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DEVELOPMENT OF AN ANNOYANCE MODEL BASED UPON ELEMENTARY AUDITORY SENSATIONS FOR STEADY-STATE AIRCRAFT INTERIOR NOISE CONTAINING TONAL COMPONENTS

JAMES R. ANGERER
BOEING COMMERCIAL AIRPLANE GROUP
SEATTLE, WASHINGTON

DAVID A. MCCURDY
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

RICHARD A. ERICKSON
BOEING COMMERCIAL AIRPLANE GROUP
SEATTLE, WASHINGTON

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FOREWORD

Introduction

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Explanation of this document's unique structure

Documents such as this one which have been prepared using the writing techniques developed by Information Mapping are characterized by a page structure called a "map." Each map is normally one to two pages in length (although there are several exceptions in this report) with a "map title" in the upper left-hand corner identifying the map's contents. When maps exceed a single page, the note "Continued on next page" appears to the right and immediately below the body of the text. A map is used to convey a single idea or concept with maps grouped and indexed in hierarchical fashion to convey higher level ideas. In this report, maps coincide with the numbered sections and subsections. Maps are subdivided into blocks of information which are delineated by horizontal lines and possess a short descriptive label in the left margin to orient the reader to each block's content as well as to provide a rapidly scanned index to the entire map. Blocks of information are not required nor intended to be paragraphs and, therefore, do not in general possess the grammatical structure of a paragraph.

Advantages

Documents employing the writing and formatting concepts taught by Information Mapping are intended to 1) be more easily read and understood, 2) increase reader comprehension of what has been read, and 3) allow readers to find specific information more rapidly by quickly identifying that which is of specific interest. An ancillary future benefit is that these documents are extremely well suited to online browsing using hypermedia tools.

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1.0 PURPOSE and SCOPE

Purpose of investigation

The purpose of this investigation was to develop a noise annoyance model, superior to those currently in use, for evaluating passenger response to sounds containing tonal components which may be heard within current and future commercial aircraft.

Noise characteristics investigated

The sound spectra investigated range from those being experienced by passengers on board turbofan-powered aircraft now in service to those cabin noise spectra passengers may experience within advanced propeller-driven aircraft of the future .

Of primary interest were the effects on passenger annoyance of the following spectral features:

- broadband background noise
- engine once-per-revolution (rotor) tones
- rotor tone harmonics
- rotor tone beating
- propeller blade passage tones
- propeller blade passage tone harmonics
- propeller blade passage tone beating

Scope of this report

A total of 240 sounds were tested in this experiment. Sixty-six of these 240 sounds were steady-state while the other 174 varied temporally due to tonal beating. This report describes the entire experiment, but is limited to an analysis of those responses elicited by the 66 steady-state sounds.

2.0 MOTIVATION

Background

Aircraft passenger cabin noise spectra are often comprised of tones imbedded in broadband noise. Tones emanate from the engines as well as from many of the mechanical systems on board turbofan-powered commercial aircraft. In the future, the introduction of advanced turboprop propulsion systems will result in propeller-induced tones in addition to other normally encountered tonal components.

Aircraft designer's goal

Because the noise control measures used to control broadband noise within aircraft passenger cabins usually differ from those for controlling tones, a certain degree of discretion is available to the aircraft designer in determining the mix between tones and broadband noise heard by passengers. The desired mix is one which assures passenger comfort while minimizing noise control costs. At the moment no reliable means is available for the designer to determine what the actual mix should be or to understand how changes in the spectra required by economic considerations will influence passenger comfort.

Needs of the airline industry

In 1988 the International Air Transport Association (IATA) published: "Guidance Material on Assessment and Future Improvements in Aeroplane Interior Noise Levels". In this document, IATA states that A-weighted sound pressure level (L_A) "should be used for summarizing the subjective response to ... noise" and "encourages" member airlines to use L_A "as a basis in developing their purchase specifications." Complimenting the above recommendation to the airlines is another statement addressed to aircraft manufacturers which "urges" them to use L_A in "setting their design goals." The recommendation to use L_A is a departure from the customary use of Overall Sound Pressure Level (OASPL) by the builders and operators of large commercial jet aircraft. This change, as well as the publishing of the entire document, was motivated by IATA's claim of persistent interior noise problems, some of which are due to tones, and the potential for significant future cabin noise problems with the introduction of propfan-powered aircraft - aircraft in which cabin noise will almost certainly contain tones. Clearly IATA is dissatisfied with OASPL as an annoyance metric, and although they now advocate the use of L_A as the preferred alternative, they also recognize in the document that specifying noise requirements solely in terms of L_A is insufficient to assure passenger comfort while minimizing noise control costs. Thus there remains a need within the airline industry for a single, reliable metric for quantifying passenger response to tone/noise complexes.

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Problems with existing metrics

We know from an increasing number of investigations (Shepherd *et al.* (1983) and Kjellberg *et al.* (1984) being just two examples) that traditional single-number metrics such as L_A are inadequate annoyance predictors, particularly for sounds containing tonal components or high levels of low frequency energy, spectral types found in some aircraft passenger cabins. In addition, tone correction procedures have not been uniformly successful (Shepherd *et al.*, 1983; McCurdy, 1988) at compensating for deficiencies in the basic metrics. As a result, existing noise metrics cannot be relied upon to meet the needs of aircraft designers or the airline industry.

Scope of prior research

There is no adequate body of data to draw upon to understand the combined effect on passenger comfort of broadband steady-state sounds containing multiple tones and their related harmonics. While there have been numerous studies of annoyance, noisiness, loudness, and unacceptability due to aircraft noise over the past four decades - see Scharf *et al.* (1977a, 1977b) for a partial list - the combined scope of these many individual studies is inadequate for confidently developing a composite annoyance metric applicable to the broad range of spectral and temporal characteristics now of interest.

References

International Air Transport Association, "Guidance Material on Assessment and Future Improvements in Aeroplane Interior Noise Levels," Document GEN / 2967 (1988).

Kjellberg A., Goldstein M., and Gamberale F., "An Assessment of dB(A) for Predicting Loudness and Annoyance of Noise Containing Low Frequency Components," J. Low Frequency Noise and Vibration, 3(3):10-16 (1984).

McCurdy D.A., "Annoyance Caused by Advanced Turboprop Aircraft Flyover Noise: Single-Rotating Propeller Configuration," NASA TP-2782 (1988).

Scharf B., Hellman R.P., and Bauer J., " Comparison of Various Methods for Predicting the Loudness and Acceptability of Noise," U.S. Environmental Protection Agency, Report 550/9-77-101 (1977a).

Scharf B. and Hellman R.P., "Comparison of Various Methods for Predicting the Loudness and Acceptability of Noise, Part II: Effects of Spectral Pattern and Tonal Components," U.S. Environmental Protection Agency, Report 550/9-79-102 (1977b).

Shepherd K.P., Leatherwood J.D., and Clevenson S.A., "Effect of Low-Frequency Tones and Turbulent-Boundary-Layer Noise on Annoyance," NASA TP-2202 (1983).

3.0 TEST METHODOLOGY

Synopsis

Seventy-two audiologically normal subjects were asked to use magnitude estimation to judge the annoyance of 240 sounds simulating passenger cabin sounds within current and future commercial aircraft. These test sounds were presented to the test subjects in an anechoic listening environment. The spectral characteristics investigated were:

- broadband background noise
- engine once-per-revolution (rotor) tones
- rotor tone harmonics
- rotor tone beating
- propeller blade passage tones
- propeller blade passage tone harmonics
- propeller blade passage tone beating

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3.1 TEST FACILITIES

Synopsis

Testing was conducted at the NASA Langley Acoustics Research Laboratory in the small anechoic listening room. Test stimuli were synthesized using the laboratory's digital synthesis system, then pre-recorded for later presentation to the test subjects. Subjects recorded their responses using HP 41-CV hand-held calculators which interfaced with the computer controlling the sound presentation sequence.

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3.1.1 TEST ENVIRONMENT

Test chamber

Testing was conducted at the NASA Langley Acoustics Research Laboratory in the small anechoic listening room. This room, shown in the photograph below, has dimensions of 4.0 by 2.5 by 2.5 meters and has seating for two test subjects. Additional details on this facility are contained in NASA Technical Memorandum 81975 (Hubbard and Powell, 1981).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Test chamber environment

Special care was necessary throughout the test program to insure the comfort of subjects. Because testing was conducted during the winter season and the chamber's temperature control system was out of order, chamber temperatures were often sufficiently cool that subjects donned their coats and remarked about the temperature. Comfortable temperatures, to the degree possible, were maintained by having the chamber doors open except during actual testing. In addition to the steps taken to maintain comfortable temperatures within the test chamber, subjects were offered the opportunity to leave the chamber for a few minutes between the one-half hour test sessions. Lighting within the chamber was adjusted to insure that the displays and keyboards of the hand-held calculators used by the subjects for recording responses were easily readable.

Reference

Hubbard H.H. and Powell C.A., "Acoustic Facilities for Human Factors Research at NASA Langley Research Center - Description and Operational Capability," NASA TM-81975 (1981).

3.1.2 SOUND SYNTHESIS AND REPRODUCTION PROCESS

Introduction

Synthesized sound stimuli were used in this experiment in place of actual aircraft interior noise recordings. These stimuli were not, however, synthesized in real time during testing itself but, rather, pre-recorded and played back for subject evaluation later. This section describes the synthesis and playback processes.

Sound synthesis process

The test stimuli were synthesized using the NASA Langley Aircraft Noise Synthesis System. A detailed description of this system is provided in NASA Technical Memorandum 89040 (McCurdy and Grandle, 1987). Based upon input for the desired spectral characteristics of each stimulus (given in Section 3.2: Test Stimuli), a digital waveform was created and output via a D/A converter through a one-third octave band equalizer and ramping switch to an Ampex ATR-100 tape recorder. The equalizer was adjusted to correct for frequency response variations in the sound reproduction system. The ramping switch introduced a 2 second ramp-up and a 1/2 second ramp-down at the beginning and end of each stimuli, respectively.

Sound reproduction process

Pre-recorded sounds were presented to test subjects using an Ampex ATR-100 tape recorder under computer control. The tape recorder output signal was fed through a computer-controlled attenuator and power limiter switch before being split and routed to high- and low-pass Rockland filters (100 Hz cut-off). The output from the low-pass filter, after passing through an Altec amplifier, went to a VMPS Larger Subwoofer. The signal from the high-pass filter, after amplification by a Crown amplifier, went to an Altec speaker. The power limiter switch was preset to insure subjects were not inadvertently exposed to unsafe noise levels.

A DEC LSI-11 computer was used to control both the tape recorder and the attenuator. Computer control provided the flexibility for varying the stimuli presentation order and level according to the needs of the experiment without having pre-recorded sequences of all the desired combinations.

Continued on next page

Frequency response corrections

To assure that sound stimuli would be accurately reproduced at the subjects' head positions, a microphone was mounted at seated head-height midway between the two seat positions to measure the frequency response characteristics of the sound transmission path between the tape recorder and test subjects. Compensation for frequency response variations was handled by a one-third octave band graphic equalizer in the sound synthesis system. In addition, because of the low frequencies involved, the frequency response of the tape recorder, which is flat in the mid-to-high frequency region, was also measured and corrected for.

Perceived realism of synthesized sounds

The realism of sounds created using the synthesis system is attested to by McCurdy and Grandle (1987). They report that, in similar previous studies, few subjects were aware that the sounds heard were artificial rather than actual recordings of aircraft noise and that annoyance responses in those studies to actual aircraft noise recordings were comparable to those responses elicited by synthesized sounds of the same event.

Reference

McCurdy D.A. and Grandle R.E., "Aircraft Noise Synthesis System," NASA TM-89040 (1987).

3.1.3 DATA ACQUISITION PROCESS

Data acquisition process

Subject responses were recorded using HP-41CV hand-held calculators. These calculators were programmed to receive a stimulus identification number from the DEC LSI-11 computer controlling the presentation of stimuli to the test subjects. The electronic transmission of this I.D. number was accomplished via an HP-IL interface. On receipt of this number, the calculators displayed the message "LISTEN" to alert subjects that the next stimulus was about to be presented. After a predetermined interval which allowed the aural stimulus to be heard, the calculators prompted the subjects for a response with the message "RESPOND." The calculators were programmed to accept only those responses entered during the quiet period following the presentation of each stimulus. Subjects were able to enter as many responses as they wished; the calculator saved only the last entry when the "LISTEN" prompt reappeared to call attention to the next stimulus. Responses were automatically stored in the calculator memory register coinciding with the stimulus I.D. number. After the testing of each subject pair was complete, the contents of the calculator storage registers were transferred to a personal computer via an RS-232 interface.

Calculator appearance

To minimize the distraction from the many calculator keys and labels which were irrelevant to our experiment, each calculator was fitted with a special hood to cover all but the 0 through 9 keys. In addition, the labels appearing on the keyboard face plate were masked with an unmarked overlay template. The calculators and connecting cables were bonded with double-back tape to clipboards to provide the test subjects with a comfortable platform upon which to use the calculators and to assure that cables connected to the calculators would not be inadvertently disconnected. The calculator as seen by the test subjects is shown in the photograph below.

3.2 TEST STIMULI

Synopsis

In this experiment, test subjects were exposed to 240 sounds. Of these 240 sounds, 66 were steady-state while the remaining 174 varied temporally due to tonal beating. The stimuli tested were an amalgamation of four different groups of sounds:

- broadband sounds falling within Beranek's preferred spectrum band
- sounds experienced by passengers on board turbofan-powered aircraft now in service
- cabin sounds passengers may experience within advanced propeller-driven aircraft of the future
- subset of sounds tested by Hellman

The spectral characteristics investigated were:

- broadband background noise
- low frequency rotor tones
- rotor tone harmonics
- rotor tone beating
- propeller blade passage tones
- propeller blade passage tone harmonics
- propeller blade passage tone beating

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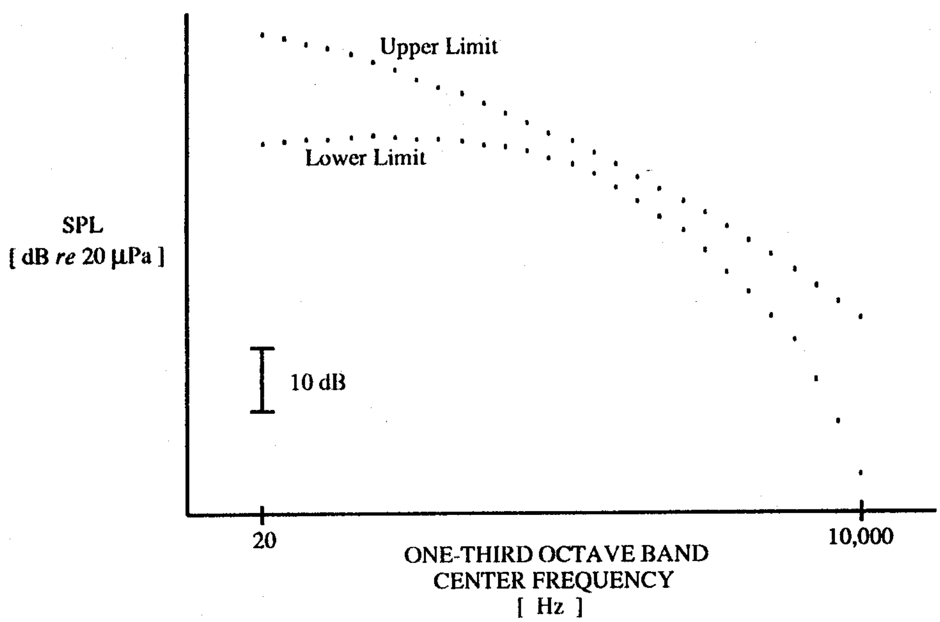
3.2.1 BROADBAND STIMULI

Introduction

Beranek (1971) recommends that, for occupant satisfaction, background noise spectral shapes within offices should fall within a limited band, hereafter referred to as the preferred spectrum band. There is no reason to suppose that individuals would prefer vastly different spectral shapes in other situations. Presumably spectral shapes judged acceptable in an office environment would be considered equally desirable in a transportation vehicle, for example. Perhaps fortunately, the broadband portion of noise within commercial aircraft passenger cabins falls approximately within this band. Because the wide variety of spectral shapes possible within this band can be perceptually quite different, however, the question arises whether there are spectral shapes within the band which are to be preferred over the alternatives. To determine if the sharpness concept introduced by Bismarck (1974) and later refined by Aures (1985) will satisfactorily differentiate preferences between broadband sounds differing only in spectral shape, a range of shapes was tested, all but one of which fall within Beranek's preferred spectrum band.

Preferred spectrum band



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Spectral shapes & levels tested

Spectral Shape Designation	Description*	Levels Tested: OASPL [dB]
BERLC	Coincident with lower boundary of Beranek's preferred spectrum band.	78 84 87 96
LOMED	Transition from lower boundary to median curve lying midway between upper and lower boundaries of Beranek's preferred band.	78 87 96
BERMDC	Transition from lower to upper boundary of Beranek's preferred spectrum band.	78 87 96
BERMC	Median curve lying midway between upper and lower boundaries of Beranek's preferred spectrum band.	78 87
MEDUP	Transition from median curve to upper boundary of the preferred spectrum band.	87
OUTSID	White noise with high frequency roll-off following the upper boundary of Beranek's preferred spectrum band.	78 81 84 87 90 93 96

* Spectra are illustrated relative to Beranek's preferred spectrum band on the following page.

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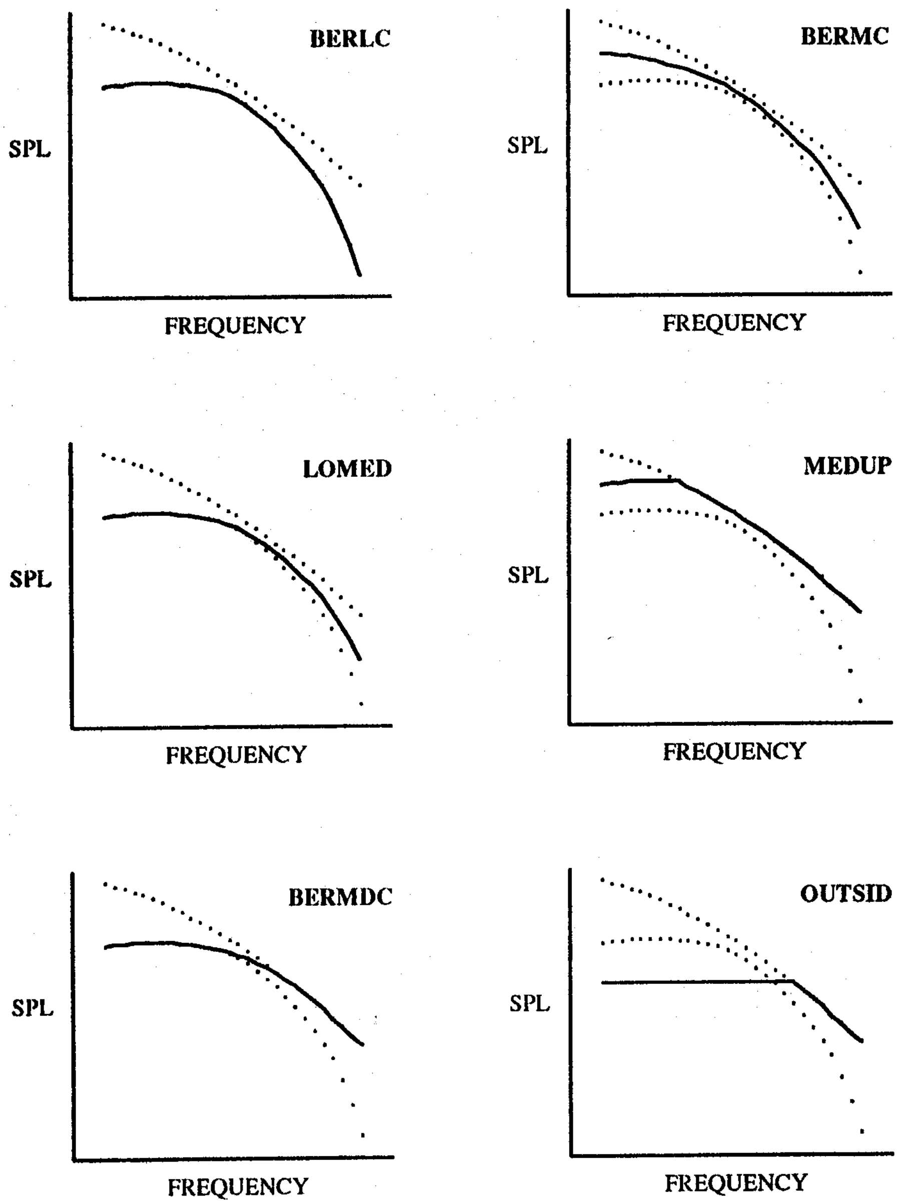
Comparison to preferred spectrum band

Graphic illustration of the six basic background spectral shapes tested (solid line) relative to Beranek's preferred spectrum band (upper and lower boundaries indicated by dotted lines):



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Spectral shape tabulations

Relative one-third octave band sound pressure levels (dB *re* 20 μPa) for 20 Hz through 10 kHz:

Band No.	BERLC	LOMED	BERMDC	BERMC	MEDUP	OUTSID
13	58.5	58.5	58.5	67.0	66.6	47.3
14	58.8	58.8	58.8	66.8	66.9	47.3
15	59.0	59.0	59.0	66.5	67.2	47.3
16	59.2	59.2	59.2	66.2	67.5	47.3
17	59.4	59.4	59.4	65.9	67.7	47.3
18	59.6	59.6	59.6	65.4	67.8	47.3
19	59.4	59.4	59.4	64.7	67.7	47.3
20	59.2	59.2	59.2	63.9	67.5	47.3
21	59.0	59.0	59.0	63.2	67.3	47.3
22	58.8	58.8	58.8	62.5	66.1	47.3
23	58.3	58.3	58.3	61.5	64.7	47.3
24	57.8	57.8	57.8	60.5	63.2	47.3
25	57.3	57.3	57.3	59.4	61.8	47.3
26	56.1	56.4	56.7	58.2	60.2	47.3
27	55.0	55.5	55.9	56.9	58.7	47.3
28	53.6	54.3	55.0	55.3	56.9	47.3
29	51.5	52.6	53.6	53.4	55.2	47.3
30	49.4	50.8	52.2	51.3	53.3	47.3
31	46.8	48.9	50.9	48.9	51.4	47.3
32	44.5	46.9	49.2	47.0	49.5	47.3
33	41.5	44.4	47.3	44.4	47.3	47.3
34	38.2	41.8	45.3	41.7	45.3	45.3
35	35.1	39.2	43.2	39.2	43.1	43.2
36	31.5	36.2	40.9	36.2	40.8	40.9
37	27.6	33.0	38.4	33.0	38.4	38.4
38	21.4	28.7	36.0	28.7	36.0	36.0
39	15.0	24.3	33.6	24.3	33.8	33.6
40	7.0	19.1	31.2	19.1	31.1	31.2

References

Aures W., "Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale, " Acustica, 59(2):130-141 (1985).

Beranek L.L., "Criteria for Noise and Vibration in Communities, Buildings, and Vehicles," In: Noise and Vibration Control, L.L. Beranek, ed., New York: McGraw-Hill Book Company (1971).

v. Bismarck G., "Sharpness as an Attribute of the Timbre of Steady Sounds," Acustica, 30(3):159-172 (1974).

3.2.2 TURBOFAN-POWERED AIRCRAFT STIMULI

Introduction

The noise spectra presented in this section are representative of cabin sounds possible, although not all equally likely, within twin engine, turbofan-powered aircraft now in service.

Variables & levels tested

Spectrum Shape	Background OASPL [dB]	Rotor Frequency [Hz]	Tone Emergence [dB]	Beat Frequency [Hz]	Beat Amplitude [% a.m.]
BERLC	73	20	0	0.2	0
LOMED	76	30	5	0.4	20
BERMDC	79	40	10	0.8	40
BERMC	82	50	15	1.0	60
MEDUP	85	60	20	2.0	80
OUTSID	88	70	25	4.0	100
	91	80	30	8.0	

Variable descriptions

Spectrum Shape: Specifies one of six broadband spectral shapes. Detailed descriptions, plots and one-third octave band sound pressure level tabulations for these six spectral shapes are provided in Section 3.2.1: Broadband Stimuli.

Background OASPL: Specifies the Overall Sound Pressure Level [dB], computed from the 20 Hz through 10 kHz one-third octave bands, for the broadband spectrum.

Rotor Frequency: Specifies the rotational frequency of the engine #1 fan shaft.

Tone Emergence: Specifies rotor tone amplitudes in decibels relative to the SPL of the background noise in the surrounding one-third octave band.

Beat Frequency: Defines the rotational frequency of the engine #2 fan shaft relative to the rotational frequency of engine #1.

Beat Amplitude: Specifies the pressure ratio between the two rotor tones in terms of percent amplitude modulation. For example, the pressure ratio $p_i / p_j = 0.8$ is equivalent to an amplitude modulation of 80%.

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Experimental design

7x7 Latin Squares (Appendix A) were used to transform the six variables and their respective ranges of values into 49 stimuli approximately uniformly distributed in the six dimensional variable space. The random assignment of the six variables to the six Latin Squares and the random assignment of the Latin Square indices to the variable levels is presented in Appendix B.

Deviations from the experimental design

Not all stimuli resulting from the Latin Square design were acceptable. A summary of the problems and incremental actions taken to resolve these problems follows.

PROBLEM	SOLUTION
Stimuli exceeded the safety requirement that playback levels not exceed an L_A value of 95 dB.	Reduced the background OASPL in 3 dB increments until compliance was achieved or until the background OASPL was reduced to 73 dB, whichever came first; If stimulus still non-compliant, then reduced the tone emergence in 5 dB increments until compliance was achieved or an emergence of −15 dB was reached, whichever came first; If stimulus still non-compliant, then discarded the stimulus.
Stimuli containing high amplitude, low frequency tonal components exceeded the capability of the speaker system to reproduce them without distortion.	Reduced the tone emergence in 5 dB increments until the total sound pressure level in the 20 through 100 Hz one-third octave bands was below 96 dB or an emergence of −15 dB was reached, whichever came first (when this option was exercised, changes made previously to meet the L_A requirement of 95 dB were reviewed and reversed if possible); If stimulus still non-compliant, then discarded the stimulus.

3.2.3 ADVANCED PROPELLER-DRIVEN AIRCRAFT STIMULI

Introduction

The noise spectra presented in this section are representative of cabin sounds passengers may experience within twin engine, advanced propeller-driven commercial aircraft of the future. The engines were assumed to be driving counter-rotating propellers.

Assumptions

In choosing the variables for investigation, the following assumptions were made concerning the operating characteristics of the hypothetical engines:

1. The rotor speeds of the forward and aft propellers on a given engine are identical.
2. The fundamental blade passage tones of the forward and aft propellers exhibit the same number of harmonics.
3. The amplitudes of harmonic tones are exponentially related to the amplitude of the fundamental. A complete description of the assumed relationship is provided in Appendix C.

Variables & levels tested

Tabulated below and on the following page, are the 12 variables and the levels tested for each, segregated to highlight the connection between the audible, engine-related noise sources anticipated within future aircraft and those spectral characteristics related to these sources which were chosen for investigation. Subdividing what would have been a single large table into four smaller tables also facilitates presenting the information, since one larger table could not be accommodated on a single page.

BROADBAND NOISE

Spectrum Shape	Background OASPL [dB]
BERLC	76
LOMED	79
BERMDC	82
BERMC	85
MEDUP	88
OUTSID	

Continued on next page

Variables & levels tested - cont'd

ROTOR TONES

Rotor Frequency [Hz]	Tone Emergence [dB]	Number of Harmonics	Beat Frequency [Hz]	Beat Amplitude [% a.m.]
20	-12	0	0.2	0
30	-8	1	0.4	20
40	-4	2	0.6	40
50	0	3	0.8	60
60	4	4	1.0	80
70	8		2.0	100
80	12		4.0	
90	16		6.0	
100	20		8.0	
250	24		10.0	
500	28		12.0	
1000				

FORWARD PROPELLER TONES

Blade Pass. Frequency [Hz]	Tone Emergence [dB]	Number of Harmonics
$6F_R$*	-12	0
7	-8	1
8	-4	2
9	0	3
10	4	4
11	8	
12	12	
13	16	
14	20	
	24	
	28	

AFT PROPELLER TONES

Blade Pass. Frequency [Hz]	Tone Emergence [dB]
$6F_R$*	-12
7	-8
8	-4
9	0
10	4
11	8
12	12
13	16
14	20
	24
	28

*$F_R \equiv$ Rotor frequency

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Variable descriptions

Spectrum Shape:	Specifies one of six broadband spectral shapes. Detailed descriptions, plots and one-third octave band sound pressure level tabulations for these six spectral shapes are provided in Section 3.2.1: Broadband Stimuli.
Background OASPL:	Specifies the Overall Sound Pressure Level [dB], computed from the 20 Hz through 10 kHz one-third octave bands, for the broadband spectrum.
Rotor Frequency:	Specifies the rotational frequency of the engine #1 fan shaft. Rotor tone frequencies greater than 100 Hz were special cases not intended to be representative of current or future engines.
Tone Emergence:	Specifies tone amplitudes in decibels relative to the SPL of the background noise in the surrounding one-third octave band.
Beat Frequency:	Defines the rotational frequency of the engine #2 fan shaft relative to the rotational frequency of engine #1.
Beat Amplitude:	Specifies the pressure ratio between corresponding tones from the two hypothetical engines in terms of percent amplitude modulation. For example, the pressure ratio $p_i / p_j = 0.8$ is equivalent to an amplitude modulation of 80%.
Blade Passage Frequency:	Defines propeller blade passage frequencies as an integral multiple of the rotor frequency.
Number of Harmonics:	Defines the number of harmonics, or overtones, to accompany the fundamental rotor tone or forward and aft propeller blade passage tones.

Experimental design

13x13 Latin Squares (Appendix D) were used to transform the 12 variables and their respective ranges of values into 169 stimuli approximately uniformly distributed in the 12 dimensional variable space. The random assignment of the 12 variables to the 12 Latin Squares and the random assignment of the Latin Square indices to the variable levels is presented in Appendix E.

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Deviations from the experimental design

Not all stimuli resulting from the Latin Square design were acceptable. A summary of the problems and incremental actions taken to resolve these problems follows.

PROBLEM	SOLUTION
When rotor tone frequenies were greater than 100 Hz, propeller blade passage tones and/or harmonics usually exceeded the upper frequency limit of the synthesizer.	Omitted propeller blade passage tones and their related harmonics when the fundamental blade passage frequency exceeded 2200 Hz.
Stimuli exceeded the safety requirement that playback levels not exceed an L_A value of 95 dB.	Reduced the background OASPL in 3 dB increments until compliance was achieved or until the background OASPL was reduced to 76 dB, whichever came first; If stimulus still non-compliant, then reduced the rotor tone emergence in 4 dB increments until compliance was achieved or an emergence of −12 dB was reached, whichever came first; If stimulus still non-compliant, then discarded the stimulus.
Stimuli containing high amplitude, low frequency tonal components exceeded the capability of the speaker system to reproduce them without distortion.	Reduced the rotor tone emergence in 4 dB increments until the total sound pressure level in the 20 through 100 Hz one-third octave bands was below 96 dB or an emergence of −12 dB was reached, whichever came first (when this option was exercised, changes made previously to meet the L_A requirement of 95 dB were reviewed and reversed if possible); If stimulus still non-compliant, then discarded the stimulus.

3.2.4 HELLMAN'S STIMULI

Introduction

A very limited subset of spectra tested by Hellman (1985) in an earlier study of noise annoyance was included in this experiment as a cursory check of the patterns seen in her annoyance data. This interest was tangential to the primary focus of our experiment.

Hellman's spectra

Six stimuli were tested from Hellman's experiment based upon her case of a 250 Hz tone imbedded in an 80 dB OASPL low-pass noise spectrum. The emergence of the tone, relative to the 250 Hz one-third octave band noise level, was increased in 5 dB increments from 5 to 30 dB. The low-pass noise spectrum was as follows:

Band No.	1/3 o.b. SPL [dB]
17	60.0
18	62.0
19	64.0
20	64.0
21	65.0
22	67.0
23	67.5
24	70.9
25	71.9
26	68.5
27	68.5
28	68.5
29	68.0
30	67.0
31	66.5
32	66.0
33	65.5
34	64.0
35	62.0
36	61.5
37	61.0
38	60.5
39	60.0
40	59.5

Reference

Hellman R.P., "Contribution of Tonal Components to the Overall Loudness, Annoyance, and Noisiness of Noise," NASA CR-3892 (1985).

3.2.5 TEMPORAL CHARACTERISTICS COMMON TO ALL STIMULI

Introduction

In addition to the unique spectral characteristics each stimulus possesses, all stimuli shared several common temporal characteristics. These common characteristics are described below.

Duration

Each stimulus was approximately 15 seconds in duration.

Stimuli onset / offset times

Stimuli onset and offset were controlled using a linear ramping switch. This switch was set to provide a 2 second ramp-up at the beginning of each stimulus and a one-half second ramp-down at the end. The 2 second onset was chosen after experimenting with shorter onset times and determining that 2 seconds was required to minimize the startle reaction which accompanied the presentation of the louder stimuli.

Random amplitude variations

The sound synthesis process introduces random amplitude variations in the time signal to improve the realism of the simulation. The modulation process is described below by quoting from the original source (McCurdy and Grandle, 1987):

> "The final part of the digital time-history generation procedure is to modulate the time history .... To produce these fluctuations, ... the time history is modulated by a slowly varying function. ... The amplitude of the modulation is inversely proportional to the ratio of the present root-mean-square value of the time history to the peak root-mean-square value of the time history. The modulation function is created by multiplying this amplitude function times a function derived from two sets of random numbers. The first set of random numbers is used to determine the lengths of a series of ramps of linearly varying amplitude. The maximum amplitude of each ramp is determined by a second series of random numbers between zero and one. The mean length for the ramps was chosen to be 0.3 sec. The time-history modulation is achieved by multiplying the time history by the modulation function."

Reference

McCurdy D.A. and Grandle R.E., "Aircraft Noise Synthesis System," NASA TM-89040 (1987).

3.3 TEST PROCEDURES

Synopsis

Seventy-two audiologically normal subjects were asked to use magnitude estimation to judge the annoyance of 240 sounds simulating passenger cabin sounds within current and future commercial aircraft. These sounds were presented in four one-half hour sessions of 60 sounds each, each session preceded by a reference sound against which the other sounds within the session were judged. To prepare subjects for this task, they were first trained in using magnitude estimation using a line-length estimation exercise. This was immediately followed with an annoyance judgment training exercise modelled after the experiment itself.

Index

3.3.1 SUBJECTS

Selection process

Eighty-six volunteer subjects were obtained from a contractual subject pool of local residents and were paid for their participation in the experiment.

Hearing acuity

All test subjects were administered audiograms (125 Hz - 6 kHz) prior to the experiment to verify normal hearing. Hearing was considered normal if thresholds were within 25 dB of audiometric zero as defined in ANSI S3.6 - 1969.

Prior test experience

The subjects were naive about the magnitude estimation test technique but several had participated in similar experiments employing category rating.

Age / gender distribution

The subject group consisted of 25 males and 61 females. Ages ranged from 20 to 62 years with a mean age of 36.5 years and a median age of 33 years. A summary of the age distribution by gender follows:

MALES		FEMALES		
20	28 (2)	21	34	47 (3)
21	29	22 (4)	36 (2)	48 (3)
23	32 (6)	23	37	51 (2)
24	33 (2)	24	38	53 (2)
25 (4)	34	26 (2)	39 (3)	54
26	39	27 (2)	40 (3)	55
27	44	28 (2)	41	56
		29	43	59
		30 (3)	44	60
		32 (4)	45 (3)	61 (2)
		33 (2)	46	62 (2)

Reference

American National Standards Institute, "Specifications for Audiometers," S3.6 - 1969.

3.3.2 EXPERIMENTAL DESIGN

Introduction

The conversion of the variables of interest into testable stimuli is covered in Section 3.2: Test Stimuli. We now address the sequence in which these stimuli were presented to the test subjects. The presentation order is based upon a Latin Square procedure developed by Cochran (1939) to adjust for residual effects from treatments applied in sequence.

Grouping and randomization of the stimuli

The individual groupings of stimuli defined in Section 3.2 were regrouped into four new randomized groups of 60 sounds each. This was accomplished by first uniformly interweaving the stimuli from the four original groups into a single list of 240 sounds. This list was then re-divided into four new groups of 60 sounds each by successively distributing the stimuli one at a time, the first to group A, the second to group B, the third to group C, the fourth to group D, then repeating this sequence so that in the end the 1st, 5th, 9th, ..., and 237th stimulus were in group A, the 2nd, 6th, 10th, ..., and 238th stimulus in group B and so forth. This strategy insured that the sounds were uniformly distributed among the four groups A through D. The stimuli order within each group was then randomized.

Stimuli presentation sequence

Testing was originally organized to be completed in three weeks plus one day. Each day was divided into two test sessions, a morning session and an afternoon session, in which each of the four groups of stimuli were presented once. The 60 sounds within each group were presented in reverse order during the afternoon sessions (denoted by the -1 exponent in the tables below and on the following page). The sequence was such that each of the groups A through D precedes and is preceded by every other group. Due to a holiday falling during the course of testing and the desire, which arose during testing, to repeat several sessions, three additional days of testing were conducted using the two sessions originally scheduled to fall on the holiday and those sessions which were to be repeated. The final session sequences used were:

WEEK 1	Mon.	Tues.	Wed.	Thur.	Fri.
A.M.	C B D A	B D A C	A C B D	D A C B	A C B D
P.M.	C^{-1} A^{-1} B^{-1} D^{-1}	D^{-1} B^{-1} C^{-1} A^{-1}	A^{-1} C^{-1} D^{-1} B^{-1}	B^{-1} D^{-1} A^{-1} C^{-1}	B^{-1} D^{-1} C^{-1} A^{-1}

Continued on next page

Stimuli presentation sequence - cont'd

WEEK 2	Mon.	Tues.	Wed.	Thur.	Fri.
A.M.	HOLIDAY	C A D B	B D C A	C D A B	B A D C
P.M.		D^{-1} B^{-1} A^{-1} C^{-1}	A^{-1} C^{-1} D^{-1} B^{-1}	D^{-1} B^{-1} A^{-1} C^{-1}	B^{-1} A^{-1} C^{-1} D^{-1}

WEEK 3	Mon.	Tues.	Wed.	Thur.	Fri.
A.M.	D B C A	A C B D	D B C A	B D A C	A C B D
P.M.	C^{-1} D^{-1} B^{-1} A^{-1}	A^{-1} C^{-1} D^{-1} B^{-1}	A^{-1} C^{-1} D^{-1} B^{-1}	B^{-1} D^{-1} C^{-1} A^{-1}	C^{-1} B^{-1} A^{-1} D^{-1}

WEEK 4	Mon.	Tues.	Wed.	Thur.	Fri.
A.M.	D B A C	C A D B	D B C A	B D A C	THE
P.M.	C^{-1} A^{-1} B^{-1} D^{-1}	D^{-1} A^{-1} B^{-1} C^{-1}	A^{-1} C^{-1} D^{-1} B^{-1}	B^{-1} D^{-1} A^{-1} C^{-1}	END

Reference

Cochran W.G., "Long-Term Agricultural Experiments," J. Royal Statistical Society, Series B, 6(2):104-148 (1939).

3.3.3 SUBJECTS' INTRODUCTION TO THE EXPERIMENT

Introduction

The subjects, upon arriving at the laboratory, were shown into the test chamber and provided the following written introduction to orient them to the testing which was to follow.

Written introduction given to subjects

INTRODUCTION

The sounds we experience in our lives are occasionally, in one way or another, annoying to us. Whether we judge those sounds to be excessively noisy, unpleasant sounding or simply too loud, the annoyance in each case depends upon the context in which those sounds are heard. We, for example, may expect and accept loud music in a disco but be annoyed if that same music comes from our neighbors' house late at night when we wish to sleep.

The experiment in which you are participating will help us understand the characteristics of airplane passenger cabin sounds which may be annoying to passengers in large commercial aircraft. The experiment consists of four 30 minute sessions divided by 3 short breaks. During each session 60 passenger cabin sounds will be presented for you to judge. None of the sounds you will hear present a risk to you. The sounds themselves have been screened to ensure safe exposure levels. In addition, the speaker system has been designed to meet stringent safety requirements so that you cannot be exposed to sounds which are known to cause injury. Also, for your safety, we are in both video and audio contact with you.

3.3.4 TEST TECHNIQUE: MAGNITUDE ESTIMATION

Introduction

Annoyance judgments in this experiment were made using the technique of magnitude estimation relative to a standard stimulus.

Background

We began the experiment using magnitude estimation without a reference stimulus as conceived by Stevens (1956). Subjects were asked to judge how annoying sounds were by assigning numbers proportional to their impression of each sound's annoyance. After completing the testing of 14 subjects, however, we felt compelled to discontinue using this technique because many of the subjects were experiencing difficulty with the concept. Whether the problem was with the concept itself or the choice of training exercises employed to illustrate the idea, one of which was circle size estimation in place of the line-length exercise ultimately used, is unknown. We resumed testing using magnitude estimates relative to a standard. Fastl (1985) reports a similar experience in which subjects preferred a reference against which to make their judgments.

Concept

Magnitude estimation with a standard is the process of assigning numbers to stimuli proportional to the strength of a perceived sensation, such as loudness or brightness, in comparison with a reference stimuli to which a number has been assigned either by the experimenter or by the subjects themselves.

Example

A typical set of instructions might include: "Let the reference sound have a value of 100. Please judge how much more or less loud each sound is for you than the reference sound by assigning a number compared to 100. If, for example, the sound is 10 times louder than the reference sound assign a value of 1000. If on the other hand the sound is only one-half as loud assign a value of 50."

References

Fastl H., "Loudness and Annoyance of Sounds: Subjective Evaluation and Data from ISO 532B," In: Proceedings of the 1985 International Conference on Noise Control Engineering (INTER-NOISE 85), pp 1403-1406, Munich, Federal Republic of Germany, September 18-20, 1985.

Stevens S.S., " The Direct Estimation of Sensory Magnitudes - Loudness," American J. Psychology, 69(1):1-25 (1956).

3.3.5 LENGTH JUDGMENT TRAINING EXERCISE

Description

The concept and application of magnitude estimation were conveyed using a line-length estimation exercise (Lodge, 1984). Test subjects were asked to read the written instructions reproduced on the following page explaining how the exercise was to be performed. After reading the instructions, the subjects were given an opportunity to ask questions.

The subjects were then shown a reference line (line A) to which a value of 100 had been assigned. The presentation of line A was followed by the sequential presentation, one at a time, of 8 random length lines for which the subjects were to judge how much longer or shorter each line was compared to line A by giving each line a number compared to 100. The presentation of the lines is illustrated in the photograph below.

Presentation order & length assignment

I.D.	length [in.]
A	14
B	30
C	0.5
D	38
E	1.8
F	17
G	1
H	4
I	9

Continued on next page

Written instructions given to subjects

SAMPLE EXERCISE #1

The experiment today uses a judgment technique called magnitude estimation. Several sample exercises have been prepare to familiarize you with this technique. In the first exercise, I am going to show you a series of lines labeled A to I. Some of the lines are longer than line A and some are shorter. Line A is your reference. Let us give it a number 100. Your task is to determine how much longer or shorter each line is compared to line A by giving each line a number compared to 100.

For example, if one of the lines seems about twice as long as line A, you would enter the number 200. If a line is ten times longer, you would enter the number 1000. On the other hand, some of the lines are shorter than line A. If a line is about half as long, you would enter a number one-half of 100, about 50. Another line about one-tenth as long would be given the number one-tenth of 100, 10.

Remember, give each line a number that seems appropriate: The longer a line appears to be compared to line A, the bigger the number you will give it compared to 100. The shorter a line compared to line A, the smaller the number you should give it compared to 100.

There is no limit to the range of numbers you may use. Do not worry about running out of numbers, there will always be a smaller number than the smallest you use and a larger one than the largest you use. It is best to be as spontaneous and quick in your response as possible. Again, your task is to assign a number proportional to how long each line is relative to the reference line. After you have reached a decision, enter the number in your calculator. There are no right or wrong answers; we are only interested in your judgment of each line.

Do you have any questions?

Reference

Lodge M., Magnitude Scaling. Quantitative Measurement of Opinions, Beverly Hills, CA: SAGE Publications, Inc. (1984), p 44.

3.3.6 ANNOYANCE JUDGMENT TRAINING EXERCISE

Introduction

To further familiarize subjects with magnitude estimation and to demonstrate the actual process to be followed in the experiment, a reference sound followed by three representative sound stimuli were presented for the subjects to judge and record their responses. The instructions for this exercise are reproduced below.

Written instructions given to subjects

SAMPLE EXERCISE #2

The next session involves three sounds similar to those you will hear in the actual experiment. This exercise is intended to further familiarize you with magnitude estimation and to illustrate the use of the calculator in front of you for making and recording your judgments.

You will hear a reference sound followed by three representative test sounds. Let us again use the number 100 for our reference. Before each test sound begins, the word LISTEN will appear in your calculator display indicating a sound is about to be presented. As you listen to each test sound, please judge how much more or less ANNOYING that sound is for you than the reference sound by assigning that sound a number compared to 100. By ANNOYING we mean your total overall perception of how UNPLEASANT, OBJECTIONABLE, DISTURBING, or UNWANTED each of these sounds is for you. Immediately following each sound, the word RESPOND will appear in your calculator display. There will then be a few seconds of silence during which to enter your decision. Again be as spontaneous and quick in your response as possible. Remember, there is no limit to the range of numbers you may use.

If you make an error while entering the number or wish to change your decision, simply wait a moment until the display begins to flash, then re-enter your decision.

Do you have any questions?

3.3.7 VOLUNTARY CONSENT FORM

Introduction

During the course of Sample Exercise #2, after the subjects were familiar with both the purpose of the experiment and the procedures to be employed but before the sound system was used, they were asked to read and sign the consent form reproduced below stating that they understood their participation was voluntary, that they had the right to withdraw, that they would abide by laboratory rules and that their health had not changed since being accepted as test subjects.

Consent form

VOLUNTARY CONSENT FORM FOR SUBJECTS
FOR HUMAN RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand the purpose of the research and the technique to be used, including my participation in the research, as explained to me by the Principal Investigator (or qualified designee).

I do voluntarily consent to participate as a subject in the human response to aircraft noise experiment to be conducted at NASA Langley Research Center on __________.
date

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the regulations of the laboratory and instruction of the Principal Investigator regarding safety, subject only to my right to withdraw declared above.

I affirm that, to my knowledge, my state of health has not changed since the time at which I completed and signed the medical report form required for my participation as a test subject.

____
PRINT NAME

____
SIGNATURE

3.3.8 TEST PROCEDURE

Introduction

Testing using the procedure described below followed completion of the two training exercises and the signing of the Voluntary Consent Form.

Test procedure

The subjects were asked to judge the annoyance of 240 stimuli. These stimuli were presented in four one-half hour sessions of 60 stimuli each. The presentation of each 60-stimuli group was preceded by the presentation of a reference standard against which the annoyance of the 60 subsequent sounds was to be judged.

Before each test sound began, the word "LISTEN" appeared in the calculator display indicating a sound was about to be presented. Immediately following each sound, the calculator prompted the subject for a response with the message "RESPOND." The calculators were programmed to accept, and automatically store in their memories, only those responses entered during the quiet period following the presentation of each stimulus. Subjects were able to enter as many responses as they wished; the calculator saved only the last entry when the "LISTEN" prompt reappeared to call attention to the next stimulus.

Test participants were given the opportunity to stand, stretch and/or leave the chamber for a few minutes between the one-half hour test sessions. During testing, they were requested not to converse or share their judgments.

Written instructions given to subjects

TEST INSTRUCTIONS

You are now going to hear a reference sound followed by a series of test sounds in irregular order. Let the reference sound have its usual value of 100. As you listen to each test sound, again please judge, as you did in the previous practice exercise, how ANNOYING each sound is for you relative to the reference sound by assigning each test sound a number compared to 100. Remember, by ANNOYING we mean your total overall perception of how UNPLEASANT, OBJECTIONABLE, DISTURBING, or UNWANTED each of these sounds is for you. As before, after the word RESPOND appears in your calculator display, you will have a few seconds of silence during which to enter your decision.

Do you have any questions before we begin?

4.0 DATA ANALYSIS

Synopsis

The analysis, which is limited to those responses elicited by the 66 steady-state stimuli, is based upon four elementary auditory sensations: Loudness, tonality, sharpness and roughness. Loudness was found to be the dominant sensation in annoyance, the relationship being described by a power function. Tonality was the second most influential sensation and is related to annoyance by an exponential function. Neither sharpness nor roughness were of practical significance. A model developed using loudness and tonality was found to be a better predictor of annoyance than either L_A or OASPL, the two most prevalent metrics used in the airline industry today for assessing the overall annoyance of sounds within the passenger cabin of commercial aircraft.

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4.1 ANALYSIS METHODOLOGY

Background

The experimental design was chosen with the intention of using statistical techniques to analyze the results directly in terms of the experimental variables: Background OASPL, tone frequencies and emergences, etc. Several factors emerged during the course of testing and the early stages of the subsequent data analysis to change those original plans. First we had an opportunity to review recent research by Aures (1985a) and Zwicker (1989). This research focused on the elementary perceptual features of sound as a means of understanding and modelling the acceptability of one sound relative to another. It was our opinion that the approaches taken by Aures and Zwicker were a more appropriate strategy, particularly for the very complex sound spectra under investigation. Feeling this new approach was intrinsically correct, we were further motivated by anomalies in the synthesized sound spectra. The synthesis algorithm, in some cases, introduced a multitude of low level, harmonically-related tones into the synthesized sounds. Because this unintended tonal structure would not be explained in a statistical analysis by the existing experimental variables and because the potential importance of these apparently minor differences between the actual and intended spectra have recently come to be more fully appreciated due to the work of Genuit and Gierlich (1989), we felt a more reliable analysis with a broader range of application would result if based upon the elementary perceptual features of sound rather than a relatively few selected physical characteristics.

Basic strategy

The data were analyzed in terms of the four basic perceptual features in Aures (1985b) sensory euphony model: Loudness, sharpness, tonality and roughness. Because power and/or exponential relationships were anticipated among these variables, the analysis and subsequent modelling of the relationships using regression techniques proceeded based upon visual evidence in the data.

Loudness

Loudness is the intensive attribute of auditory sensation. It has long been recognized as a key factor in the perceived annoyance of sounds. It was calculated in this investigation using a computer program based upon ISO 532B published by von Paulus and Zwicker (1972).

Continued on next page

Sharpness

Sharpness is an indication of a signal's timbre, "that attribute of auditory sensation in terms of which a subject can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar" - ANSI S3.20-1973. Sharpness was computed using two different procedures, one published by von Bismarck (1974) and the other published by Aures (1985b). These procedures yield numbers indicating the relative position of the loudness concentration on a critical band rate scale. The distinction between the two procedures is in the loudness normalization term. Aures, based upon research of his own, concluded that Bismarck's procedure did not fully compensate for the interactive effects of loudness on timbre perception.

Tonality

Tonality is a composite measure of the perceived strength of unmasked tonal energy within a complex noise spectrum. Tonality, which was computed using the procedure reported by Aures (1985b), is based upon a simple masking and energy summation model with corrections for the perceived tonalness of pure tones and narrow bands of noise as a function of both frequency and bandwidth.

Roughness

Roughness is the unpleasant auditory sensation elicited when signals contain relatively rapid amplitude fluctuations. Here "relatively rapid" means modulation rates ranging from approximately 20 Hz to about 300 Hz. For reasons which were never able to be discovered, the computational procedure employed for roughness in this investigation produced results which were slightly but systematically different from those published by Aures (1985c). We used our procedure despite these differences because we felt it captured the essence of the auditory roughness concept.

Continued on next page

References

American National Standards Institute, "Psychoacoustical Terminology," ANSI S3.20 - 1973 (R1986).

Aures W., "Der Sensorische Wohlklang als Funktion psychoakusticscher Empfindungsgrößen," Acustica, 58(5):282-290 (1985a).

Aures W., "Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale, " Acustica, 59(2):130-141 (1985b).

Aures W., "Ein Berechnungsverfahren der Rauhigkeit," Acustica, 58(5):268-281 (1985c).

v. Bismarck G., "Sharpness as an Attribute of the Timbre of Steady Sounds," Acustica, 30(3):159-172 (1974).

Genuit K. and Gierlich H.W., "Investigation of the Correlation Between Objective Noise Measurement and Subjective Classification," SAE Paper 891154, In: Proceedings of the 1989 SAE Noise and Vibration Conference, Traverse City, Michigan, May 16-18, 1989.

International Organization for Standardization, "Acoustics - Method for Calculating Loudness Level," ISO 532 - 1975(E).

v. Paulus E. and Zwicker E., "Programme zur automatischen Bestimmung der Lautheit aus Terzpegeln oder Frequenzgruppenpegeln," Acustica, 27(5):253-266 (1972).

Zwicker E., "On the Dependence of Unbiased Annoyance on Loudness," In: Proceedings of 1989 International Conference on Noise Control Engineering, pp 809-814, Newport Beach, CA, USA, December 4-6, 1989.

4.2 PRE-ANALYSIS DATA SCREENING

Subject reliability

The responses from 12 of the 72 subjects tested using magnitude estimation relative to a standard were discarded. These 12 subjects (who represented 17% of the subject pool) appeared unable to perform magnitude estimation reliably. This is in contrast to the 3 - 5% expected to experience difficulty (Lodge, 1984). The determination of subject reliability was based upon performance on a line-length estimation exercise used to introduce subjects to magnitude estimation immediately prior to the main test sessions. Subsequent analysis of the data was, therefore, limited to the responses from the remaining 60 subjects.

Data normality

We checked for normality in the 60 subject data set. Upon computing the mean for each subject's 240 responses, we found with few exceptions that the distribution of the 60 means was log normal as expected. Investigations of the responses for those subjects whose means were not log normally distributed usually revealed one or more individual responses by those subjects which were clearly unintended. The errors appeared to be attributable to inherent limitations in the ability of the hand-held calculators to perform the real-time task of recording subject responses. Those individual responses which were clearly unintended were discarded. The means were then recomputed and the normality rechecked. The distribution of the 60 means was then found to be reasonably log normal.

Presentation order effects

We next conducted an analysis of variance on the temporal factors in the experiment to determine if corrections for temporal biases were necessary before proceeding with the primary analysis. The main effects examined were: Week-of-the-month, day-of-the-week, time-of-day, and order-of-presentation. There are no significant ($p<0.05$) main effects among the four variables checked but there is an unexplained stratification structure in one of the interaction terms. We were unable to clarify the source of this stratification, so no correction was applied to the data to compensate for it.

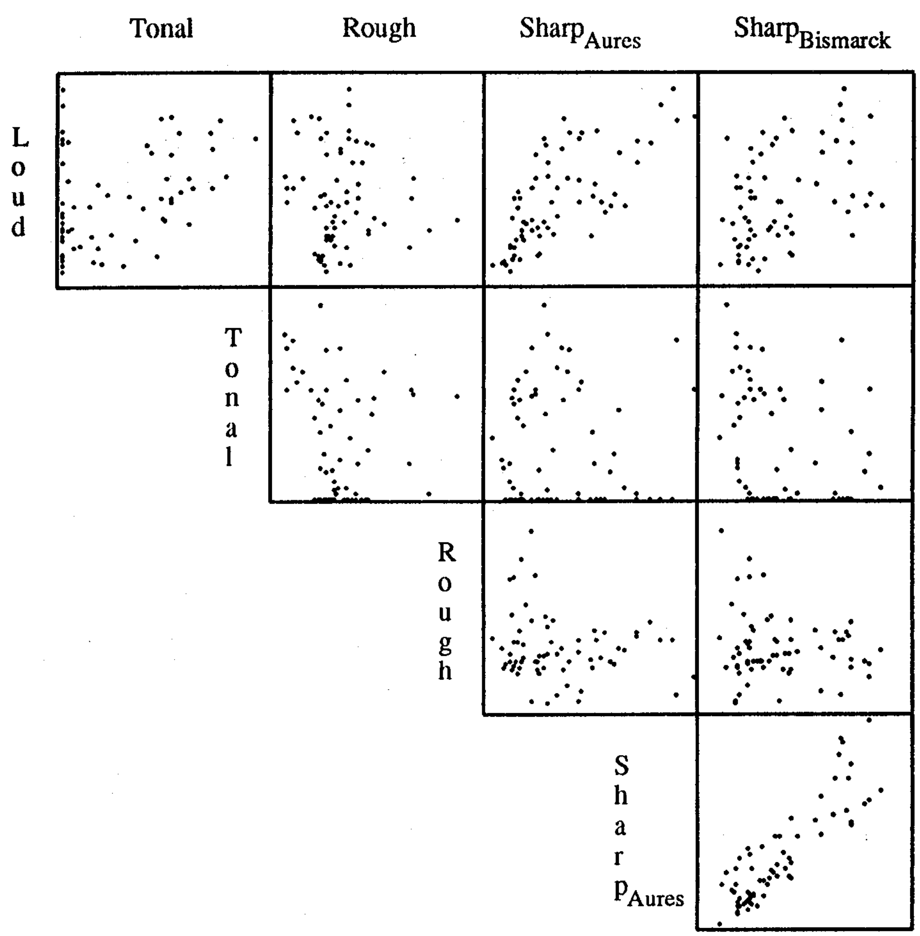
Demographic effects

Dempsey and Leatherwood (1975) report that demographic factors such as age, weight, and sex do not contribute to an explanation of response variations for this type of study; therefore, the influence of these variables was not checked.

Continued on next page

Stimuli distribution

The experimental design was based upon Latin Squares to assure a uniform sampling of the n-dimensional variable space under investigation. Owing to an unanticipated change in our analysis plans (see discussion in Section 4.1), we analyzed the data in terms of the four elementary auditory sensations: Loudness, tonality, sharpness and roughness. These new variables, derived from the spectral characteristics of each stimulus, were, however, not uniformly distributed in their own variable space. Below are scatter plots showing the distribution pattern of each independent variable relative to all the others. As may be seen, the five dimensional variable space is not uniformly represented.



Continued on next page

References

Dempsey T.K. and Leatherwood J.D., "Experimental Studies for Determining Human Discomfort Response to Vertical Sinusoidal Vibration," NASA TN D-8041 (1975).

Lodge M., Magnitude Scaling. Quantitative Measurement of Opinions, Beverly Hills, CA: SAGE Publications, Inc. (1984), p 45.

4.3 ANALYSIS AND RESULTS

Synopsis

In our plotting of the annoyance response data against the five sensory attributes of interest - loudness, sharpness (Aures), sharpness (Bismarck), tonality and roughness - the most prominent relationship observed was between loudness and annoyance. This relationship was found to be well described by a power law function of the form $y = x^a$ where x is loudness and y is annoyance. The second most important relationship observed was between annoyance and tonality. This relationship was approximately described by an exponential of the form $y = a^x$ where x is tonality and y is annoyance. Neither sharpness nor roughness systematically influenced the measured responses.

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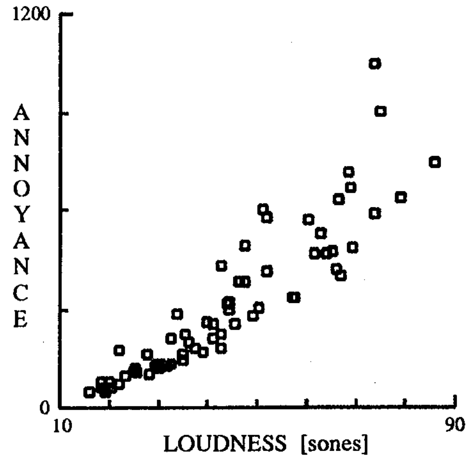
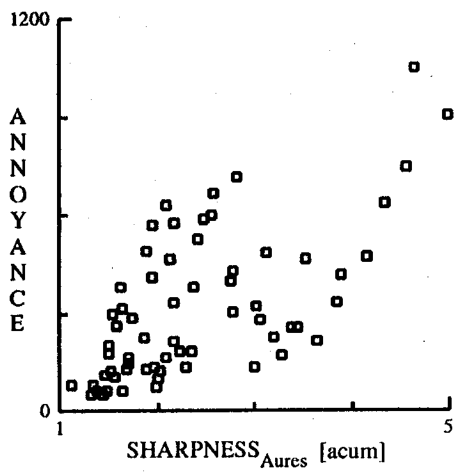
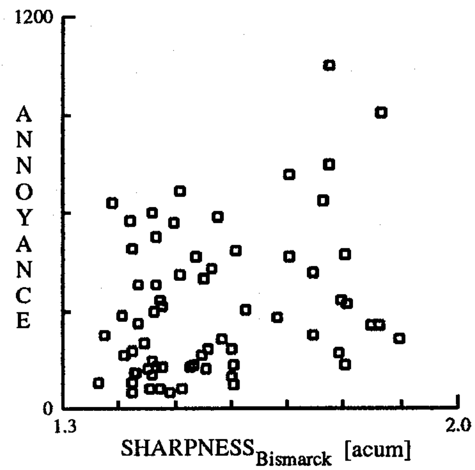
4.3.1 RAW ANNOYANCE DATA vs. SENSORY ATTRIBUTES

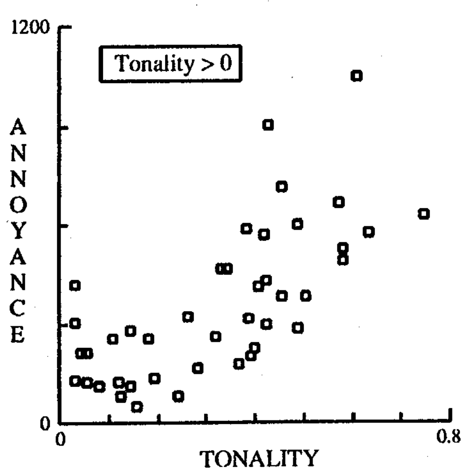
Raw data

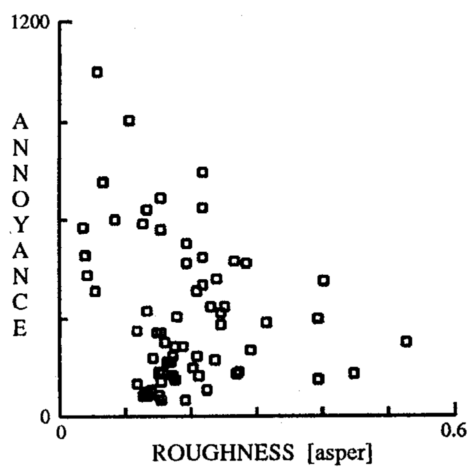
Geometric means were used to coalesce the 60 individual annoyance estimates for each stimulus into a single composite annoyance indicator for that stimulus. These geometric means, labeled ANNOYANCE on the axes to the right and below, are plotted for initial evaluation against the five sensory attributes of interest: Loudness, sharpness (Aures), sharpness (Bismarck), tonality and roughness.







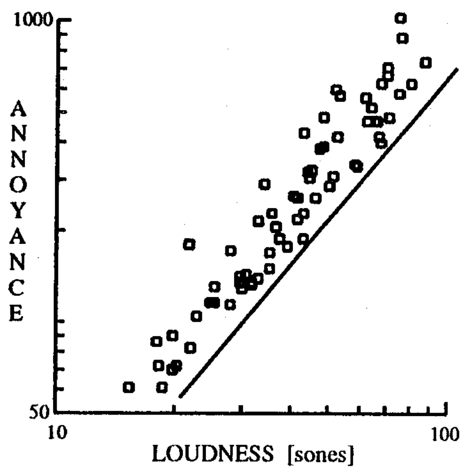


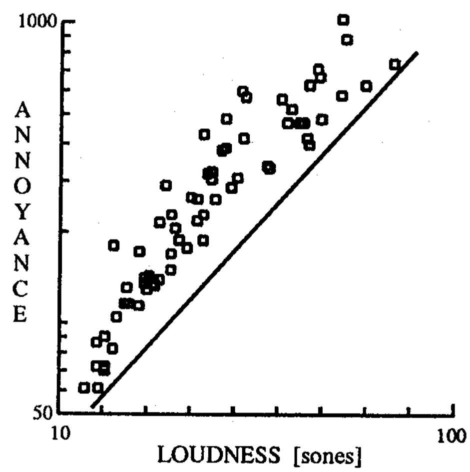


4.3.2 QUALITATIVE RELATIONSHIP: ANNOYANCE vs. LOUDNESS

Annoyance vs. loudness

The most pronounced relationship observed in the data is that between annoyance and loudness. The trend observed between these two variables suggests this relationship is either a power function of the form $y = x^a$ or an exponential of the form $y = a^x$. If the variability in the data is sufficiently small, as it appears to be, the more appropriate form may be quickly discerned by comparing the results plotted on log-log axes versus when plotted on semi-log axes. The power function will appear as a straight line on the log-log axes while the exponential form will appear as a straight line on the semi-log axes. The replotted data are shown below with reference lines added for qualitatively assessing data linearity.





Choosing an appropriate model

The data plotted in log-log coordinates, above left, exhibit greater linearity than the data plotted in semi-log coordinates to the right. This comparison qualitatively supports the view that the basic relationship between annoyance and loudness is a power function of the form $y = x^a$ where x is loudness and y is annoyance.

4.3.3 MATHEMATICAL MODEL: ANNOYANCE = f (LOUDNESS)

Model: Annoyance = f (loudness)

Linear regression was used to derive a quantitative relationship between annoyance and loudness based upon the premise that this relationship is best described by a power function. The response variables in the regression were the common logarithms of the geometric means computed from the 60 individual annoyance estimates for each stimulus. The parameter estimates and summary table resulting from the regression analysis are shown below.

PARAMETER ESTIMATES

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
Intercept	1	− 0.091	0.1038	− 0.88	0.3825
$\log_{10}$ Loud	1	1.566	0.0647	24.20	0.0001

ANALYSIS of VARIANCE

Source	DF	SS	MS	F	Prob > F
Model	1	5.8256	5.8256	585.6	0.0001
Error	64	0.6366	0.0100		
C Total	65	6.4622			

Comments on model residuals

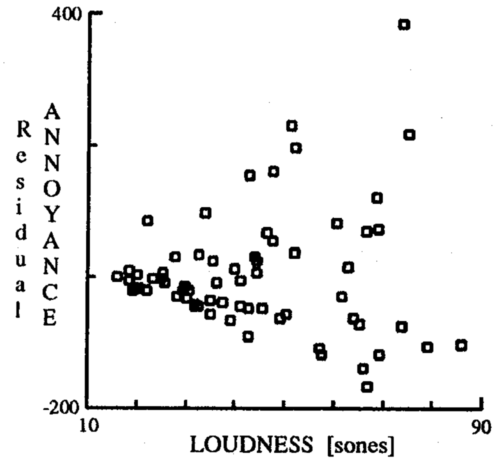
The residuals from the loudness model are plotted on the following page. Our expectation that a power function is the appropriate relationship between annoyance and loudness is confirmed by the random distribution of the annoyance residuals around zero when plotted against loudness. Annoyance residuals are the differences between measured annoyance and that annoyance predicted by the power function model for each stimulus.

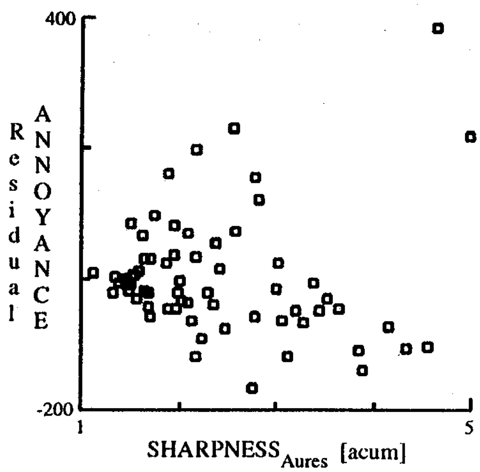
The model residuals, in addition to confirming the choice of model form, served as the basis for exploring the relationships between annoyance and the remaining four sensory attributes: Tonality, sharpness (Aures), sharpness (Bismarck), and roughness.

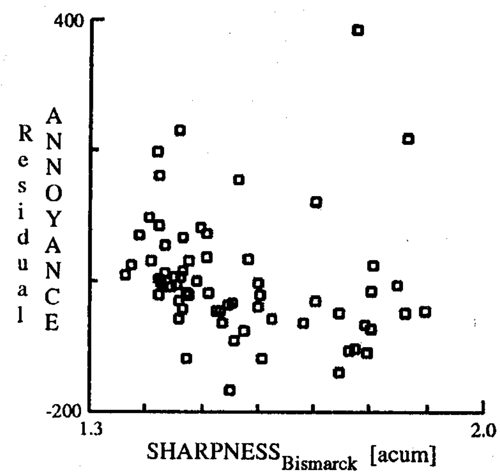
Continued on next page

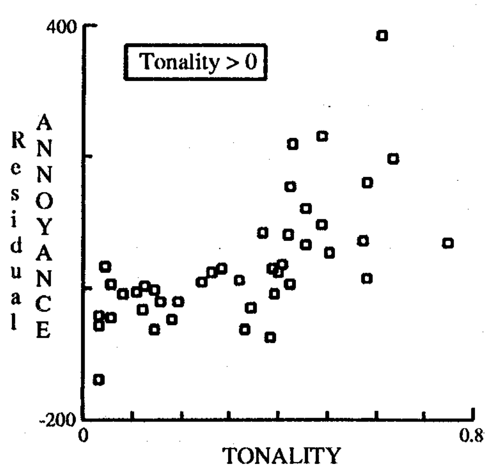
Residuals: Loudness-based model

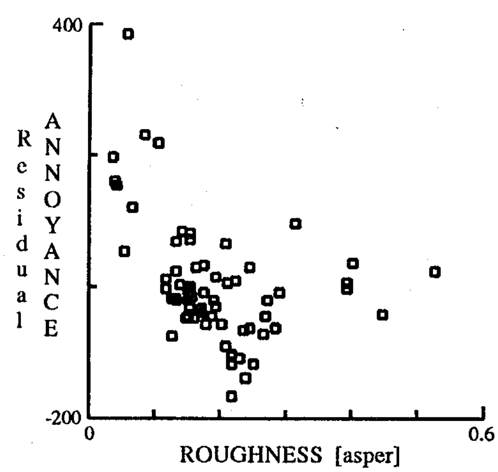
Differences between the measured responses and those predicted by a simple power law relationship between loudness and annoyance, labeled "Residual ANNOYANCE" on the axes to the right and below, are plotted against the five sensory attributes of interest: Loudness, sharpness (Aures), sharpness (Bismarck), tonality and roughness.







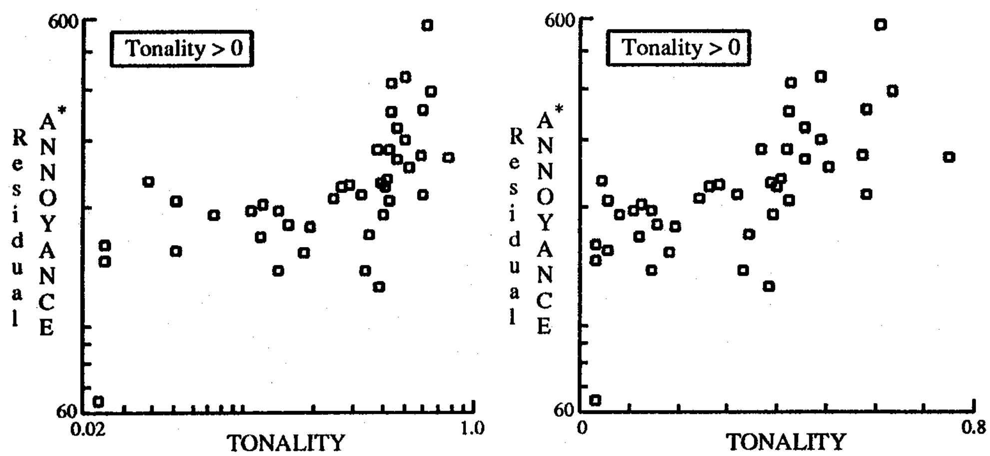




4.3.4 QUALITATIVE RELATIONSHIP: ANNOYANCE vs. TONALITY

Annoyance vs. tonality

The second most prominent pattern observed in the data is that between annoyance and tonality. This pattern also appears to exhibit the characteristic exponential growth associated with functions of the form $y = x^a$ and $y = a^x$. Plotting the annoyance residuals in both log-log and semi-log coordinates again provides insight into which is the more appropriate model form. The replotted data are shown below.



* To accommodate logarithmic plotting, all residuals were increased by 200 to eliminate negative values.

Choosing an appropriate model

The annoyance residuals plotted above in semi-log coordinates (upper right) exhibit considerably greater linearity than when plotted in log-log coordinates (upper left) although even in semi-log coordinates, the data does not appear to be completely linear. This suggests that the relationship between annoyance and tonality may only be described to a first approximation by an exponential relationship of the form $y=a^x$ where x is tonality and y is annoyance. An alternate possibility is that the exponential model is correct but that the apparent curvature remaining in the data is the result of our incomplete sampling of the loudness/tonality/sharpness/roughness variable space.

4.3.5 MATHEMATICAL MODEL: ANNOYANCE = f (LOUDNESS, TONALITY)

Model: Annoyance = f (loudness, tonality)

Linear regression was used to derive a quantitative relationship between annoyance, loudness and tonality. The regression model was based upon the premise that a power function relationship exists between annoyance and loudness and that an exponential relationship is an appropriate first-order approximation for the relationship between annoyance and tonality. The response variables in the regression were the common logarithms of the geometric means computed from the 60 individual annoyance estimates for each stimulus. The parameter estimates and summary table resulting from the regression analysis are shown below.

PARAMETER ESTIMATES

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
Intercept	1	0.099	0.0658	1.51	0.1367
$\log_{10}$ Loud	1	1.397	0.0426	32.80	0.0001
Tonality	1	0.394	0.0377	10.46	0.0001

ANALYSIS of VARIANCE

Source	DF	SS	MS	F	Prob > F
Model	2	6.2296	3.1148	843.8	0.0001
Error	63	0.2326	0.0037		
C Total	65	6.4622			

Comments on model residuals

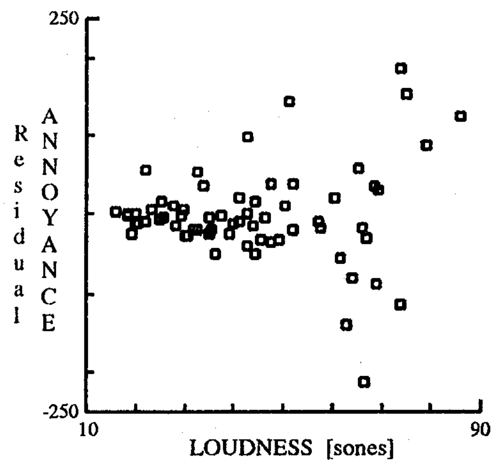
The residuals from the loudness/tonality model are plotted on the following page. While a simple exponential was expected to be only a first-order approximation for the relationship between annoyance and tonality, the relatively random distribution of the annoyance residuals around zero when plotted against tonality suggests that the exponential explains most of the systematic variation in the data due to tonality.

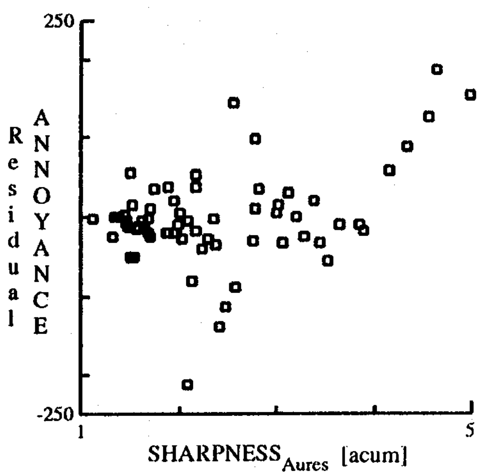
The model residuals, in addition to confirming the choice of model form, served as the basis for exploring the relationships between annoyance and the remaining three sensory attributes: Sharpness (Aures), sharpness (Bismarck), and roughness.

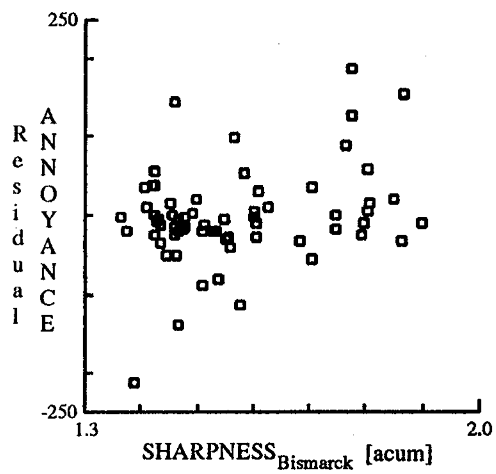
Continued on next page

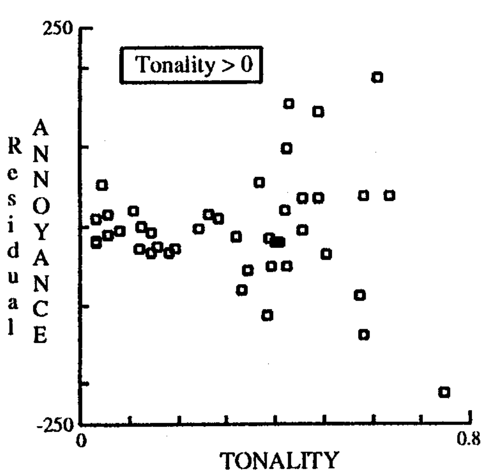
Residuals: Loudness/ tonality based model

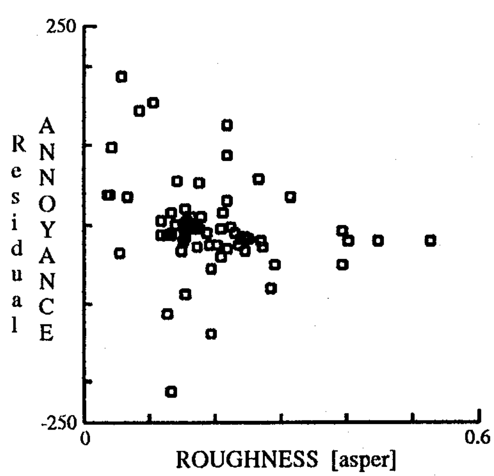
Differences between the measured responses and those predicted by the loudness/tonality model, labeled "Residual ANNOYANCE" on the axes to the right and below, are plotted against the five sensory attributes of interest: Loudness, sharpness (Aures), sharpness (Bismarck), tonality and roughness.











4.3.6 QUALITATIVE RELATIONSHIP: ANNOYANCE vs. SHARPNESS AND ROUGHNESS

Sharpness

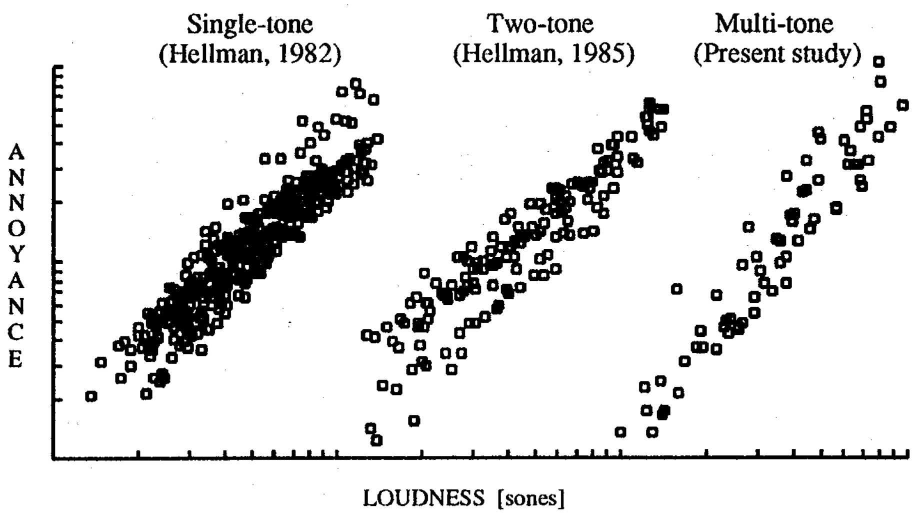
Despite indications of a potential relationship between annoyance and sharpness in the raw data, there was no clear visual evidence in the residuals during any step of the selection process while developing the loudness/tonality model that either form of sharpness (Aures or Bismarck) was strongly influential in subject responses to the stimuli tested.

Roughness

There was no evidence either in the raw data or in any of the residuals computed during the several steps of the analysis that roughness systematically influenced the subject responses measured.

Loudness / annoyance relationship

The strong relationship observed between loudness and annoyance is consistent with our general experience that loudness is a central element in annoyance and the results of similar studies by Hellman (1982, 1985). Plotted in log-log coordinates below are the results of Hellman's two studies in comparison with our own. It should be noted that the three data sets are not shown in their correct absolute positions with respect to each other in the loudness/annoyance plane. In an effort to improve clarity, they have been repositioned in non-overlapping positions adjacent to each other.



NOTE: Data not shown to scale.

In each case, the relationship is best described by the power law, although the exponents are all slightly different. There may be many reasons for these differences but the two most probable causes are experimental biases associated with the magnitude estimation technique (see Gescheider (1988) for a review) and sensory factors other than loudness influencing the annoyance judgments. An example of the former is the impact that the presence or absence of a reference stimulus has on magnitude estimation judgments. This bias may explain the differences between Hellman's results and our own because she used absolute magnitude estimation whereas we used magnitude estimation with a standard. MacMillan *et al.* (1974) have shown that the presence of a standard increases the exponent. An example of other sensory factors influencing the annoyance judgment is the change in exponent accompanying the addition of tonality to our regression model of annoyance. The loudness exponent decreased from 1.57 to 1.40.

Continued on next page

Tonality

We found that tonality explains an important part of the variability in our data in contrast to Zwicker's (1989) conclusion that annoyance due to the presence of tones in broadband noise is explained by loudness alone. While it is unknown on what basis Zwicker makes his statement, we would have arrived at a similar conclusion had our test only encompassed tonality values less than 0.4. It was only when tonality exceeded 0.4 that tonality emerged as an important factor in annoyance.

Sharpness

Of interest at the beginning of the experiment was whether sharpness would satisfactorily differentiate preferences between broadband sounds differing only in spectral shape. The somewhat linear relationship between sharpness and annoyance evident in the raw data suggested sharpness might explain a portion of the variance in the measured annoyance responses. It became progressively evident after explaining a large part of the variability with loudness and most of the remaining variability with tonality that sharpness was not strongly influential in the judged annoyance of the types of sounds we tested. Sharpness was, however, found to be statistically significant although only marginally so. Judging from the residuals after the effects of loudness were removed from the annoyance responses (shown in Section 4.3.3), we determined that the somewhat linear pattern observed in the raw data between Aures' sharpness and annoyance was a result of the dependence of sharpness upon loudness.

Our finding that sharpness is not an important attribute in the subjective annoyance response toward noise is in contrast to the use of sharpness by Aures (1985) in his sensory euphony model and by Zwicker (1989) in his unbiased annoyance model. It is possible that our not finding sharpness important results from our incomplete sampling of the loudness/tonality/sharpness/roughness variable space.

Roughness

Our not finding roughness important in the annoyance response toward noise is consistent with Zwicker and Fastl's (1990) conclusion that roughness is not a factor in noise annoyance. Of course not finding roughness important may also be a result of our incomplete sampling of the loudness/ tonality/sharpness/roughness variable space.

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4.5 EVALUATION OF CONVENTIONAL SINGLE-NUMBER METRICS

Synopsis

L_A and OASPL are the two most prevalent metrics used in the airline industry today for assessing the overall annoyance of sounds within the passenger cabin of commercial aircraft. For that reason, the performance of these two metrics in explaining the annoyance response data gathered during this experiment is evaluated in this section with respect to each other and the loudness/tonality model developed in Section 4.3. The results of the evaluation, based upon a comparison of confidence intervals and predictive power, indicate that the loudness/tonality model does the best job of explaining the data with L_A a close second and OASPL a very distant third.

Index

4.5.1 EVALUATION METHODOLOGY

Introduction

L_A and OASPL are the two most prevalent metrics used in the airline industry today for assessing the overall annoyance of sounds within the passenger cabin of commercial aircraft. For that reason, the performance of these two metrics in explaining the annoyance response data gathered during this experiment is evaluated with respect to each other and to the loudness/tonality model developed in Section 4.3.

Evaluation based upon metrics utility

A number of different strategies, some more appropriate than others, have been employed in the past for assessing which of several metrics is the most reliable predictor of noise annoyance. These previous approaches, however, do not provide two pieces of information which users of these metrics need to know about the predictions made with them: 1) The uncertainty associated with individual predictions, and 2) how large differences between predictions must be to be meaningful. In this report, comparisons between the three predictors under consideration are, therefore, made in terms of both the error band size (95% confidence intervals) for individual predictions and the size of differences required between predictions for those differences to be judged detectable by the passenger population.

95% confidence intervals

Confidence intervals provide a means of assessing the uncertainty or ambiguity associated with predictions made using a particular model or metric. The wider the band, the less likely predictions made with the model represent the true annoyance and, therefore, the lower the prediction's utility to the user.

Predictive power

Predictive power is a measure of how large the difference must be between two annoyance predictions for users of those predictions to correctly conclude the difference will be detectable by a group of passengers. Knowledge of this threshold difference is important to users - predicted differences smaller than the minimum detectable difference may not be economically worth acting upon, whereas larger differences represent an opportunity to provide a more comfortable passenger environment.

4.5.2 DEFINITIONS: OASPL and L_A

Introduction

OASPL and L_A, as used in subsequent comparisons within this section, are defined below. The essential fact to be aware of is that the computed values for these metrics are based upon the 20 Hz through 10 kHz preferred one-third octave bands. For historical information, common usage, formal definitions and computational procedures for OASPL and L_A as well as many other metrics, see an excellent summary by Pearsons and Bennett (1974).

OASPL

OverAll Sound Pressure Level, expressed in dB re 20 μPa, is defined as the logarithmic sum of the sound pressure levels in the twenty-seven preferred one-third octave bands centered at 20 Hz through 10 kHz:

$$\text{OASPL} \equiv 10 \log_{10} \sum_{i=1}^{27} 10^{(\text{SPL}_i / 10)}$$

where: SPL_i are the twenty-seven one-third octave band sound pressure levels.

L_A

A-weighted sound pressure level, expressed in dB re 20 μPa, is defined as the logarithmic sum of A-weighted sound pressure levels in the twenty-seven preferred one-third octave bands centered at 20 Hz through 10 kHz:

$$L_A \equiv 10 \log_{10} \sum_{i=1}^{27} 10^{((\text{SPL}_i + \text{A-wtg}_i) / 10)}$$

where: SPL_i are the twenty-seven one-third octave band sound pressure levels and A-wtg_i are the respective one-third octave band SPL weightings.

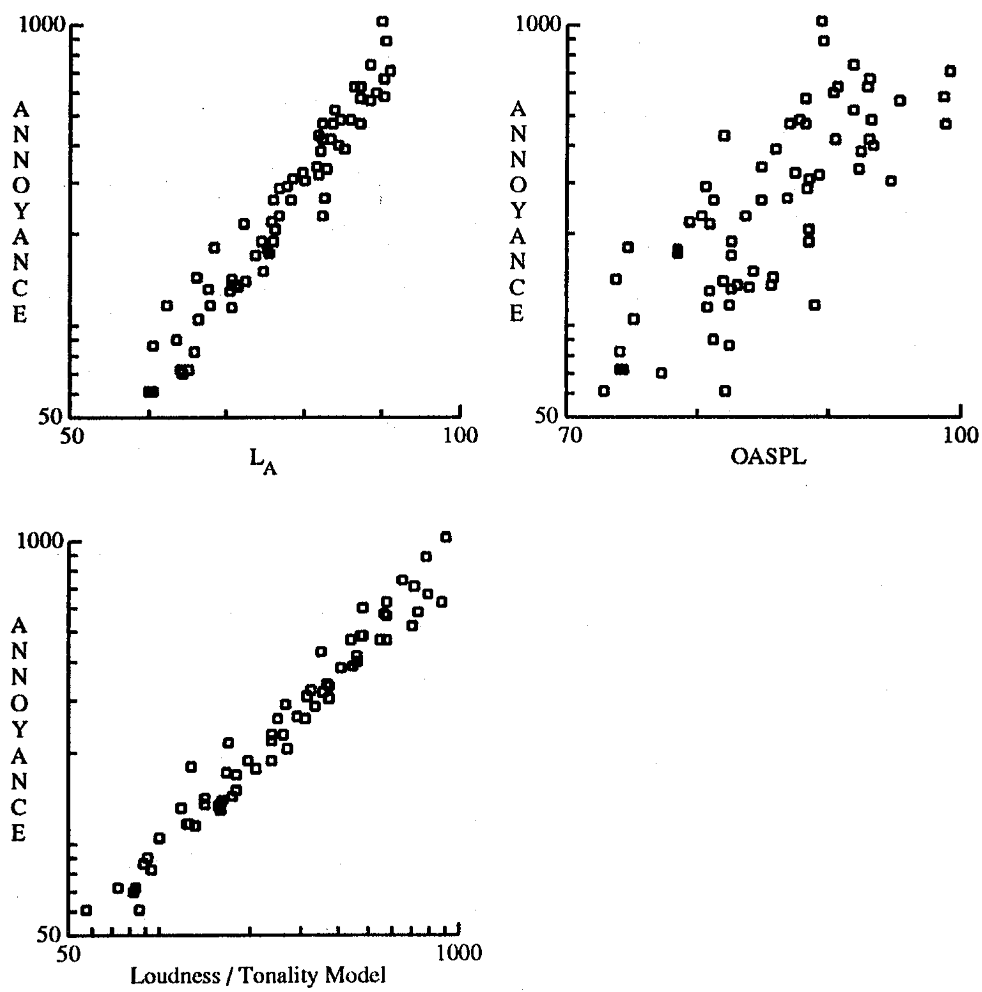
Reference

Pearsons K.S. and Bennett R.L., "Handbook of Noise Ratings," NASA CR-2376 (1974).

4.5.3 RELATIONSHIP OF L_A AND OASPL TO ANNOYANCE

Data scatter

Scatter diagrams of L_A and OASPL versus annoyance are shown below on semi-log axes in comparison with each other and the loudness/tonality model. Semi-log coordinates were chosen to illustrate the linear relationship observed between L_A, OASPL and the logarithm of annoyance and provide a convenient format for visually comparing the relative abilities of the three predictors to explain the annoyance response data acquired in this experiment. Of the three predictors, predictions from the loudness/tonality model appear to exhibit the least scatter with L_A doing almost as well. OASPL, in contrast, exhibits significantly greater scatter than either of the other two.



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Prediction models: L_A & OASPL

Based upon the strong linearity observed between L_A, OASPL and log annoyance, linear regression was used to develop quantitative expressions relating L_A and OASPL to $\log_{10}$ annoyance. Summary tables for the regression analysis are shown below.

Summary statistics for regression analysis

PARAMETER ESTIMATES

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
Intercept *	1	0.099	0.0658	1.51	0.1367
$\log_{10}$ LOUD	1	1.397	0.0426	32.80	0.0001
TONALITY	1	0.394	0.0377	10.46	0.0001
Intercept	1	-0.286	0.0905	-3.16	0.0024
L_A	1	0.035	0.0012	29.91	0.0001
Intercept	1	-0.797	0.3318	-2.40	0.0193
OASPL	1	0.038	0.0039	9.67	0.0001

ANALYSIS of VARIANCE

Metric	Source	DF	SS	MS	F	Prob > F
Loud / Tonal Model *	Model	2	6.2296	3.1148	843.8	0.0001
	Error	63	0.2326	0.0037		
	C Total	65	6.4622			
L_A	Model	1	6.0307	6.0307	894.6	0.0001
	Error	64	0.4315	0.0067		
	C Total	65	6.4622			
OASPL	Model	1	3.8363	3.8363	93.5	0.0001
	Error	64	2.6259	0.0410		
	C Total	65	6.4622			

* Reproduced from Section 4.3.5

4.5.4 CONFIDENCE INTERVALS FOR PREDICTIONS

Introduction

Confidence bands provide a means of assessing the uncertainty or ambiguity associated with individual predictions made using a particular model or metric. The wider the band, the less likely predictions made with the model represent the true annoyance and, therefore, the lower the prediction's utility to the user.

95% confidence intervals

Confidence intervals for predictions made using regression models developed from experimental data depend upon the input to those models. Because the dependence is extremely weak for the range of values likely to be used as input to the predictors under consideration here, the confidence intervals will only be reported at their narrowest points. These points correspond to an L_A of 76.7 dB, an OASPL of 85.3 dB, and for loudness/tonality values of 39.2 sones and 0.20 respectively. Note that tonality is dimensionless. At the narrowest point, the 95% confidence band for the loudness/tonality model spans 0.245 $\log_{10}$ annoyance units, the band for the L_A regression line spans 0.331 $\log_{10}$ annoyance units and the band for the OASPL regression line spans 0.815 units.

Interpretation of 95% confidence intervals

Because the output of the annoyance models is expressed in $\log_{10}$ annoyance units, the confidence bands reported above are also specified in these units. A clearer perspective on the size of the confidence bands and the relationship between them can be gained by examining these bands in non-logarithmic units. In this experiment, the annoyance judgments were made on a simple ratio scale where, if one sound was judged twice as annoying as another, it was assigned a number twice as large as the number assigned to the less annoying sound. Taking the antilog of model outputs returns us to this ratio scale and allows confidence intervals to be expressed as a percentage. Accordingly, at the narrowest point of the confidence band, the true annoyance (with 95% confidence) may be as much as 33% more or less annoying than predicted using the loudness/tonality model, as much as 46% more or less annoying than predicted using L_A, and as much as 156% more or less annoying than predicted by OASPL. From this comparison of the confidence intervals, we see that the loudness/tonality model exhibits the least ambiguity, L_A is a close second and OASPL a very distant third.

4.5.5 PREDICTIVE POWER

Introduction

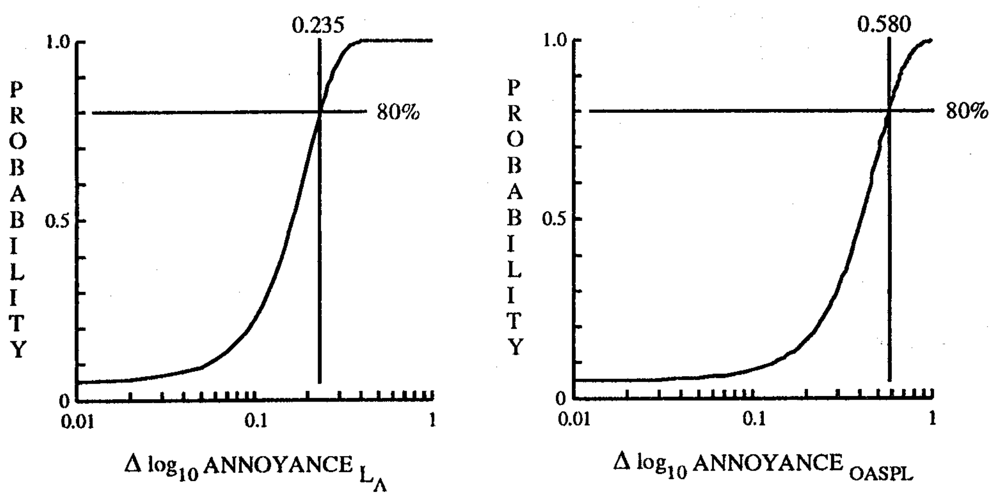
Predictive power is a measure of how large the difference must be between two annoyance predictions for users of those predictions to correctly conclude the difference will be detectable by a group of passengers. Knowledge of this discrimination threshold is important to users because predicted differences smaller than the minimum detectable difference may not be economically worth acting upon, while larger differences represent an opportunity to provide a more comfortable passenger environment. For further information on the concept of predictive power, see Lipsey (1990).

Predictive power as a measure of performance

Annoyance prediction models can only approximate the true discrimination ability of the passenger population. The more accurately a model explains passenger annoyance response, the more closely the discrimination ability of the model matches that of the passenger population. Thus, examination of a model's predictive power, in addition to telling users when a predicted change in annoyance justifies action, provides a means of evaluating the performance of that model in comparison to other metrics. Since, when doing annoyance predictions, we will normally be interested in knowing the size of the discrimination threshold which assures a specified probability of detection, performance of the three annoyance models will be compared by evaluating the minimum required differences between predictions for these differences to be detectable with a probability of 80%.

Example: L_A vs. OASPL

Below are representative curves for L_A and OASPL showing the probability that a group of passengers will detect a specified difference in predicted annoyance at the 0.05 significance level. The minimum differences necessary to assure an 80% probability of detection are indicated.



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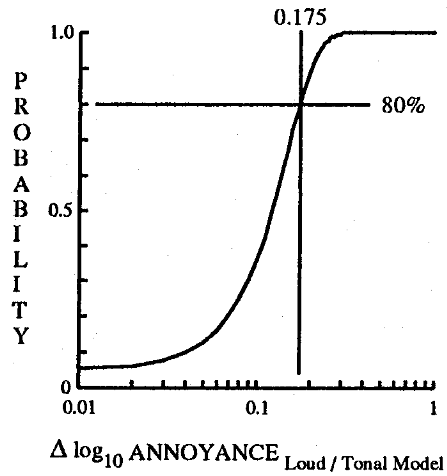
Example: Loudness/ tonality model

For comparison, a representative curve for the loudness/tonality model is also provided showing the probability that a group of passengers will detect a specified difference in predicted annoyance at the 0.05 significance level. The minimum difference necessary to assure an 80% probability of detection is indicated.



Comparison of predictive power

For there to be an 80% probability that a predicted difference is detectable, the difference between two predictions from the loudness/tonality model must be at least 0.175 $\log_{10}$ annoyance units. For L_A the difference must be at least 0.235 units and for OASPL at least 0.580 units. To provide perspective on these $\log_{10}$ annoyance unit differences, a one unit change in $\log_{10}$ annoyance corresponds to a 28.5 dB change in L_A and a 26.7 dB change in OASPL. Thus for there to be an 80% probability that two noise signatures are not equally annoying, the difference in their levels must be 6.7 dB if L_A is used as the predictor and 15.5 dB if OASPL is used. Of the three predictors, however, the loudness/tonality model is to be preferred. This outcome may be anticipated from the previous comparison of confidence intervals since those metrics which exhibit the greatest ambiguity are least able to reliably discriminate the relative annoyance of two stimuli.

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4.5.6 DISCUSSION

Influence of error

The comparisons between the confidence intervals and predictive power for L_A, OASPL and the loudness/tonality model were intended primarily to convey the differences in the abilities of these three predictors to explain annoyance. The confidence intervals and power curves, however, reflect more than how well each predictor approximates our annoyance response to noise. They also reflect random errors and individual differences in the data. And in the case of the loudness/tonality model, they reflect how well the sensations of loudness and tonality are modelled by their respective algorithms. For loudness, there is evidence that the algorithm may be in error for low frequency tones (Fastl *et al.*, 1990). Thus, if extraneous error and variability were eliminated, the true width of confidence intervals and the absolute differences required between two predictions for the differences to be detectable will in all cases be somewhat less than reported here.

L_A, OASPL and loudness

The linear relationships observed between L_A, OASPL and the logarithm of annoyance are consistent with loudness being the key factor in annoyance. The importance of loudness is perhaps the reason L_A is dramatically better than OASPL as an annoyance indicator since L_A has its pedigree in the reciprocal of the 40 phon equal loudness contour measured by Bell Laboratory in 1927 (Bruel, 1980). Because L_A, OASPL and loudness all derive from sound intensity, we expect them to be coarsely correlated with each other. Thus, whatever relationship exists between loudness and annoyance will be reflected to some degree in relationships between annoyance and any basic sound intensity measure. In general, however, simple energy summations such as L_A and OASPL will not indicate annoyance as well as loudness-based models. As Hellman and Zwicker (1987) have shown in the case of L_A, loudness may increase while L_A decreases. The pattern of loudness-based models outperforming the L_A metric may be observed in the data of similar annoyance studies by Hellman (1985a, 1985b).

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4.5.6 DISCUSSION, Continued

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5.0 CONCLUSIONS

Conclusions

1. Loudness is the dominant sensation governing annoyance.
2. The relationship between annoyance (y) and loudness (x) is governed by a power law of the form $y = x^a$.
3. The power law relationship between loudness and annoyance is consistent with the results published by others.
4. Tonality explains an important part of the variability in the data in contrast to Zwicker's (1989) conclusion that annoyance due to the presence of tones in broadband noise is explained by loudness alone.
5. Neither sharpness nor roughness were of practical significance in explaining annoyance, although sharpness was statistically significant.
6. A model based upon loudness and tonality is a better predictor of annoyance than either L_A or OASPL.
7. L_A is a better predictor of annoyance than OASPL.

Caveat

Cermak (1979) makes the very salient point that selectively choosing specific spectral characteristics to vary in an experiment, as we have done, leads to conclusions about the variables chosen for manipulation rather than about those factors which may in fact be most influential in determining annoyance. Because this experiment relied exclusively on synthesized sound stimuli, the results from this experiment must be applied bearing this in mind.

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Usage

For reader convenience, all references are fully cited at the end of each section in which they appear. This collected compilation, in alphabetical order by principal author, is provided for those wishing or needing to quickly peruse the bibliography in its entirety.

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APPENDICES

Index

APPENDIX A - 7x7 LATIN SQUARES

1	2	3	4	5	6	7
2	3	4	5	6	7	1
3	4	5	6	7	1	2
4	5	6	7	1	2	3
5	6	7	1	2	3	4
6	7	1	2	3	4	5
7	1	2	3	4	5	6

Square I

1	2	3	4	5	6	7
3	4	5	6	7	1	2
5	6	7	1	2	3	4
7	1	2	3	4	5	6
2	3	4	5	6	7	1
4	5	6	7	1	2	3
6	7	1	2	3	4	5

Square II

1	2	3	4	5	6	7
4	5	6	7	1	2	3
7	1	2	3	4	5	6
3	4	5	6	7	1	2
6	7	1	2	3	4	5
2	3	4	5	6	7	1
5	6	7	1	2	3	4

Square III

1	2	3	4	5	6	7
5	6	7	1	2	3	4
2	3	4	5	6	7	1
6	7	1	2	3	4	5
3	4	5	6	7	1	2
7	1	2	3	4	5	6
4	5	6	7	1	2	3

Square IV

1	2	3	4	5	6	7
6	7	1	2	3	4	5
4	5	6	7	1	2	3
2	3	4	5	6	7	1
7	1	2	3	4	5	6
5	6	7	1	2	3	4
3	4	5	6	7	1	2

Square V

1	2	3	4	5	6	7
7	1	2	3	4	5	6
6	7	1	2	3	4	5
5	6	7	1	2	3	4
4	5	6	7	1	2	3
3	4	5	6	7	1	2
2	3	4	5	6	7	1

Square VI

APPENDIX B - ASSIGNMENT OF LATIN SQUARES TO TURBOFAN-POWERED AIRCRAFT VARIABLES

Introduction

7x7 Latin Squares (Appendix A) were used to transform the six variables and their respective ranges of values under investigation for the turbofan-powered aircraft type into 49 stimuli approximately uniformly distributed in the six dimensional variable space. The random assignment of the six variables to the six Latin Squares and the random assignment of the Latin Square indices to the variable levels is presented below.

Assignment of Latin Squares

The random assignment of the six 7x7 Latin Squares (Appendix A) to the experimental variables was as follows:

Square I --- Tone emergence
Square II --- Broadband background
Square III --- Broadband spectrum shape
Square IV --- Rotor frequency
Square V --- Amplitude modulation
Square VI --- Beat frequency

Assignment of Latin Square indices

The indices within the Latin Squares were randomly assigned to the variable levels as follows:

Latin Square Indice	Spectrum Shape	Background OASPL [dB]	Rotor Frequency [Hz]	Tone Emergence [dB]	Beat Frequency [Hz]	Beat Amplitude [% a.m.]
1	LOMED	88	50	0	0.4	20
2	BERMC	76	30	30	2.0	80
3	BERLC	73	60	25	8.0	0
4	OUTSID	91	80	20	0.2	100
5	BERMC	82	40	10	4.0	40
6	BERMDC	79	70	5	1.0	0
7	MEDUP	85	20	15	0.8	60

APPENDIX C - AMPLITUDE RELATIONSHIP AMONG HARMONICS

Introduction

Each rotor and propeller blade passage tone potentially had up to four harmonics associated with it, the actual number N varying as a parameter in the experiment. An exponential relationship was chosen to compute the amplitudes of the harmonic tones relative to the amplitudes of their respective fundamentals.

Motivation for exponential relationship

The reason for choosing an exponential relationship was to achieve strong low order harmonics relative to the fundamental tone while attenuating the N+1 harmonic 60 dB. The 60 dB attenuation was chosen arbitrarily but intended to create a harmonic progression where the N+1 harmonic would be inaudible.

Equation for exponential relationship

The attenuation of each harmonic, in decibels, relative to the amplitude of the fundamental was determined using the following equation:

$$\text{attenuation [dB]} = e^{ah} - 1$$

Exponent descriptions

The exponent "a", defined so the amplitude of the N+1 harmonic is 60 dB below the fundamental, is chosen based upon the total number of harmonics N:

$$\begin{aligned} a = {} & 2.0554 \text{ for a single harmonic } (N = 1) \\ & 1.3703 \text{ for 2 harmonics } (N = 2) \\ & 1.0277 \text{ for 3 harmonics } (N = 3) \\ & 0.8222 \text{ for 4 harmonics } (N = 4) \end{aligned}$$

The exponent "h" is the specific harmonic number whose attenuation is to be determined, that is, the first, second, third or fourth harmonic in the series.

Example

As an example, if a tone were to have four harmonics (N = 4), "a" would be set equal to 0.822 and attenuations would be computed for values of h = 1, 2, 3 and 4. The result is that the first harmonic would be 1.3 dB lower than the amplitude of the fundamental, the second harmonic would be 4.2 dB lower, the third 10.8 dB lower, the fourth 25.8 dB lower and the fifth, N+1, would be 60 dB lower.

APPENDIX D - 13x13 LATIN SQUARES

Square I

1	2	3	4	5	6	7	8	9	10	11	12	13
2	3	4	5	6	7	8	9	10	11	12	13	1
3	4	5	6	7	8	9	10	11	12	13	1	2
4	5	6	7	8	9	10	11	12	13	1	2	3
5	6	7	8	9	10	11	12	13	1	2	3	4
6	7	8	9	10	11	12	13	1	2	3	4	5
7	8	9	10	11	12	13	1	2	3	4	5	6
8	9	10	11	12	13	1	2	3	4	5	6	7
9	10	11	12	13	1	2	3	4	5	6	7	8
10	11	12	13	1	2	3	4	5	6	7	8	9
11	12	13	1	2	3	4	5	6	7	8	9	10
12	13	1	2	3	4	5	6	7	8	9	10	11
13	1	2	3	4	5	6	7	8	9	10	11	12

Square II

1	2	3	4	5	6	7	8	9	10	11	12	13
3	4	5	6	7	8	9	10	11	12	13	1	2
5	6	7	8	9	10	11	12	13	1	2	3	4
7	8	9	10	11	12	13	1	2	3	4	5	6
9	10	11	12	13	1	2	3	4	5	6	7	8
11	12	13	1	2	3	4	5	6	7	8	9	10
13	1	2	3	4	5	6	7	8	9	10	11	12
2	3	4	5	6	7	8	9	10	11	12	13	1
4	5	6	7	8	9	10	11	12	13	1	2	3
6	7	8	9	10	11	12	13	1	2	3	4	5
8	9	10	11	12	13	1	2	3	4	5	6	7
10	11	12	13	1	2	3	4	5	6	7	8	9
12	13	1	2	3	4	5	6	7	8	9	10	11

Continued on next page

Square III

1	2	3	4	5	6	7	8	9	10	11	12	13
4	5	6	7	8	9	10	11	12	13	1	2	3
7	8	9	10	11	12	13	1	2	3	4	5	6
10	11	12	13	1	2	3	4	5	6	7	8	9
13	1	2	3	4	5	6	7	8	9	10	11	12
3	4	5	6	7	8	9	10	11	12	13	1	2
6	7	8	9	10	11	12	13	1	2	3	4	5
9	10	11	12	13	1	2	3	4	5	6	7	8
12	13	1	2	3	4	5	6	7	8	9	10	11
2	3	4	5	6	7	8	9	10	11	12	13	1
5	6	7	8	9	10	11	12	13	1	2	3	4
8	9	10	11	12	13	1	2	3	4	5	6	7
11	12	13	1	2	3	4	5	6	7	8	9	10

Square IV

1	2	3	4	5	6	7	8	9	10	11	12	13
5	6	7	8	9	10	11	12	13	1	2	3	4
9	10	11	12	13	1	2	3	4	5	6	7	8
13	1	2	3	4	5	6	7	8	9	10	11	12
4	5	6	7	8	9	10	11	12	13	1	2	3
8	9	10	11	12	13	1	2	3	4	5	6	7
12	13	1	2	3	4	5	6	7	8	9	10	11
3	4	5	6	7	8	9	10	11	12	13	1	2
7	8	9	10	11	12	13	1	2	3	4	5	6
11	12	13	1	2	3	4	5	6	7	8	9	10
2	3	4	5	6	7	8	9	10	11	12	13	1
6	7	8	9	10	11	12	13	1	2	3	4	5
10	11	12	13	1	2	3	4	5	6	7	8	9

Continued on next page

Square V

1	2	3	4	5	6	7	8	9	10	11	12	13
6	7	8	9	10	11	12	13	1	2	3	4	5
11	12	13	1	2	3	4	5	6	7	8	9	10
3	4	5	6	7	8	9	10	11	12	13	1	2
8	9	10	11	12	13	1	2	3	4	5	6	7
13	1	2	3	4	5	6	7	8	9	10	11	12
5	6	7	8	9	10	11	12	13	1	2	3	4
10	11	12	13	1	2	3	4	5	6	7	8	9
2	3	4	5	6	7	8	9	10	11	12	13	1
7	8	9	10	11	12	13	1	2	3	4	5	6
12	13	1	2	3	4	5	6	7	8	9	10	11
4	5	6	7	8	9	10	11	12	13	1	2	3
9	10	11	12	13	1	2	3	4	5	6	7	8

Square VI

1	2	3	4	5	6	7	8	9	10	11	12	13
7	8	9	10	11	12	13	1	2	3	4	5	6
13	1	2	3	4	5	6	7	8	9	10	11	12
6	7	8	9	10	11	12	13	1	2	3	4	5
12	13	1	2	3	4	5	6	7	8	9	10	11
5	6	7	8	9	10	11	12	13	1	2	3	4
11	12	13	1	2	3	4	5	6	7	8	9	10
4	5	6	7	8	9	10	11	12	13	1	2	3
10	11	12	13	1	2	3	4	5	6	7	8	9
3	4	5	6	7	8	9	10	11	12	13	1	2
9	10	11	12	13	1	2	3	4	5	6	7	8
2	3	4	5	6	7	8	9	10	11	12	13	1
8	9	10	11	12	13	1	2	3	4	5	6	7

Continued on next page

Square VII

1	2	3	4	5	6	7	8	9	10	11	12	13
8	9	10	11	12	13	1	2	3	4	5	6	7
2	3	4	5	6	7	8	9	10	11	12	13	1
9	10	11	12	13	1	2	3	4	5	6	7	8
3	4	5	6	7	8	9	10	11	12	13	1	2
10	11	12	13	1	2	3	4	5	6	7	8	9
4	5	6	7	8	9	10	11	12	13	1	2	3
11	12	13	1	2	3	4	5	6	7	8	9	10
5	6	7	8	9	10	11	12	13	1	2	3	4
12	13	1	2	3	4	5	6	7	8	9	10	11
6	7	8	9	10	11	12	13	1	2	3	4	5
13	1	2	3	4	5	6	7	8	9	10	11	12
7	8	9	10	11	12	13	1	2	3	4	5	6

Square VIII

1	2	3	4	5	6	7	8	9	10	11	12	13
9	10	11	12	13	1	2	3	4	5	6	7	8
4	5	6	7	8	9	10	11	12	13	1	2	3
12	13	1	2	3	4	5	6	7	8	9	10	11
7	8	9	10	11	12	13	1	2	3	4	5	6
2	3	4	5	6	7	8	9	10	11	12	13	1
10	11	12	13	1	2	3	4	5	6	7	8	9
5	6	7	8	9	10	11	12	13	1	2	3	4
13	1	2	3	4	5	6	7	8	9	10	11	12
8	9	10	11	12	13	1	2	3	4	5	6	7
3	4	5	6	7	8	9	10	11	12	13	1	2
11	12	13	1	2	3	4	5	6	7	8	9	10
6	7	8	9	10	11	12	13	1	2	3	4	5

Continued on next page

Square IX

1	2	3	4	5	6	7	8	9	10	11	12	13
10	11	12	13	1	2	3	4	5	6	7	8	9
6	7	8	9	10	11	12	13	1	2	3	4	5
2	3	4	5	6	7	8	9	10	11	12	13	1
11	12	13	1	2	3	4	5	6	7	8	9	10
7	8	9	10	11	12	13	1	2	3	4	5	6
3	4	5	6	7	8	9	10	11	12	13	1	2
12	13	1	2	3	4	5	6	7	8	9	10	11
8	9	10	11	12	13	1	2	3	4	5	6	7
4	5	6	7	8	9	10	11	12	13	1	2	3
13	1	2	3	4	5	6	7	8	9	10	11	12
9	10	11	12	13	1	2	3	4	5	6	7	8
5	6	7	8	9	10	11	12	13	1	2	3	4

Square X

1	2	3	4	5	6	7	8	9	10	11	12	13
11	12	13	1	2	3	4	5	6	7	8	9	10
8	9	10	11	12	13	1	2	3	4	5	6	7
5	6	7	8	9	10	11	12	13	1	2	3	4
2	3	4	5	6	7	8	9	10	11	12	13	1
12	13	1	2	3	4	5	6	7	8	9	10	11
9	10	11	12	13	1	2	3	4	5	6	7	8
6	7	8	9	10	11	12	13	1	2	3	4	5
3	4	5	6	7	8	9	10	11	12	13	1	2
13	1	2	3	4	5	6	7	8	9	10	11	12
10	11	12	13	1	2	3	4	5	6	7	8	9
7	8	9	10	11	12	13	1	2	3	4	5	6
4	5	6	7	8	9	10	11	12	13	1	2	3

Continued on next page

Square XI

1	2	3	4	5	6	7	8	9	10	11	12	13
12	13	1	2	3	4	5	6	7	8	9	10	11
10	11	12	13	1	2	3	4	5	6	7	8	9
8	9	10	11	12	13	1	2	3	4	5	6	7
6	7	8	9	10	11	12	13	1	2	3	4	5
4	5	6	7	8	9	10	11	12	13	1	2	3
2	3	4	5	6	7	8	9	10	11	12	13	1
13	1	2	3	4	5	6	7	8	9	10	11	12
11	12	13	1	2	3	4	5	6	7	8	9	10
9	10	11	12	13	1	2	3	4	5	6	7	8
7	8	9	10	11	12	13	1	2	3	4	5	6
5	6	7	8	9	10	11	12	13	1	2	3	4
3	4	5	6	7	8	9	10	11	12	13	1	2

Square XII

1	2	3	4	5	6	7	8	9	10	11	12	13
13	1	2	3	4	5	6	7	8	9	10	11	12
12	13	1	2	3	4	5	6	7	8	9	10	11
11	12	13	1	2	3	4	5	6	7	8	9	10
10	11	12	13	1	2	3	4	5	6	7	8	9
9	10	11	12	13	1	2	3	4	5	6	7	8
8	9	10	11	12	13	1	2	3	4	5	6	7
7	8	9	10	11	12	13	1	2	3	4	5	6
6	7	8	9	10	11	12	13	1	2	3	4	5
5	6	7	8	9	10	11	12	13	1	2	3	4
4	5	6	7	8	9	10	11	12	13	1	2	3
3	4	5	6	7	8	9	10	11	12	13	1	2
2	3	4	5	6	7	8	9	10	11	12	13	1

APPENDIX E - ASSIGNMENT OF LATIN SQUARES TO ADVANCED PROPELLER-DRIVEN AIRCRAFT VARIABLES

Introduction

13x13 Latin Squares (Appendix D) were used to transform the 12 variables and their respective ranges of values under investigation for the advanced propeller-driven aircraft type into 169 stimuli approximately uniformly distributed in the 12 dimensional variable space. The random assignment of the 12 variables to the 12 Latin Squares and the random assignment of the Latin Square indices to the variable levels are presented below.

Assignment of Latin Squares

The random assignment of the twelve 13x13 Latin Squares (Appendix D) to the experimental variables was as follows:

Square I	----	Forward propeller BPF* tone emergence
Square II	----	Rotor tone beat amplitude
Square III	----	Rotor tone harmonic shape
Square IV	----	Aft propeller BPF tone emergence
Square V	----	Rotor tone beat frequency
Square VI	----	Broadband spectrum shape
Square VII	----	Rotor tone emergence
Square VIII	----	Broadband background OASPL
Square IX	----	Front propeller blade passage frequency
Square X	----	Rotor tone frequency
Square XI	----	Aft propeller blade passage frequency
Square XII	----	Propeller tone harmonic shape

* BPF ≡ Blade Passage Frequency

Continued on next page

Assignment of Latin Square indices

The indices within the Latin Squares were randomly assigned to the variable levels. These assignments are shown in the tables below and on the following page. The segregation of the 12 variables into four tables according to their association with the broadband portion of the spectrum, the rotor tones or the propeller tones was done to highlight the connection between the audible, engine-related noise sources anticipated within future aircraft and those spectral characteristics related to the sources which were chosen for investigation. Subdividing what would have been a single large table into four smaller tables also facilitated presenting the information since one larger table could not be accommodated on a single page.

LATIN SQUARE INDICE	BROADBAND NOISE	
	Spectrum Shape	Background OASPL [dB]
1	BERMC	88
2	BERMDC	85
3	MEDUP	82
4	MEDUP	88
5	BERMC	76
6	BERMDC	82
7	BERLC	82
8	BERLC	79
9	LOMED	79
10	OUTSID	76
11	LOMED	79
12	OUTSID	85
13	MEDUP	85

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APPENDIX E - ASSIGNMENT OF LATIN SQUARES TO ADVANCED PROPELLER-DRIVEN AIRCRAFT VARIABLES, Continued

Assignment of Latin Square indices - cont'd

LATIN SQUARE INDICE	ROTOR TONES				
	Rotor Frequency [Hz]	Tone Emergence [dB]	Number of Harmonics	Beat Frequency [Hz]	Beat Amplitude [% a.m.]
1	1000	16	3	6.0	40
2	30	8	0	0.4	40
3	60	12	0	10.0	20
4	70	28	0	0.2	40
5	500	-8	4	4.0	100
6	40	24	2	8.0	60
7	90	-12	3	0.8	80
8	100	24	1	1.0	20
9	50	0	4	12.0	0
10	20	12	4	6.0	60
11	80	4	1	0.6	0
12	20	-4	2	0.8	100
13	250	20	2	2.0	80

LATIN SQUARE INDICE	FORWARD PROPELLER TONES			AFT PROPELLER TONES	
	Blade Pass. Frequency [Hz]	Tone Emergence [dB]	Number of Harmonics	Blade Pass. Frequency [Hz]	Tone Emergence [dB]
1	$11F_R{}^*$	20	4	$10F_R{}^*$	0
2	8	-4	3	11	12
3	6	16	1	8	28
4	8	0	1	12	-4
5	12	28	0	9	4
6	6	4	4	10	20
7	12	12	2	6	8
8	14	-8	0	8	12
9	9	24	2	9	-8
10	11	8	3	14	-12
11	10	12	0	11	16
12	10	24	2	14	24
13	9	-12	4	12	24

$^*F_R \equiv$ Rotor frequency

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James R. Angerer and Richard A. Erickson: Boeing Commercial Airplane Group, Seattle, Washington.
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16. Abstract

An experiment was conducted to develop a noise annoyance model for evaluating passenger response to sounds containing tonal components. Seventy-two test subjects used magnitude estimation to judge the annoyance of 66 steady-state sounds simulating passenger cabin sounds within current and future commercial aircraft. The sounds investigated ranged from those being experienced by passengers on board current turbofan-powered aircraft to those cabin noise sounds passengers may experience within future advanced propeller-driven aircraft. The spectral characteristics investigated were: (1) broadband background noise; (2) engine rotor tones; (3) rotor tone harmonics; (4) propeller blade passage tones; and (5) propeller blade passage tone harmonics. The analysis was based upon four elementary auditory sensations: loudness, tonality, sharpness, and roughness. Loudness was found to be the dominant sensation in annoyance with tonality being the second most influential sensation. Neither sharpness nor roughness were of practical significance. A model developed using loudness and tonality was found to be a better predictor of annoyance than either A-weighted sound pressure level (L_A) or overall sound pressure level (OASPL).

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