech intelligibility enough to keep the message clear, but for those who cannot or will not wear such protection, there has been no useful alternative to missing an occasional message. However, there are theoretically good approaches to message improvement under the borderline condition in which the noise is just a bit too much for signal clarity.

In this noisy situation, pilots commonly listen to a single sound source (the cockpit loudspeaker) immersed in a field of fairly homogeneous noise (the engine and wind noises outside the plane and the rattles and squeaks inside). The noise *masks* the signal to a greater or lesser degree. Typically, such a situation is no better than one in which both signal and noise are heard with only one ear (monaural listening). Yet, the brain offers certain two-eared (binaural) advantages for appropriate signals. This study was devised to test whether the inexpensive introduction of an unusual binaural signal into the cockpit would in fact improve speech intelligibility by a significant and useful amount.*

Monaural masked thresholds are relatively poor, for a given amount of masking noise, compared to certain binaural masked thresholds. The binaural manipulations of signal and noise that lead to these differences in masking level (*masking-level differences* or MLDs) have come under systematic investigation since the late 1940s, when Hirsh,[3 4 5] Licklider,[10] and Hirsh and Webster[6] first noticed a peculiar kind of what they termed "binaural summation." Since then, nearly every study that has concerned itself with quantifying MLDs has used earphones rather than loudspeakers in order to insure independent control of each aspect of the signal at each ear.

In these earphone studies, the binaural ability to select wanted from unwanted input signals improves (over the monaural ability) by amounts that are equivalent to an increase in level of a tonal signal by as much as 15 or 20 dB (which is equivalent to decreasing the noise by approximately the same amount), even though no *actual* change in signal or noise sound pressure occurs at either ear. The size of the change is striking. Such large shifts in masked threshold, though, only occur for non-intellective signals that contain low-frequency energy. For high-frequency signals, the changes are small, even under the most effective of binaural conditions. (That there is any MLD at all at high frequencies is still somewhat mysterious; for a theoretical view of the reasons, and also for an overview of masking-level-difference phenomena, see the papers by Durlach[1] and Jeffress.[8])

The maximum MDLs—the maximum changes in masked threshold—occur for the binaural conditions that are the most unusual and the least likely to be encountered in the real world. For example, one of the greatest improvements over monaural masking is found in the situation in which the same noise appears at both ears but the signal appears at only one ear. Another way to

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* In these tests, an in-phase binaural signal was compared with an out-of-phase binaural signal; both signals were generated in two loudspeakers. In many airplanes, the communication system has only one speaker, but the effect of two in-phase loudspeakers is perceptually the same as the effect of one loudspeaker located midway between the two.[2 7] We used the paired speakers in order to insure that the radiated acoustic energy would remain constant.

describe this same phenomenon is to consider the case in which a signal is turned on in one ear, and while it is there, enough noise is added to the same ear to mask out the tone. Then, when noise is added at the opposite ear, the tone again becomes audible. (A further implication is that, if the tone is also added at the opposite ear, it can no longer be heard.)

Other high-MLD situations are those in which the signal is presented to both ears identically, and the noise, presented to both ears, has its phase inverted (flipped, or shifted 180°) on one side. The converse situation is also a good one for producing release from masking. In it, the signal is flipped 180° and the noise is in phase at the two ears.

Both tonal and noise-band signals show large shifts in detectability under appropriate binaural conditions, but tests using speech signals[9 11 14 15] suggest quite a different pattern of analysis. In the best possible earphone-listening condition, a test of the binaural improvement in speech intelligibility (the *intelligibility-level difference* or ILD), translated into the amount of release from masking, turns out to be only 5 or 6 dB. Two reasons for this kind of lessening in signal-processing capability seem possible, and in all probability, both of them are active in producing the result. First, a listener who is asked to respond to the intelligibility of a signal rather than to its presence or its absence is operating at a sound pressure well above the masking noise, where the brain's ability to decrease the effectiveness of a masker may not be nearly so great or so important—the usual MLD study concerns itself with a threshold phenomenon, but since intelligibility is measured at suprathreshold levels, ILDs must be expected to result from a somewhat different sort of analysis. Second, the task of "understanding" rather than "detecting" is relatively quite complex; many workers have interpreted data on speech-signal reception to mean that a grossly different variety of mental function is used than is called for with tones, noise, clicks, or other non-intellective or non-semantic signals.[12] For most writers, the difference is partially explained by the additional mass of neural tissue required for speech analysis. The concept is sensible and easy to agree with. Most of the auditory nervous system (and perhaps large portions of the rest of the brain as well) seems to shift gears as soon as an acoustic input is recognized as speech; the analysis problem for intellective material is far more complex than for any other kind of signal that human observers receive.

A recent paper from this laboratory[14] reported a replication of the earphone findings for intelligibility-level differences, but the signal presentation system used pairs from a circular array of loudspeakers in an anechoic space. Despite the obvious differences between manipulating the phase of signals presented via earphones, and manipulating signal attributes with loudspeakers, each of whose outputs must reach both ears, at least to some degree, ILDs representing about a 5-dB shift in noise level are common. Thus, in this particular series of tests, it was found that one may produce nearly as much binaural effect on speech with loudspeaker presentations as with earphone presentations. This finding resulted from comparisons of the results from pairs of symmetrically placed loudspeakers that had both signal and noise in phase, with the same loudspeakers when they had noise in phase, but signals 180° out. For most subjects, the phase-reversed signals appear to originate inside the listener's head; this percept was first described in detail by Jeffress[7]; shortly afterward, Hanson and Kock[2] published an independent description. A number of investigators have experimented with the process since, and almost all of the work has been done in anechoic, semi-anechoic, or related sorts of sound-treated, low-reverberation chambers.

If this laboratory's findings[14] are to be applicable to a practical listening situation in which the intelligibility improvement might serve a safety function, it must be demonstrated that the ILD can still be created when the loudspeakers are mounted in reverberant surroundings. Further, natural situations need not have precisely correlated noise at the two ears. In order to test the effects of both of these deleterious conditions on the intelligibility-improving techniques previously investigated, an extremely difficult listening situation was selected: tests were performed in a light airplane, in flight.

II. Method.

In a Beech Bonanza rented for the purpose, three loudspeakers were mounted across the rear of the cabin ceiling (Figure 1). One loudspeaker was at either side of the cabin, and one was in the center; all faced forward. Each loudspeaker was wired to a control panel that permitted the selection of which loudspeakers were used at a given time, and also permitted the inversion of the phase at any loudspeaker (Figure 2). With this arrangement, it was possible to produce symmetrical or asymmetrical signals with any combination of phase relations for listeners in either front seat of the plane. For example, for the person riding in the co-pilot's position, the center and right-hand loudspeakers, used together, give a symmetrical signal; the right and left loudspeakers are asymmetrical.

The noise source for these tests was the aircraft itself. The cabin-noise intensities are representative of those to be found in most light, single-engine aircraft.[13] The signal was one of four modified-rhyme tests that were developed by the National Academy of Science–National Research Council Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) for use in testing aviators. Standardization of materials has been under way for several years at various government laboratories, primarily the Naval Aerospace Medical Research Laboratory at Pensacola, Florida (private communication, Carl Williams and Ronald Robertson). CHABA-furnished tapes were played on a battery-operated Nagra III tape recorder (which features exceptionally stable speed), then through an Amplivox S-402 amplifier (also battery operated) and a Hewlett-Packard 350B attenuator, and finally, via the phase-reversal and switching arrangement, through the appropriate loudspeaker.

Subjects were 32 men and 5 women, all selected for normal hearing, for age between 18 and 30 years, and for willingness to ride in a light air-

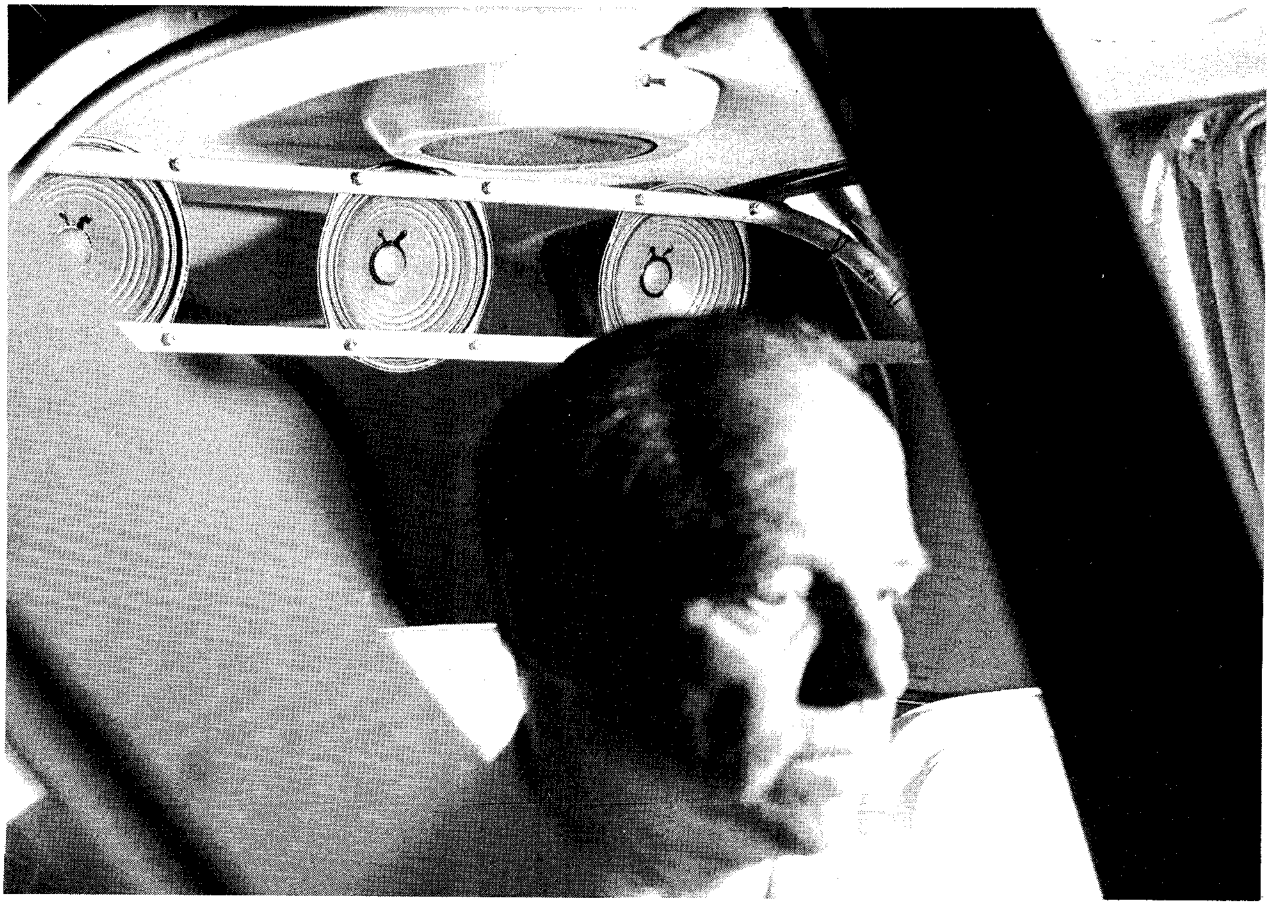

FIGURE 1. Loudspeaker-mounting bracket in rear of test airplane.

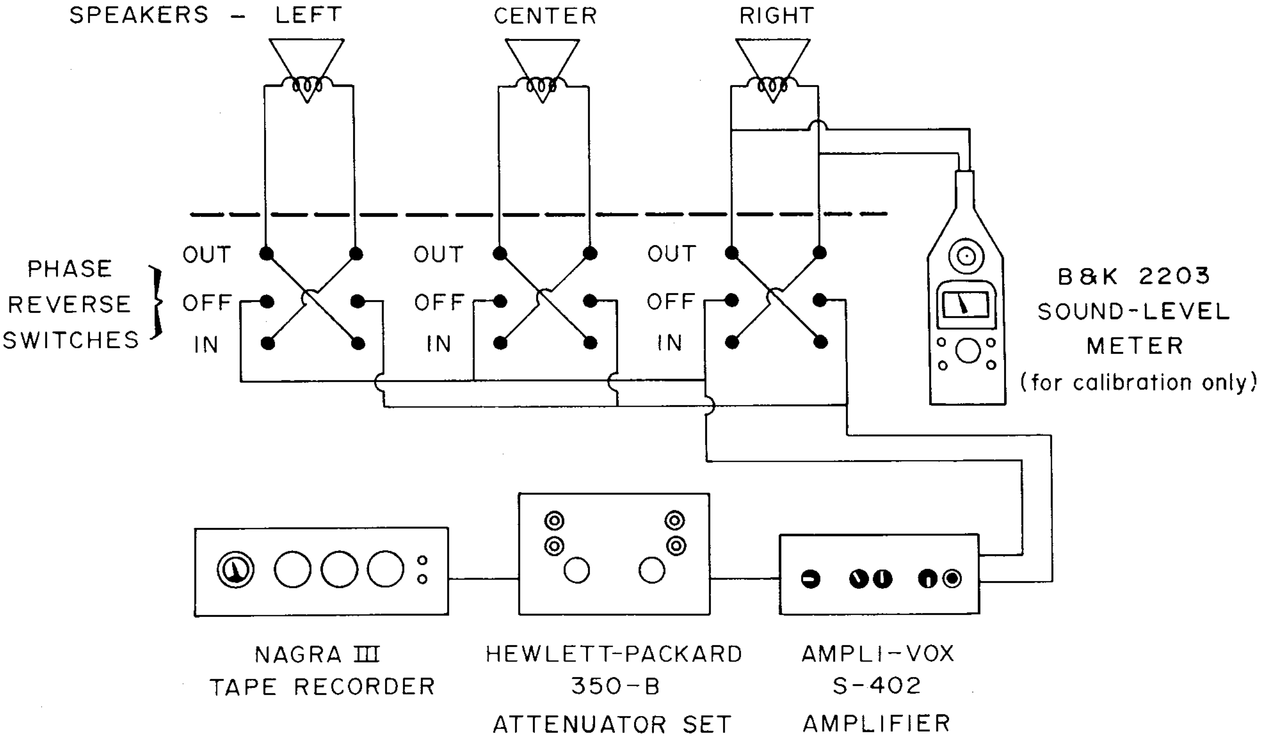

FIGURE 2. Diagram of signal-presentation equipment.

plane. The experimenter sat in the back seat with the equipment; subjects rode in the right-hand front seat, and carried a clipboard to which answer forms were attached. For each word on the test tape, the answer form listed six rhyming words, only one of which was correct. Subjects were instructed to mark which of the six words they thought they heard for each presentation. Instructions for the task were given before takeoff. Total time in the plane for each subject averaged less than 45 minutes.

The four lists of recorded test words were used in random order. In addition, four conditions were randomly assigned to the four lists: (1) the center and right-hand loudspeakers were used in phase with each other, (2) the center and right-hand loudspeakers were used out of phase with each other, (3) the left-hand and right-hand loudspeakers were used in phase, and (4) the left-hand and right-hand loudspeakers were used out of phase.

Signal levels were adjusted so that, when the plane was in level flight at cruising speeds, the signal-to-noise ratio was approximately the same as CHABA called –2dB on comparable recordings in noise. At this intensity, average scores varied between 30 and 50% for these subjects.

III. Results.

An analysis of variance was performed on the percent-correct intelligibility scores (Table 1). The lowest scores occurred for in-phase conditions, and the highest occurred for out-of-phase conditions. In statistical analyses, this difference in effectiveness in combating the masking effects of noise is significant ($p<.01$).

TABLE 1

Mean Intelligibility Scores

Symmetrical		Asymmetrical	
In-phase	Out-of-phase	In-phase	Out-of-phase
33.68	46.43	37.41	40.92
SD=9.56	SD=9.83	SD=8.57	SD=7.06

On a Newman-Keuls test, four comparisons of conditions show significant differences ($p<.01$): symmetrical in-phase is significantly different from symmetrical out-of-phase; symmetrical in-phase is significantly different from asymmetrical out-of-phase; asymmetrical in-phase is significantly different from symmetrical out-of-phase; and asymmetrical out-of-phase is significantly different from symmetrical out-of-phase. Other comparison were not significant.

No significant difference was found between symmetrical and asymmetrical presentations for in-phase conditions. However, a comparison of symmetrical with asymmetrical presentations for out-of-phase conditions shows the symmetrical pattern to be slightly better than the asymmetrical ($p<.01$). Clearly, a symmetrical, out-of-phase signal can be expected to lead to higher intelligibility than the asymmetrical, in-phase signal that is commonly available to light-aircraft pilots.

Preliminary to gathering the data, there was some concern that scores might improve as subjects learned the tasks. Tests of this possibility, though, indicate no measurable order effects.

IV. Discussion.

Numerically, the aircraft tests show a much smaller increase in intelligibility scores than was noted in the laboratory tests. Two kinds of reasons account for this difference—the first and more obvious reasons are those associated with those characteristics of the test environment that are relatively detrimental to the auditory system's ability to analyze binaural signals; the other reasons are a bit more subtle and are associated with differences in the test materials. The primary differences between the aircraft and the laboratory environments are reverberation and noise sources. In the laboratory tests, reverberation is kept to a level that is too small to measure; in the airplane, the bulkheads are highly reflective, which permits more of the signal from the contralateral loudspeaker to reach each ear, and that in turn must be expected to decrease the perceptual effect. In the laboratory, the noise source was arranged so that identical noise waveforms reached both ears simultaneously; in the airplane, noise sources include the combustion noises of the engine, exhaust noise, the sounds of air streaming past the fuselage, propeller noise, airframe rattles, and so on. Thus, unlike the situation in which an interaurally correlated, laboratory-produced noise produces the lowest possible baseline (as is the case for most MLD and ILD experiments), the relatively uncorrelated noise in an aircraft-listening situation produces a somewhat elevated baseline.

In the laboratory studies, the test materials were long passages of continuous discourse. In the aircraft study, the test lists comprised single words, which are much more difficult to understand because no context is available to offer cues as to what is coming next. Therefore, a given improvement in apparent signal-to-noise ratio produces a smaller measured change in intelligibility scores for the modified-rhyme test than for the continuous-discourse test. In order to compare the results of the two kinds of experiments, it is not appropriate to investigate ILDs, since they are so susceptible to variations in the test materials. Instead, those intelligibility values must be transformed into MLD values. In this case, the unpublished data from the Naval Aerospace Medical Research Laboratory on the modified-rhyme test show that the 12-15 percent increase in intelligibility score with the inversion of phase at one loudspeaker is equivalent to a noise decrease of about 2 dB. For the kind of speech material used in air-to-ground and ground-to-air transmissions, a 2-dB improvement might be expected to produce, instead, an increase of 20 percent or so in intelligibility. In the laboratory situation where the baseline values are determined for highly correlated noise, and where the reverberation is low, such a symmetrical, out-of-phase presentation might produce an increase of 40 percent or more.

V. Conclusions.

Free-field tests of binaural unmasking show that the human auditory system is capable of improving speech intelligibility for symmetrically placed, out-of-phase loudspeakers by an amount equivalent to a 4-dB shift in signal-to-noise ratio. Similar tests performed in the cabin of a light aircraft show the improvement to be equivalent to approximately 2 dB. The difference is attributable to a situation in which the noise is inhomogeneous, and in which both the signal and noise are subjected to modification by reverberant walls. Yet, even in this difficult listening situation, the brain's ability to select wanted from unwanted sounds can improve the intelligibility of ground-to-air transmissions by about 20 percent. In critical situations, such an improvement in apparent signal-to-noise ratio could make the difference between a safe and an unsafe flight.

References

1. Durlach, N. I.: Binaural Signal Detection: Equalization and Cancellation Theory. In: Tobias, J. V. (Ed.) *Foundations of Modern Auditory Theory. Volume II*, New York, Academic Press, 1972.
2. Hanson, R. L., and W. E. Kock: Interesting Effect Produced by Two Loudspeakers Under Free Space Conditions, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 29:145, 1957.
3. Hirsh, I. J.: Binaural Summation: A Century of Investigation, PSYCHOLOGICAL BULLETIN, 45:193–206, 1948.
4. Hirsh, I. J.: Binaural Summation and Interaural Inhibition as a Function of the Level of Masking Noise, AMERICAN JOURNAL OF PSYCHOLOGY, 61:205–213, 1948.
5. Hirsh, I. J.: The Influence of Interaural Phase on Interaural Summation and Inhibition, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 20:536–544, 1948.
6. Hirsh, I. J., and F. A. Webster: Some Determinants of Interaural Phase Effects, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 21:496–501, 1949.
7. Jeffress, L. A.: Method for the Study of the Localization of Airborne Sound, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 27:208, 1955.
8. Jeffress, L. A.: Binaural Signal Detection: Vector Theory. In: Tobias, J. V. (Ed.) *Foundations of Modern Auditory Theory. Volume II*, New York, Academic Press, 1972.
9. Levitt, H., and L. R. Rabiner: Binaural Release from Masking for Speech and Gain in Intelligibility, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 42:601–608, 1967.
10. Licklider, J. C. R.: The Influence of Interaural Phase Relations Upon the Masking of Speech by White Noise, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 20:150–159, 1948.
11. Schubert, E. D.: Some Preliminary Experiments on Binaural Time Delay and Intelligibility, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 28:895–901, 1956.
12. Stevens, K. N., and A. S. House: Speech Perception. In: Tobias, J. V. (Ed.) *Foundations of Modern Auditory Theory. Volume II*, New York, Academic Press, 1972.
13. Tobias, J. V.: Cockpit Noise Intensity: Fifteen Single-Engine Light Aircraft, AEROSPACE MEDICINE, 40:963–966, 1969.
14. Tobias, J. V.: Auditory Processing for Speech Intelligibility Improvement, AEROSPACE MEDICINE, 41:728–733, 1970.
15. Tobias, J. V., and J. F. Curtis: Binaural Masking of Noise by Noise, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 31:127, 1959.