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Audibility of Multiple, Low-Frequency Tonal Signals in Noise

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Abstract

The main purpose of this study is to examine the audibility of multiple, low-frequency tones that are placed in distinct auditory channels. Three experiments are described, the goals of which are to determine if the presence of sound in multiple channels results in enhanced audibility and to assess the applicability of the Statistical Summation Model (SSM) to this frequency range. This model predicts that for the case of multiple signals that are in separate auditory channels, implying statistical independence, each with sensitivity value d_i', the resulting total sensitivity is given by the square root of the sum of the squares of the individual d_i' values.

In common with previous studies conducted at higher frequencies, the signals are pure tones and the maskers are broadband noise. The requirement that low frequency tones be placed in separate auditory filters limited the number of tones to a maximum of three. The first of the three experiments measured the change in masked thresholds for two- and three-tone signals relative to the level of the equally-detectable single tones. The multiple tone signals were composed of combinations of 55, 120 and 200 Hz tones. The measured changes in thresholds exceeded those predicted by the SSM, although they did not differ statistically from the model predictions. The second experiment employed the same overall approach but acquired more data and concentrated on the three-tone signal. Once again, the measured changes in masked threshold exceeded the model predictions, this time to a statistically-significant degree.

Two issues were postulated with the potential to yield inflated changes in masked threshold: interaction between tones resulting in perceptible intermodulation/difference tones, and the assumption that the tones were in distinct auditory filters and statistically independent of one another. The third experiment used two sets of three-tone signals to address these latter concerns. The first set of three tones was composed of harmonically related tone frequencies of 55, 110 and 165 Hz, which was an attempt to reduce effects of intermodulation difference tones. The second set of three tones was chosen to be 110, 220 and 330 Hz, again reducing effects of difference tones, but also providing greater separation between tones. Results for the first set of three tones compared to those of the earlier experiments indicated that intermodulation was not an important effect. The second set of three tones (110, 220, 330 Hz) yielded changes in masked thresholds that, on average, were in good agreement with the SSM, although intersubject variability was large and prohibited a definitive conclusion regarding the concern that tone spacing was inadequate.

The results of the three experiments showed that the masked threshold of sounds with multiple (two or three) equally-detectable low frequency tones was lower than those of the single tones. In other words, it is clear that audibility is enhanced by the presence of signals in multiple auditory filters. This finding is consistent with most previous research conducted at higher frequencies. In contrast with previous research, test subjects were, on average, able to detect multitone sounds at lower levels than those predicted using the SSM. Analyses that included Monte Carlo simulations showed that normally distributed errors in the single tone thresholds result in biased estimates of the thresholds of multitone sounds. This phenomenon is likely responsible for at least a substantial fraction of the unexpected deviation of measurements from SSM predictions.

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1 Introduction

This research effort is concerned with the audibility of low frequency noise that typically arises either from sources with dominant low frequency content (e.g., helicopters and sonic booms) or sources at long distances for which high frequency content has been attenuated by the atmosphere and terrain (e.g., distant jet aircraft and road traffic). For the purpose of this study, “low frequency” is defined as being below about 200 Hz.

The human hearing system has been functionally characterized as a bank of bandpass filters and numerous experimenters have investigated the attributes of these presumed filters over the past eighty years. However, characterization of the lower frequency filters has received relatively little attention when compared to those in the frequency range important for speech perception. Work by Jurado [1, 2] indicates that the human hearing system has a “lowest” or “bottom” bandpass filter and thus, sound below its tip frequency is perceived via the lower skirt of this lowest band. The center frequency, shape and bandwidth of this lowest auditory filter determined by Jurado were recently confirmed by Rafaelof et al. [3] using a different test facility and a somewhat different test methodology.

Low frequency sound from sources such as those described above is generally not restricted to a single auditory filter. Thus, assessment of the audibility of low frequency sound requires an understanding of the influence of simultaneous acoustic excitation of multiple auditory filters. While many studies over the past decades have been concerned with loudness of broadband sounds spanning a wide frequency range, relatively few have studied low frequency audibility.

The studies of audibility of sounds with spectra that span multiple auditory filters have primarily used pure tones in the presence of broadband masking noise. For example, an early study by Schafer et al. [4] examined the audibility of single tones and multiple, equally-detectable, tones spanning a frequency range from 600 to 1550 Hz in the presence of noise. Relative to the threshold of a single tone, the threshold of a two-tone complex was 0-2 dB lower, and that of a four or eight tone complex was approximately 0-3 dB lower. Additional tones yielded no changes in threshold. Schafer et al. proposed a model that predicted an approximately 1.5 dB reduction in threshold for two tones and an approximately 3 dB reduction for four tones. Schafer suggested that the change in threshold was due to the increased opportunity for detection that occurs for multiple tones. For example, two tones with individual probabilities of detection (POD) of 50% will, when heard together, have a 75% POD and four tones will have a 94% POD. The change in sound pressure level between 50% and 75% or 94% POD is determined by the shape of a typical psychoacoustic function that relates POD to the signal to noise ratio of tones in noise. This modeling approach, attributed to Schafer, was subsequently named the independent thresholds model (ITM).

Green [5] examined the audibility of two-tone complexes relative to single tones. Four frequencies were employed: 500, 1000, 1823, and 2000 Hz and the thresholds of all possible pairs as well as single tones were determined in the presence of white noise. The single-tone threshold values were used to construct the pairs of equally-detectable tones. Results were compared with three models. The first, the “No-Summation Model”, predicts that multiple tones, separated by more than a critical bandwidth, will be no more detectable than the most-detectable component. In other words, an observer is only able to listen to one critical band at a time. The data from the experiment clearly show this model to be in error. The other two models consist of the ITM proposed by Schafer et al., described earlier, and the “Statistical Summation Model” (SSM) [6, 7]. The latter is based on statistical decision theory, which was developed in the 1950s. Green and Swets [8] contains a summary of much of this important work. Green [5] concluded that the SSM had slightly better agreement with his measurements than did the ITM, but the author recognized that the use of only two components did not provide a good test of the difference between the models.

Green et al. [9] examined the detection of both single tones and multiple tones between 250 and 4,000 Hz in the presence of white noise. All tone frequencies were harmonics of 250 Hz. Thresholds of the single tones were first determined, followed by threshold measurements of 12 and 16-tone complexes consisting of equally detectable tones. The reduction in threshold of the multiple tones, relative to single tones, was large (approximately 6 dB), and consistent with the SSM described earlier. In addition, it was noted that the phase relationship between the tonal components had no effect on measured thresholds.

Buus et al. [10] performed two related experiments that examined masked thresholds of single tones and multitone complexes. The first experiment investigated single tones (220, 1100, 3850 Hz) and an 18-tone complex consisting of selected harmonics of a 110 Hz fundamental, chosen such that adjacent components were separated from one another by approximately one equivalent rectangular bandwidth (ERB) of the relevant auditory filters. The harmonics were at equal level and in random phase and the masker was a uniformly-masking noise. Psychometric functions were measured and the results compared with the three models described earlier. As before, the "No-Summation Model" was rejected due to the multitone complex being detected at levels lower than those of the individual components. The other two models, the ITM and the SSM were both consistent with the measured data. The second experiment was designed to distinguish between those two models. The approach adopted was to examine the detection of tones presented at random. This contrasts with the first experiment (and many others) in which test subjects are exposed to the same stimulus (i.e., fixed frequency) within an experimental block. The SSM predicts that thresholds will be higher in the random condition than in the fixed condition because of the need to monitor all auditory channels in which the signal could appear. The ITM predicts that thresholds should be the same in the fixed and random conditions. The results clearly indicate elevated thresholds under random conditions, thus favoring the SSM. However, the results were not consistent with subjects employing an optimum decision rule.

In summary, previous studies clearly show that detection is aided by the presence of signal energy in more than one auditory channel. Furthermore, in most instances the studies show stronger support for the SSM than other proposed models. However, none of the previous studies have investigated whether these findings are applicable to low frequencies.

The main purpose of this research effort is to improve audibility predictions at low frequencies through examination of sounds that span multiple auditory channels. In particular, it is important to determine if the presence of sound in multiple channels results in enhanced audibility and to assess the applicability of the SSM to this frequency range. In common with the studies already described, the signals are pure tones and the maskers are broadband noise. Since the emphasis is on low frequencies, there are several challenges that differ from those encountered in the work described earlier. The restricted frequency range limits the number of tones that can be placed in separate auditory filters. This constraint has two effects: the change in masked threshold that is likely to occur with the addition of a small number of tones is small, and the threshold of the multitone sounds may be very sensitive to errors made in the determination of the masked thresholds of the individual tones. Furthermore, as noted by Jurado [1, 2] and Rafaelof [3], there appears to be a larger variation between individuals' auditory filter characteristics at lower frequencies than is observed at higher frequencies. As a result, an incremental approach consisting of a series of small experiments was adopted, with the aim of addressing potential problems in a logical and systematic sequence, and with the goal of creating a model to predict the audibility of low frequency sounds that span multiple auditory channels.

2 Experimental Approach and Test Procedures

2.1 Test Facility

The test facility, the Exterior Effects Room (EER) [11] (Figure 1 and Figure 2) at the NASA Langley Research Center and its configuration are identical to those employed by Rafaelof et al. [3]. One test subject at a time was seated close to a subwoofer loudspeaker (16L in Figure 1). The test sounds that can be presented to the subject are constrained by the performance of the loudspeaker, and also by background noise in the laboratory, primarily from the building's heating and air conditioning system. The EER's heating and air conditioning system was switched off when test subjects were present.

A further constraint is due to the generation of rattle sounds by, for example, light fixtures vibrating in response to high amplitude, low frequency sound generated in the psychoacoustic testing. These rattle sounds could potentially provide auditory cues associated with the presence of inaudible signals, but fortunately they occur only at high signal sound levels that can be avoided during testing.

Figure 1: Exterior Effects Room (EER) at the NASA Langley Research Center.

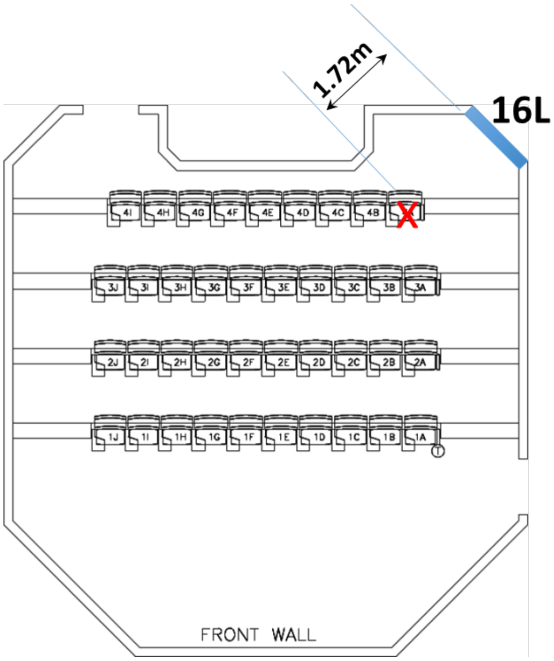

Figure 2: Single subject test setup: seat 4A in front of 16L subwoofer speaker.

2.2 Test Stimuli

The acoustic test stimuli utilized in the following experiments had common characteristics. All pure tones and broadband sounds were digitally generated. Sound pressure measurements made at a position corresponding to the center of a test subject's head were used to construct an equalization filter so that desired tone levels and uniform masker spectrum levels could be obtained. As will be described below, the test stimuli included random, band-limited noise. The bursts of noise used in the experiments were identical, thus avoiding random differences in masker level from one observation interval to another, as would occur if the noise bursts were different random time series with equal spectral levels. A three-interval, three-alternative forced-choice (3AFC) adaptive procedure was adopted for the experiments and further details are presented below. Each of the test stimuli, presented in groups of three, had a duration of 0.75 seconds with a 0.15 second interval of silence between stimuli. A Tukey window, with the first and last 4% of the window equal to half of a cosine, was applied to all test stimuli to minimize transient effects.

2.3 Test Subjects

Test subjects that participated in the experiments were selected from two distinct groups. The first consisted of volunteers from the laboratory staff. This group was used for pilot studies, not described herein, and for the first experiment described below. The other group of test subjects was selected from a pool of local residents with a wide range of ages and socioeconomic backgrounds and who were compensated for their participation in the experiments. These participants had previously taken part in a similar experiment [3] and had demonstrated good low frequency (below 100 Hz) hearing acuity and the ability to reliably perform adaptive, 3AFC procedures. That previous experiment indicated that subjects' age and gender had no discernable effect on hearing thresholds, so no effort was made to achieve a balance of age and gender for this experiment. Subjects' hearing was retested immediately prior to their participation in each experiment to verify normal hearing within 20 dB over the frequency range of 125 Hz to 4000 Hz [12].

2.4 Test Method

Threshold measurements of signals in the presence of masking noise were made using an adaptive, three-alternative forced choice procedure. As shown on the left side of Figure 3, the signal was randomly assigned to one of the three intervals. As illustrated on the right-hand side of Figure 3, a tablet computer screen indicated the sound being presented within a trial, followed by another screen for the subject to indicate which of the three intervals contained the signal. This was followed by the third screen that provided feedback for correct/incorrect responses. An adaptive, 3-down 1-up staircase procedure was employed [13] in which three correct responses results in a reduction in sound level and a single incorrect response results in an increase in sound level. The starting amplitude of each sound was well above the expected threshold. In order to rapidly approach the threshold level, the initial step size was 6 dB and a 2-down 1-up procedure was employed until the second reversal. The step size was then reduced to 4 dB and a 3-down 1-up procedure was followed for a further two reversals after which the step size was reduced to 2 dB. Each staircase was limited to 50 trials. The threshold was estimated as the average of the levels of the turnpoints past the third reversal. This corresponds to 79.4% correct and a d' value of 1.61 [14]. A discussion of factors that guided the selection of the adopted test method can be found in Appendix B of Ref. [3].

Staircases were interleaved within a test session so that subjects were not able to discern the pattern of the adaptive procedure. The sequence of trials within a session was based on a random selection from the test conditions being interleaved. This selection was different for each test subject in all of the experiments. Further testing details are provided for each experiment below.

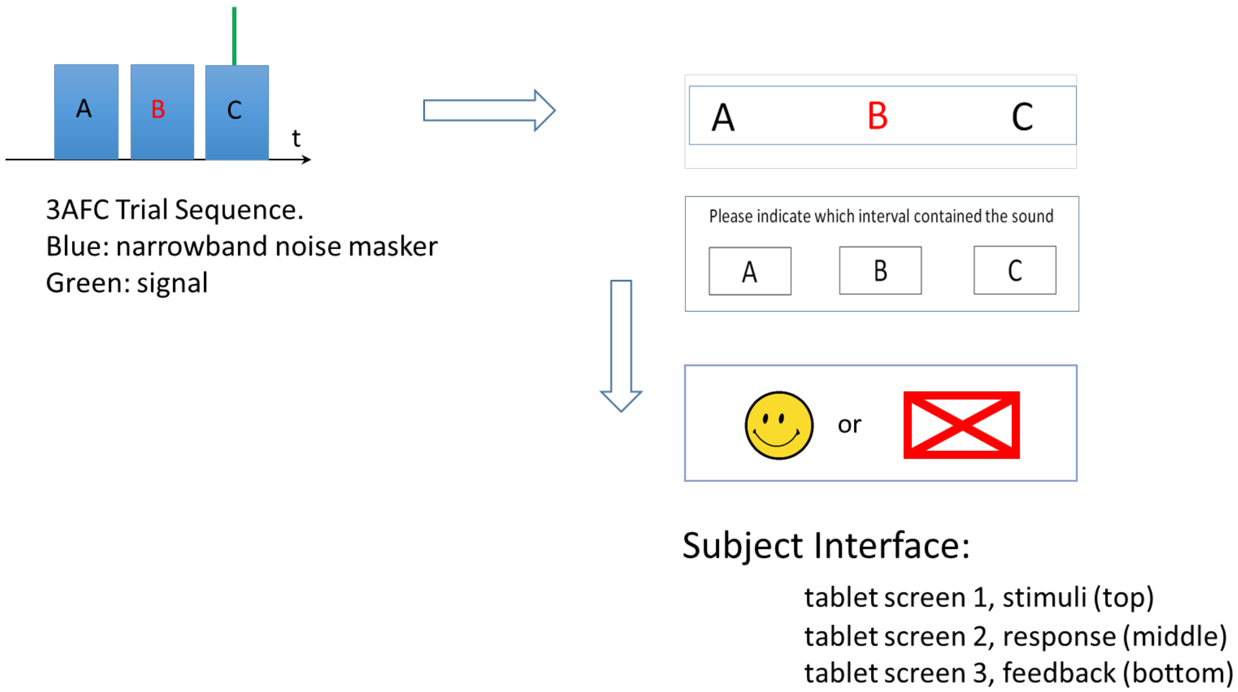

Figure 3: 3AFC trial sequence vs. time (left) and its representation on subject's tablet (right), followed by response and feedback tablet screenshots.

2.5 Laboratory Procedure

Upon arrival at the laboratory the subjects were given written instructions detailing the test. After reading the instructions the subjects completed consent forms. Copies of the test instructions and informed consent forms are given in Appendix A. The subjects were then given a verbal explanation of the task that was to be performed using the tablet computer, followed by familiarization and training sessions. The familiarization session consisted of listening to some representative sounds and the training session required the subjects to provide their responses using the tablet computer. Test sessions were approximately 8 or 12 minutes in length for two and three interleaved staircases, respectively, and separated by short rest breaks during which the subjects were free to leave the EER. Further details are given for each experiment below.

3 Experiment A – Exploratory Study of Masked Thresholds for One, Two, and Three Tones (55, 120, 200 Hz)

3.1 Experiment A – Description

The objective of this experiment is to measure the change in masked threshold that occurs when multiple auditory filters contain a tone, each of which is equally audible when presented alone. As discussed in the introduction, the limited frequency range presents several challenges. For these reasons, this first experiment was considered to be exploratory in nature; it was unknown whether uncontrollable measurement errors would prevent sufficiently precise quantification of the sought-after effect.

It was desired that tone frequencies be separated from one another by a minimum of approximately two filter bandwidths, i.e., two equivalent rectangular bandwidths (ERB). This separation might be viewed as excessive, but reflects the large variation in filter characteristics observed across test subjects at low frequencies [1-3]. This resulted in three tone frequencies within the bandwidth of interest. The lowest frequency (55 Hz) was chosen since it approximates the tip frequency of the “bottom” or “lowest” auditory filter. The ERB of this filter is estimated to be in the range 35-40 Hz [1-3]. The other tone frequencies (120 and 200 Hz) cover the remaining frequency range of interest. The ERB values at those frequencies were derived using the well-known equation,

$$\mathrm{ERB} \;=\; 24.7\left(4.37F+1\right)$$

in which F is filter center frequency in kHz [15]. The ERBs at 120 and 200 Hz are thus estimated to be 38 and 46 Hz, respectively. Typical measured filter shapes for the lowest filter can be found in Refs. [1-3]. Measured filter shapes centered on 120 Hz and 200 Hz can be found in Figure 3 of Ref. [15] and in the left pane of Figure 7 of Ref. [16]. All of these measured filter shapes have steep upper and lower skirts with the exception of the relatively shallow slope of the upper skirt of the lowest filter. Thus, although the desired separation of approximately two filter bandwidths between tone frequencies was achieved, the shallow slope of the upper skirt of the lowest filter provides less attenuation of its neighboring tone than is the case for the other tone pairs.

The chosen broadband masker (nominal spectral level of 32.7 dB/Hz and 40-250 Hz) is illustrated in Figure 4 along with the ambient noise present in the test facility. The ambient noise clearly exceeds the nominal masker level at frequencies below 40 Hz, although this is of little concern since the lowest (bottom) auditory filter has an extremely steep lower skirt, thus greatly attenuating the ambient noise below 40 Hz.

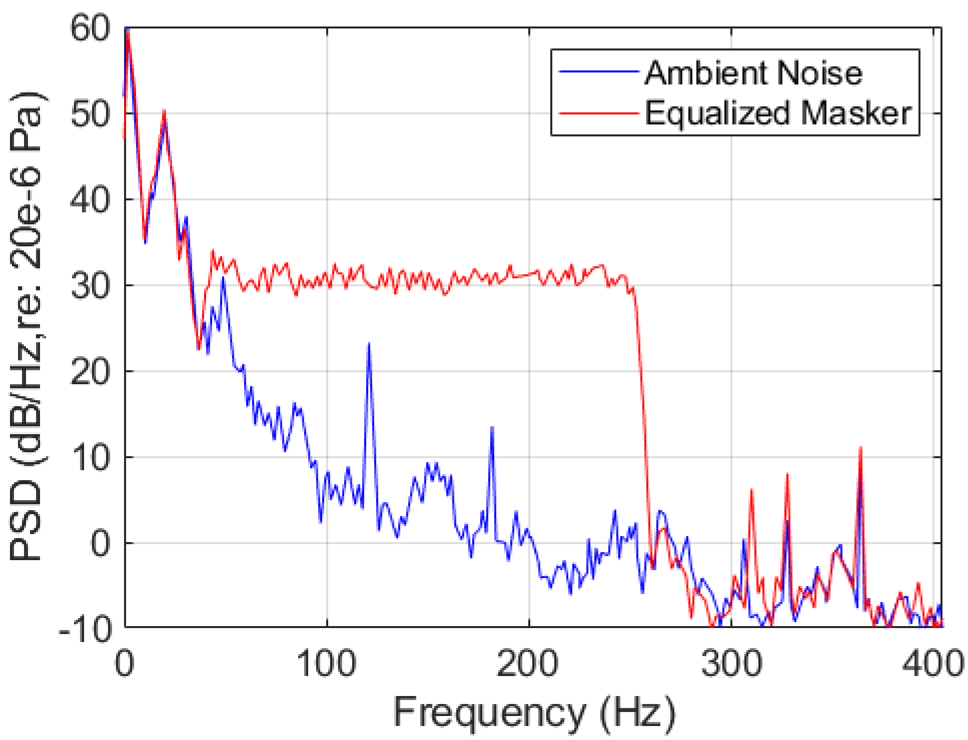

Figure 4: Power spectral density of ambient noise and equalized masker measured at the location of the test subject's head.

The first step in this experiment was to determine the threshold of each tone in the presence of the masker. Five experienced subjects (laboratory staff) completed 50-trial staircases using the adaptive 3AFC procedure described above. The three test frequencies were interleaved within a single session. Masked thresholds were then calculated for each frequency and each test subject. The measured thresholds are shown in Figure 5 for the five test subjects, one of whom repeated the test on another occasion. Clearly, there is variability both between and within subjects' masked thresholds for single tones.

The three single-tone threshold values allowed the creation of new test signals consisting of combinations of two and three equally-detectable tones. All four possible tone complexes were formed, three pairs and one triad. These new test signals were custom-made for each test subject based on their individual masked thresholds. It should be noted that although they were equally detectable in the presence of the masker, the individual tones in a complex generally had unequal masked threshold levels and were different for each test subject. This approach was also used by Green [5, 9] and is in contrast to some previous studies (e.g., Ref. [10]) that employed a "uniformly masking noise" that aimed to mask tones equally, regardless of frequency. The application of such an approach at low frequencies is problematic due to less confidence regarding auditory filter shapes and bandwidths, and large potential differences between individuals.

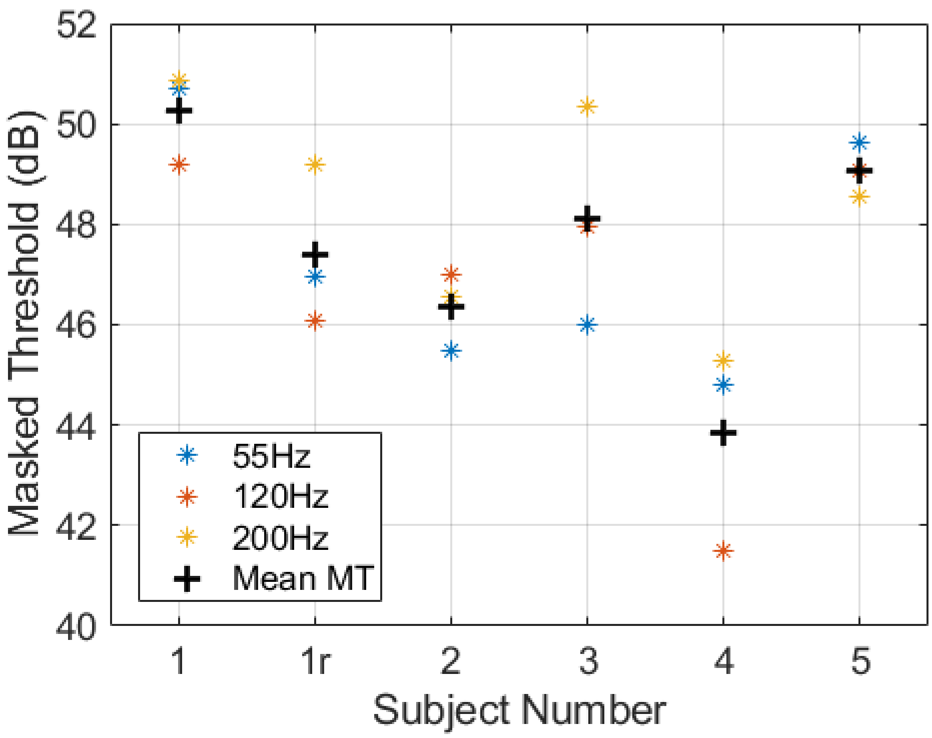

Figure 5: Experiment A – Masked threshold levels of single tones (55, 120, 200 Hz) for five test subjects (subject 1 repeated the test).

Masked thresholds were next determined for the tone complexes using the same subjects and 3AFC procedure as before. The four signals (three pairs of tones and one triad) were divided into two test sessions, each of which interleaved two of the four signals. All sessions contained all three tones, thus ensuring that the same auditory channels were required to be active in each session. The determination of masked thresholds for the single tones, the pairs and the triad were accomplished in less than two hours for each test subject.

3.2 Experiment A – Results and Discussion

The masked thresholds of the tone pairs and triad are presented in Figure 6. The ordinate is the change in amplitude of the tone pair or triad relative to the levels at which each member of the pair (or triad) was individually detectable. For example, the masked thresholds for a particular test subject were 47 dB at 55 Hz and 46 dB at 120 Hz. These two tones at those levels were added together to form a new test sound, the level of which was varied in order to determine its masked threshold. The masked threshold of this new sound was found to be, for example, 2 dB below the original levels of the component tones (45 and 44 dB in this example). Thus, it would be concluded that detection is improved by the presence of sound in multiple auditory filters, the magnitude of the improvement being 2 dB. The figure shows the changes in masked thresholds for all subjects and all sounds. One subject repeated the test on a second occasion.

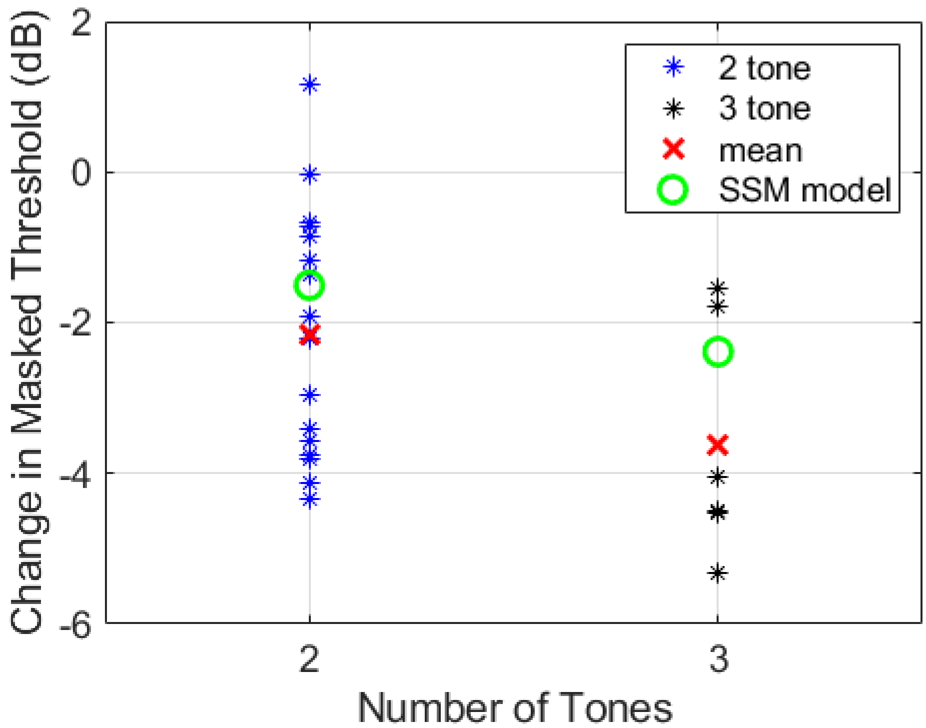

Figure 6: Experiment A – Change in masked threshold levels for tone pairs and a triad relative to level of equally-detectable single tones.

Also shown on the figure are predictions of the SSM. As mentioned earlier, this model is based on signal detection theory, a summary of which may be found in Ref. [8]. A central element of the theory is the sensitivity index, usually represented by d', which is a statistic that provides a measure of the separation (in this instance within the internal response of the human hearing system) between a signal in the presence of noise and noise alone. In the case of multiple signals that are in separate auditory filters, implying statistical independence, and each with value d'_i, the resulting sensitivity, d'_n, is:

$$d'_n = \sqrt{\left(\sum_i^n d_i'^2\right)}$$

in which the subscript *i* represents each auditory filter and *n* is the number of filters.

Since each tone in the pair or triad has the same value of d' ($d' = 1.61$ for the test procedure implemented in this experiment), and because d' is proportional to the signal intensity, the summation across two and three auditory filters is expected to result in reductions in masked threshold of 1.5 and 2.4 dB, respectively, i.e., $10\log_{10}\sqrt{n}$. If tones were closely spaced in frequency (i.e., within a single auditory filter), the change in threshold would be much larger: 3 and 4.8 dB, respectively, for the case of total power summation.

Examination of Figure 6 clearly indicates that the presence of sound in multiple auditory filters aids detection. The data for almost all tone pairs and the tone triad fall below 0 dB. It also appears that tones exciting three filters are more detectable than for two filters. Table 1 summarizes all the data for this first experiment.

Table 1: Experiment A – Masked threshold levels for single tones and changes in masked threshold levels for tone pairs and a triad relative to level of equally-detectable single tones.

Subject #	**Masked Threshold (dB)**			**Change in Masked Threshold (dB)**			
	55 Hz	120 Hz	200 Hz	55/120 Hz	55/200 Hz	120/200 Hz	55/120/200 Hz
1	50.69	49.19	50.88	-4.12	-0.03	-2.95	-5.31
2	45.50	47.01	46.55	-2.21	-3.42	-3.75	-4.04
3	46.01	47.95	50.34	-3.80	-1.18	-0.87	-1.80
4	44.80	41.50	45.27	-0.67	-1.37	-4.33	-4.50
5	49.63	49.07	48.56	-3.56	-4.12	-0.72	-4.54
1r	46.96	46.09	49.19	-1.18	-1.91	1.15	-1.56
Mean	47.27	46.80	48.46	-2.59	-2.01	-1.91	-3.62
Std. Dev.	2.38	2.86	2.18	1.45	1.51	2.11	1.56

The mean reduction in masked threshold levels for the pairs of tones exceeds the model prediction (2.17 vs. 1.5 dB for the model). There was some concern that the tones in the first pair (55 and 120 Hz) were not as isolated from one another as desired, which could result in larger changes in the masked threshold. However, the other pairs (55 and 200, 120 and 200 Hz) also exhibit larger changes in masked thresholds than the model predicts, which indicates that lack of isolation is likely not an important factor. The mean reduction in masked threshold for the tone triad, 3.62 dB, also exceeds the model prediction of 2.4 dB. However, the model predictions fall within the 95% confidence intervals of the measured mean values for both the pairs and the triad. The 95% confidence intervals on the mean are quite large, particularly for the tone triad (approximately ±1.6 dB), which has one-third the number of observations of the tone pairs.

4 Experiment B – A Study of Masked Thresholds for One and Three Tones (55, 120, 200 Hz)

4.1 Experiment B – Description

The aim of this follow-on study was unchanged from Experiment A, namely to measure changes in masked thresholds when equally-detectable tones are presented in separate auditory filters. Based on the model predictions, the size of the expected effect being sought in this experiment is 2.4 dB. There are numerous methodological and testing issues that can introduce measurement errors of a similar magnitude. Based on the execution of Experiment A, some methodological changes were made. The first of these was the use of compensated test subjects. These five participants had previously taken part in a similar experiment [3] and had demonstrated good low frequency (below 100 Hz) hearing acuity and the ability to reliably perform adaptive, 3AFC procedures. The design of Experiment A resulted in far more data being collected for pairs of tones than for tone triads. Also, the design had a potential weakness in the testing sequence, which required that masked thresholds were first determined for single tones, followed by the tone pairs and triads. This design ran the risk that any effects due to subjects' fatigue or learning would be confounded with experimental conditions.

As a result of these considerations, the design of Experiment B was a modified version of that used in Experiment A. As before, the masked threshold of each individual tone was determined using the 3AFC method and three interleaved staircases. This was followed by the creation of a new sound, composed of the three, equally detectable tones. The masked threshold of this triad was measured twice using two interleaved staircases. This entire sequence (individual tones followed by the tone triad) was repeated twice more, and was accomplished in a single laboratory visit for each test subject. Unlike Experiment A, this one did not investigate tone pairs, only tone triads.

4.2 Experiment B – Results and Discussion

Data acquired in this experiment are summarized in Table 2, in which masked thresholds for the three single tones are presented for each subject and for each of the three repeat conditions. Columns 5 and 6 of the table contain the change in masked thresholds that result from the formation of the triad, each tone of which is equally detectable. Statistical comparisons of the data for all subjects indicate there are no significant differences between the three repeats, suggesting that any learning or fatigue effects are small relative to other sources of measurement errors. Figure 7 presents the single tone masked thresholds for each subject and each repeat. As indicated in the figure and in Table 2, there are clearly differences between test subjects, both in terms of their mean responses and the data scatter. For example, subject 3 exhibits both lower threshold values and lower scatter, perhaps indicating better frequency selectivity and attentiveness. More interesting is the reduced standard deviation of threshold values for the multitones relative to the single tones. This is the case for both Experiments A and B, as shown in the last row of Table 1 and Table 2. It is clear that the variance of the masked thresholds for the single tones is composed of two components, one due to intersubject differences and the other due to intrasubject variability (Figure 5 and Figure 7). Recall that the tone pairs and triads are customized for each test subject based upon their measured thresholds for the individual tones. This process is designed to reduce intersubject differences in the measurement of the masked thresholds of the pairs and triads. Thus, it is not surprising that the observed variance in the thresholds of the pairs and triads is less than that observed for the individual tones. It is noteworthy that the standard deviation for the pairs and triads is typically between about 1.4 and 2.0 dB, which is similar to the estimates of 1.6 and 1.9 dB reported for intrasubject variability by Rafaelof et al. (Appendix B, Ref. [3]).

Table 2: Experiment B – Masked threshold levels for single tones and changes in masked threshold levels for two staircases of tone triads relative to level of equally-detectable single tones.

Subject #	Masked Threshold (dB)			Change in Masked Threshold (dB)	
				Triad	
	55 Hz	120 Hz	200 Hz	Staircase (a)	Staircase (b)
1	53.59	46.45	46.32	-3.14	-5.48
1	52.96	47.21	46.24	-4.78	-1.23
1	49.07	46.25	44.46	-4.11	-3.42
2	47.57	45.28	46.67	-1.91	-3.66
2	47.28	46.16	47.16	-3.27	-3.54
2	48.17	46.59	46.99	-6.17	-4.81
3	46.28	44.25	46.03	-4.64	-7.43
3	46.04	44.95	45.54	-5.14	-4.39
3	44.14	43.82	44.50	-4.29	-1.37
4	55.04	53.19	51.21	-4.12	-4.63
4	51.07	49.98	46.37	-0.41	-1.74
4	53.39	51.44	48.64	-4.26	-2.33
5	45.41	47.38	50.40	-2.95	-4.12
5	47.01	46.99	50.63	-4.03	-4.50
5	51.38	46.24	51.27	-5.00	-6.46
Mean	49.23	47.08	47.50	-3.88	-3.94
Std. Dev.	3.42	2.59	2.35	1.41	1.78

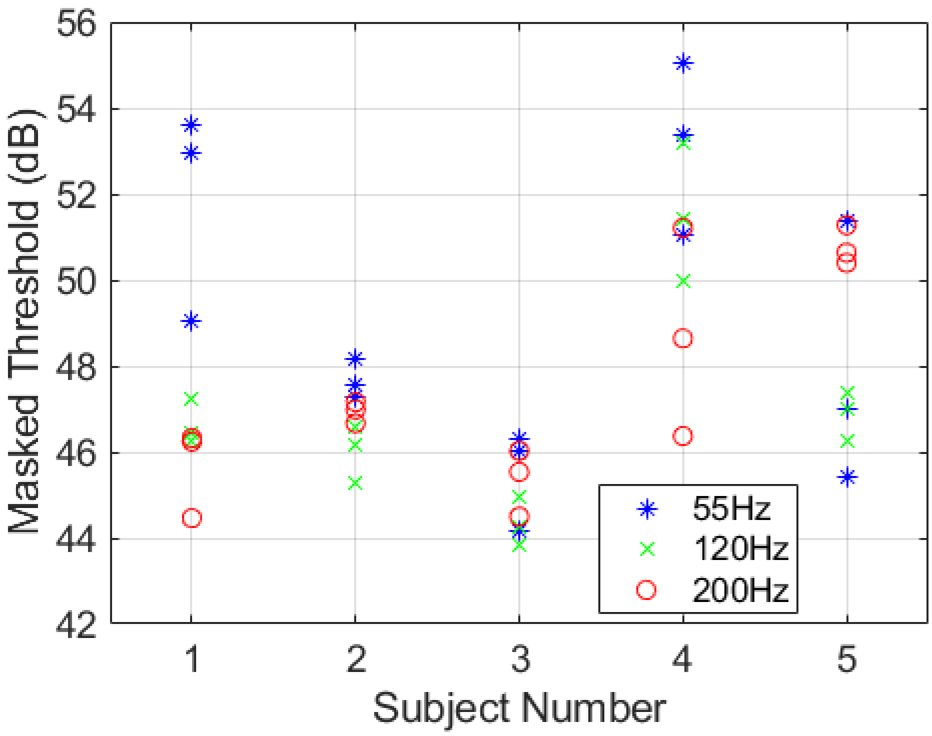

Figure 7: Experiment B – masked threshold levels for single tones (55, 120, 200 Hz).

Table 2 indicates that the masked threshold of the triad is well below that of the single tones. The mean reduction in threshold, across both subjects and repeats, is calculated to be 3.91 dB. This can be compared to the reduction measured in Experiment A, which is 3.62 dB (Table 1). The standard deviations associated with these two estimates are 1.38 dB (Experiment A) and 1.30 dB (Experiment B). Figure 8 presents the mean changes in masked threshold measured in Experiments A and B. Also shown are the changes in level predicted by the SSM. The difference between the mean threshold shift for the tone pairs and the triads is unlikely to have arisen by chance ($p=0.007$), indicating that detection is improved when more tones are added. The difference between the predicted threshold shift for the triad (2.4 dB) and the mean measured shift (3.81 dB) is unlikely to have arisen by chance since the predicted value falls outside the 95% confidence interval of the measurement. In contrast, the prediction for the tone-pairs (1.5 dB) is within the 95% confidence interval of the measurement (mean value of 2.17 dB). The fact that the triads exhibit a significant deviation from model predictions and the pairs do not, may reflect the smaller expected effect size for the pairs and fewer observations relative to the triad.

There are several possible explanations for the deviation of the data from the model. The first concerns the manner in which any errors in measuring the single tone masked thresholds will affect the measured threshold of a tone pair or triad. Recall that the creation of the tone pair or triad relies on the measured masked thresholds of the individual component tones. Clearly, these measured thresholds will have some uncertainty and such errors will be embedded in the tone pair or triad which will, in turn, affect the change in masked threshold of the pair or triad relative to the (assumed) starting point of *equally detectable tones*.

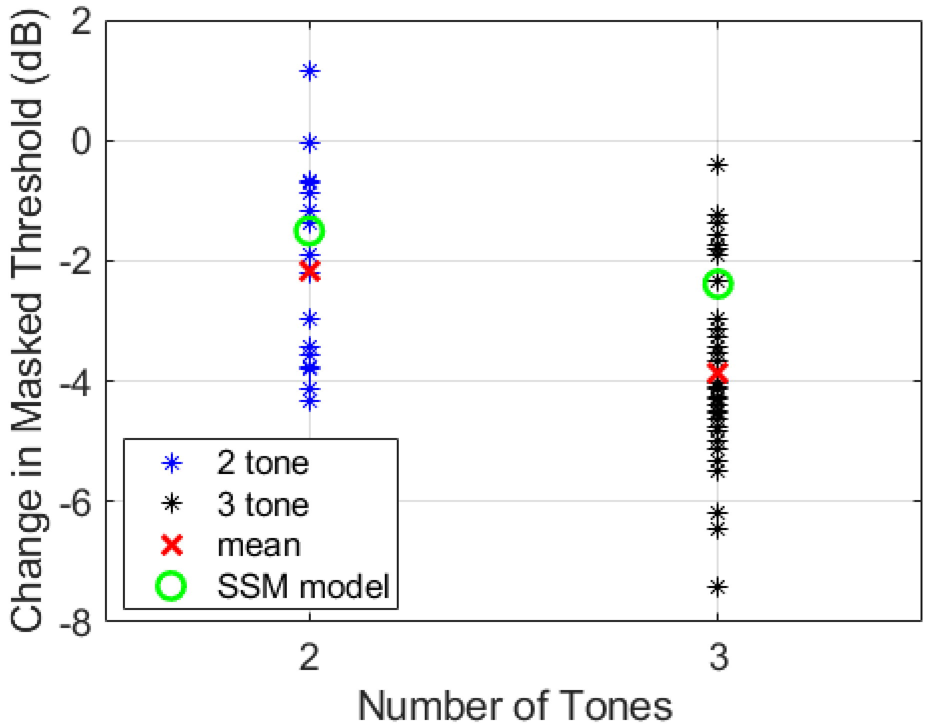

Figure 8: Experiments A and B – Change in masked threshold levels for tone pairs and triads relative to level of equally-detectable single tones.

It is a simple matter to use the SSM to investigate the effect of an error in one component tone on the masked threshold of a pair or triad of tones. Consider a pair of equally-detectable tones, each in separate auditory filters. As discussed above, the expected reduction in masked threshold is 1.5 dB. If it is further assumed that d' is directly proportional to signal intensity, then an error in the masked threshold of a single tone of, say, 3 dB will have the following effect: let the measured values of the equally detectable individual tones correspond to $d' = 1.61$. If one of them is in error and 3 dB too high, then its actual d' value is 3.22. The Statistical Summation Model predicts a reduction in masked threshold of 1.98 dB, that is,

$$10\log_{10}\sqrt{1.61^2 + 1.61^2} - 10\log_{10}\sqrt{1.61^2 + 3.22^2}\ .$$

In other words, an error of +3 dB in one component will result in the masked threshold of a pair of tones that is 1.98 dB less than that expected for two error-free tones.

Figure 9 shows the results of similar such calculations for a range of perturbations to one tone of a pair. The overall behavior is clear. If the estimated masked threshold of one of the tones is below where it should be, the effect on the masked threshold of the pair is quite small. A perturbation of -6 dB in one component results in an error of only about 1 dB. However, if the estimated masked threshold is higher than it should be, the error for the pair is much larger (almost 5 dB for a +6 dB error in one component). The explanation for this asymmetry lies in the manner in which the tone pairs (or triads) are formed from the measured masked thresholds of each tone. If one of the masked thresholds is lower than it should be, then the masked threshold of the pair (or triad) will be largely controlled by the other tone(s), resulting in a small error. However, if one of the masked thresholds is higher than it should be, then this tone will tend to dominate the masked threshold of the pair (or triad). This asymmetric behavior seems to be present in the plots in Figure 6 and Figure 8, where more data points fall below the model predictions than fall above.

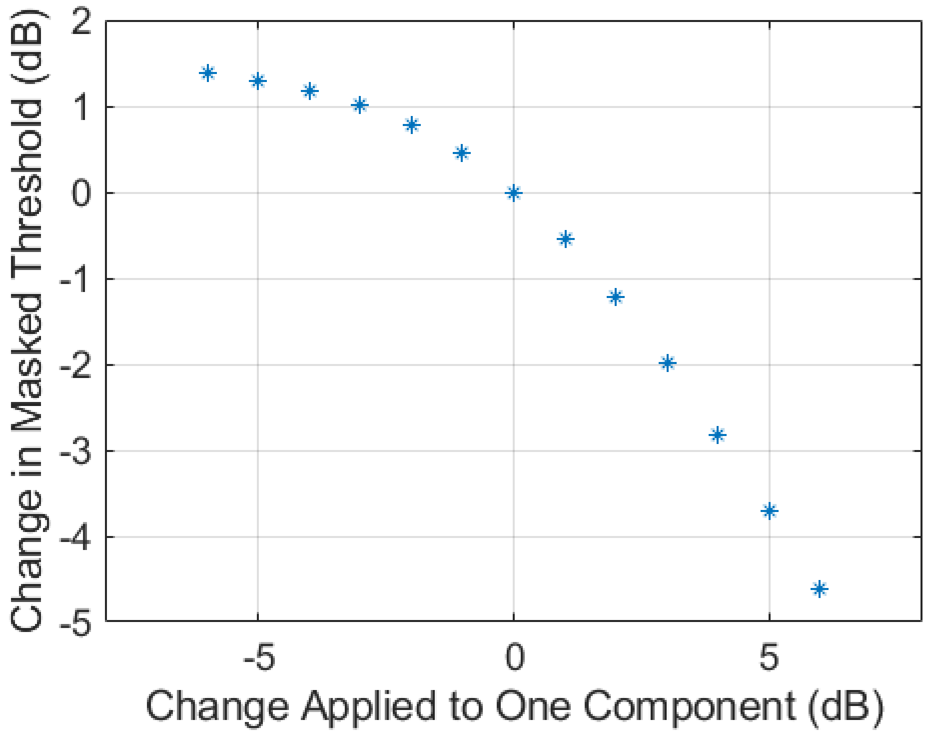

Figure 9: Effect of error in masked threshold of one tone on masked threshold level of a tone pair.

A more sophisticated examination of this phenomenon was performed using a Monte Carlo simulation (see *Acknowledgments*) in which it was assumed that measured masked thresholds of single tones have a normal distribution when their amplitudes are expressed in decibels. Using a range of assumed values for the standard deviation, thousands of simulations enabled the effects of errors in the individual tones on multi-tone thresholds to be estimated. As described above, the difference between the model prediction (2.4 dB) and the measured mean change in masked threshold for the tone triad ranged between about 1.2 and 1.5 dB in Experiments A and B. The Monte Carlo simulations indicate that the standard deviation of the individual tone thresholds would have to be approximately 3 dB in order to be consistent with the measured mean masked thresholds of the tone triad. Estimates of within-subject variance using an essentially identical test methodology as used herein can be found in Appendix B of Ref. [3]. Those estimates of standard deviations were 1.6 and 1.9 dB, considerably less than the 3 dB value necessary to explain the deviation of the multi-tone masked thresholds from the model. It seems likely, however, that the asymmetry evident in the data is at least partly due to the propagation of errors in individual tones to the tone pairs and triads.

It is perhaps tempting to suggest that the use of longer staircases would have resulted in greater precision in estimating masked thresholds of the single tones which would in turn have given greater confidence when creating the two- or three-tone signals. This is undoubtedly true, but as demonstrated by the analysis provided in Appendix B of Ref. [3], a point of diminishing returns is quickly reached as staircases are made longer. Generally, the level of uncertainty is related to the square-root of the number of trials in a staircase. Therefore, in order to lengthen the staircases to a useful extent, multiple sessions of single tone results would need to have been combined. For instance, increasing the number of trials by a factor of two (yielding 100 trial staircases), would have only reduced the uncertainty by a factor of approximately 0.7, but would have created experimental blocks (sessions) of 300 trials, a taxing task for test subjects.

Experiment B was, in part, formulated to examine effects of learning and fatigue that could potentially influence the results of serially executed staircases. No such effects were found. In retrospect, a superior test design would have been to aggregate the measured thresholds for each of the three individual tones as the test progressed. This would have lowered the uncertainty in the single tone levels that were used to create the triads and may have provided an interesting diagnostic measure of differing levels of uncertainty in the triads as the test progressed.

The tone frequencies in the first two experiments were chosen to be as general as possible within the frequency range of interest and to be in separate auditory filters. Published data describing average auditory filter shapes and bandwidths were relied upon. There is a concern that differences between individuals' filters can be large, particularly at the lower frequencies (e.g., Ref. [2] – "Individual differences in asymmetry tended to increase as f_s (filter center frequency) decreased, mostly due to individual variation in the sharpness of the upper skirts."). Such differences might allow the tones at 55 and 120 Hz to be integrated by a single auditory filter, resulting in the multitone thresholds being lower than model predictions. For example, the extreme case of perfect intensity addition for two tones within a filter along with a third tone in a separate auditory filter results in a predicted reduction in masked threshold of 3.5 dB, rather than 2.4 dB had all tones been in separate filters. Although an extreme example that is unlikely to actually occur, the predicted reduction in masked threshold of 3.5 dB is similar to the mean values measured in Experiments A and B (Figure 8).

Other potential explanations for the better-than-predicted summation of signals across auditory filters relate to the SSM assumption of statistical independence between auditory filters. For example, the interaction of tones and the creation of intermodulation difference tones can result in perceptible temporal variation within the multitone waveform. It has been suggested (e.g., Refs. [17, 18]) that detection can be affected by characteristics of the sounds that are not captured by simple measures such as sound energy and intensity. In particular, temporal patterns in the envelope of the time history can be important. An example of such a phenomenon that is known to affect the perception and character of sound and that might be important for detection is roughness [19]. It is believed to be important for modulation frequencies between about 20 and 300 Hz, with maximum effect around 70 Hz. The chosen frequencies of 55, 120 and 200 Hz create difference tones of 65 and 80 Hz which therefore might affect audibility. The next experiment was designed to address some of these concerns.

5 Experiment C –Masked Thresholds for One and Three Tones (55, 110, 165 Hz, and 110, 220, 330 Hz)

5.1 Experiment C – Description

The aim of Experiment C is to address two concerns that were identified from the results presented for Experiments A and B. The first is the potential for intermodulation difference tones to provide an additional auditory cue that lowers masked thresholds. The selected tone frequencies in the first experiments were 55, 120 and 200 Hz. These were changed to harmonically-related frequencies of 55, 110 and 165 Hz. The difference tones of 55 Hz (110-55 and 165-110 Hz) and 110 Hz (165-55 Hz) coincide with tone frequencies and are expected to reduce auditory cues associated with temporal variation of the multitone waveform.

The second concern to be addressed in this experiment is the potential overlap between auditory filters centered at 55 and 110 Hz. A second set of tone frequencies was selected that eliminated the 55 Hz tone and added one at a higher frequency. Three tones (110, 220 and 330 Hz) were selected, which although not as low in frequency as desired, are well separated and unlikely to overlap to any significant degree. The broadband masker in the previous experiments (40 – 250 Hz) was extended to 500 Hz because of the addition of the higher frequency (300 Hz) tone. Masked thresholds of the individual tones in both tone sets were determined using three interleaved staircases. This condition was repeated for four of the five subjects. The average masked thresholds for each test subject were used to create the tone triads consisting of equally detectable tones. The masked threshold of the tone triad was then measured twice using two interleaved staircases. The same five subjects participated in experiments B and C.

Table 3: Details of Experiment C.

Set #	Tone Frequencies (Hz)	# Interleaved Staircases / # Replications	
		Individual Tones	Tone Triads
1	55/110/165	3/2	2/1
2	110/220/330	3/2	2/1

5.2 Experiment C – Results and Discussion

Comparisons of masked thresholds for the tone triads in Set one of this experiment (Table 4) and experiment B are shown in Figure 10. Recall that Experiment B consisted of tones at 55, 120 and 200 Hz and Experiment C consisted of tones at 55, 110 and 165 Hz. The reduction of interaction tones has no significant effect on the mean masked threshold, changing it by only 0.4 dB. This result indicates that interaction tones are of little or no importance.

Table 4: Experiment C (set 1) – Masked threshold levels for single tones and changes in masked threshold levels for two staircases of tone triads relative to level of equally-detectable single tones.

Subject #	Masked Threshold (dB)			Change in Masked Threshold (dB)	
				Triad	
	55 Hz	110 Hz	165 Hz	Staircase (a)	Staircase (b)
1	48.78	45.57	46.34	-2.71	-1.87
1	52.12	43.08	46.56		
2	47.95	37.58	46.02	-3.13	-3.12
2	49.08	38.63	47.39		
3	50.05	38.37	45.76	-2.73	-3.18
3	45.27	38.74	44.78		
4	47.86	44.80	54.08	-3.80	-6.82
4	50.52	43.58	45.82		
5	49.99	42.12	48.36	-6.63	-1.36
Mean	49.07	41.39	47.23	-3.80	-3.27
Std. Dev.	1.95	3.07	2.76	1.64	2.14

The masked thresholds for the second set of triad tones in Experiment C (110, 220 and 330 Hz) (Table 5) are presented in Figure 11, along with the triad tone results from Experiment B (55, 120, 200 Hz). The mean masked threshold for the higher frequency tone triad of Experiment C is less than that measured in Experiment B. The mean reduction in masked threshold, across subjects and repeats, was found to be 3.91 dB in Experiment B (Table 2). The mean reduction for Experiment C is 2.3 dB. This compares to the model prediction of 2.4 dB. This close agreement is undoubtedly fortuitous since the variability of measured masked thresholds, both within and between subjects, is quite large, as evidenced by Figure 11 and Table 4. It is particularly striking that for two test subjects (3 and 4) there is little reduction in masked threshold for the triad relative to single tones.

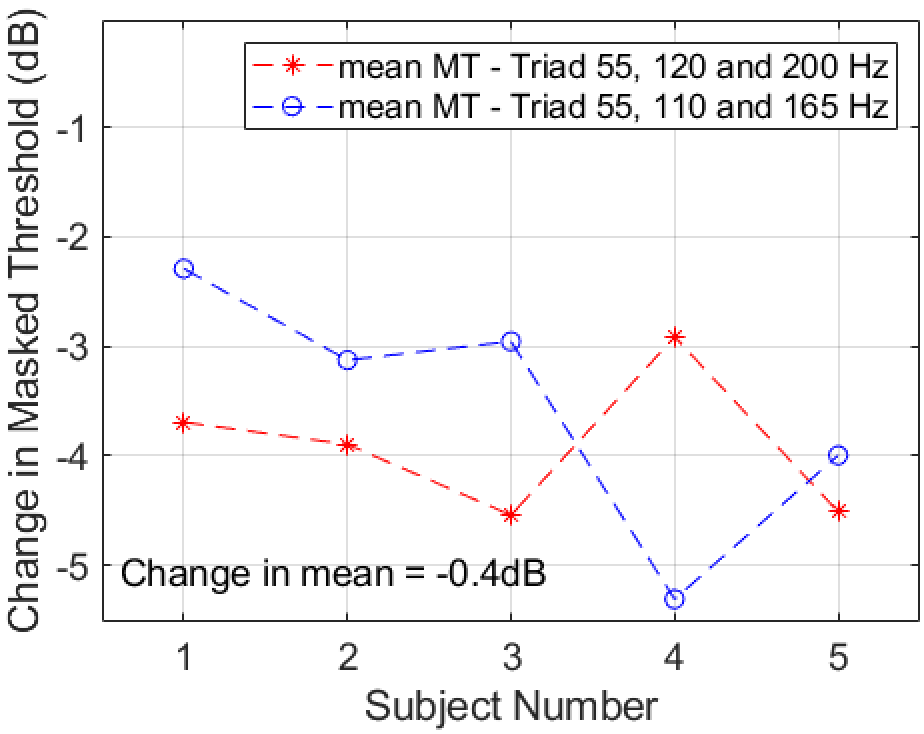

Figure 10: Experiment B and Experiment C (set 1) – change in masked threshold levels of tone triads relative to level of equally-detectable single tones.

Table 5: Experiment C (set 2) – Masked threshold levels for single tones and changes in masked threshold levels for two staircases of tone triads relative to level of equally-detectable single tones.

Subject #	**Masked Threshold (dB)**			**Change in Masked Threshold (dB)**	
				Triad	
	110 Hz	220 Hz	330 Hz	Staircase (a)	Staircase (b)
1	41.05	45.02	45.51	-4.34	-3.66
1	43.11	46.17	44.88		
2	41.30	39.63	45.70	-4.55	-2.59
2	39.72	41.95	44.75		
3	38.90	42.95	44.99	-0.39	-1.08
3	38.16	38.52	42.93		
4	42.84	41.58	46.18	-0.13	-0.37
4	40.69	42.24	45.19		
5	42.56	46.06	44.69	-3.53	-2.38
Mean	40.93	42.68	44.98	-2.59	-2.01
Std. Dev.	1.75	2.69	0.91	2.16	1.30

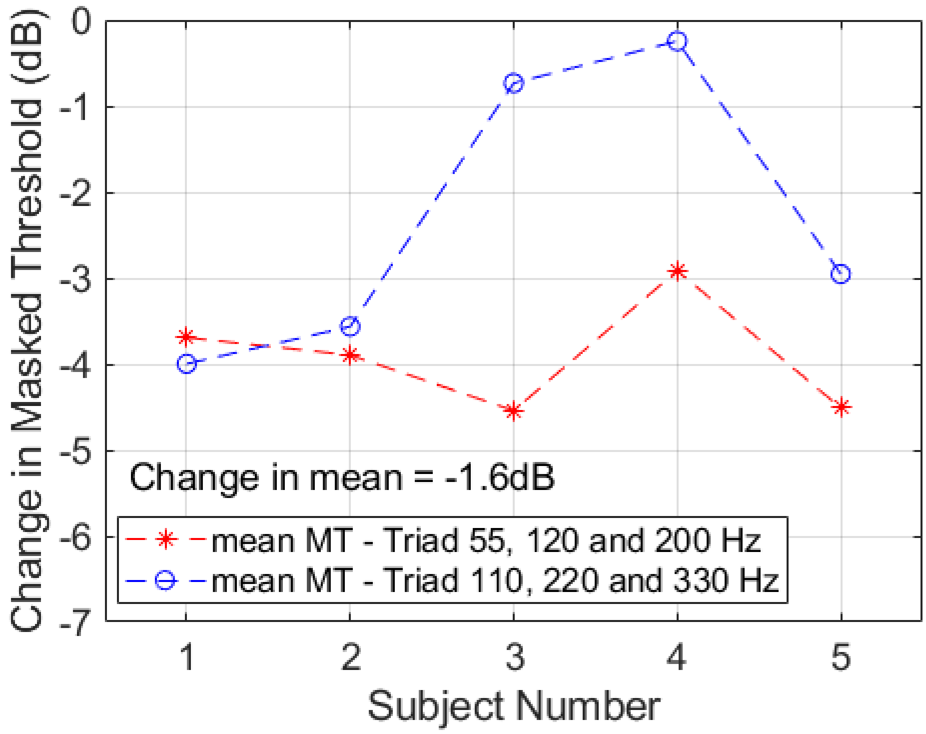

Figure 11: Experiment B and Experiment C (set 2) – change in masked threshold levels of tone triads relative to level of equally-detectable single tones.

Table 4 and Table 5 indicate that the standard deviations of the thresholds of the triads are less than those for single tones. This finding was noted in the previous two experiments, and likely reflects a reduction in intersubject variance that results from the customization of the triads.

Figure 12 presents all of the data acquired in Experiments A, B and C for tone pairs and tone triads, regardless of the tone frequencies. As was noted for the individual experiments, the mean reductions in masked thresholds are greater than the predictions of the SSM. The difference between the predicted reduction in threshold shift for the triads (2.4 dB) and the measured value (3.5 dB) is unlikely to have arisen by chance ($p<0.05$). As reported in Experiment A, the measured shift for the tone-pairs (2.17 dB) is consistent with the predicted value (1.5 dB) ($p=0.05$). This may reflect the smaller expected effect size for the pairs and the reduced number of observations for the pairs relative to the triad.

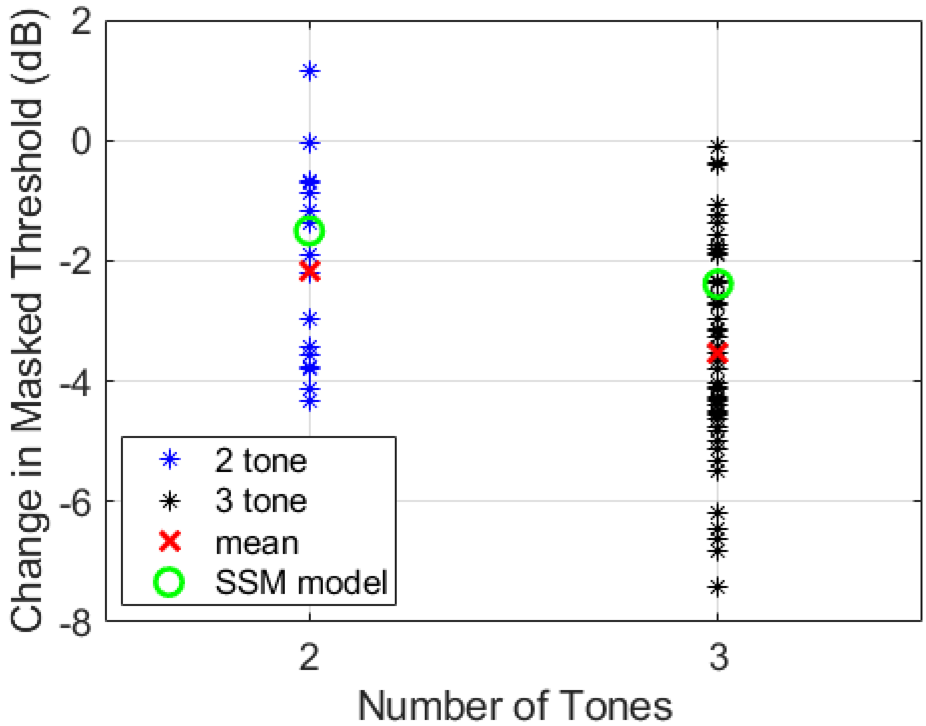

Figure 12: Experiments A, B and C – Change in masked threshold levels of tone pairs and triads relative to level of equally-detectable single tones.

6 Summary and Conclusions

A series of three experiments was conducted to examine the audibility of multiple low frequency tones that were placed in distinct auditory filters. The first step in each experiment was to conduct psychoacoustic tests to determine the masked threshold of individual tones in the presence of a broadband masker using an adaptive 3-alternative forced choice procedure. The masked threshold derived for each tone and for each test subject enabled the creation of multitone sounds consisting of equally-detectable components. Each of these multitone sounds was custom-made for each test subject. The masked thresholds of two- and three-tone sounds were then determined in the same manner as used for the individual tones. The customization of the multitone sounds was intended to reduce the effect of intersubject differences. This was successful, as evidenced by lower standard deviations of the multitone masked thresholds relative to those of the single tone thresholds.

The requirement that low frequency tones be placed in separate auditory filters limited the number of tones to a maximum of three. The first experiment measured the change in masked thresholds for two- and three-tone signals, composed of combinations of 55, 120 and 200 Hz tones. According to the Statistical Summation Model (SSM), the expected change in masked threshold is 1.5 and 2.4 dB for the two- and three-tone signals, respectively. The measured mean changes in thresholds exceeded these values, but not to a statistically important degree.

The second experiment employed the same overall approach but acquired more data and concentrated on the three-tone signal. When combined with tone triad data from Experiment A, the measured changes in masked threshold exceed the model predictions to a statistically-significant degree.

Several issues were postulated with the potential to yield inflated changes in masked threshold. The first concern was the potential interaction between tones resulting in perceptible intermodulation/difference tones. The second issue concerns the assumption that the tones were in distinct auditory filters and statistically independent of one another. This is of most concern for the lowest auditory filter with a center frequency near 50 Hz. The upper skirt of this filter is relatively shallow. Also, there is much intersubject variability in the shape of the lowest filters that potentially enables perception of the two tones at 55 and 120 Hz to occur in a single filter, thus resulting in larger-than-expected changes in masked threshold.

The third experiment used two sets of three-tone signals to address these latter concerns. The first was composed of harmonically related tone frequencies of 55, 110 and 165 Hz, which was an attempt to reduce effects of intermodulation difference tones. This contrasts with the earlier selection in Experiments A and B of 55, 120 and 200 Hz tones that are not harmonically related. The second set of tones was chosen to be 110, 220 and 330 Hz, again reducing effects of difference tones, but also providing greater separation between tones. Results for the first set of tones compared to those of the earlier experiments indicated that intermodulation was not an important effect. The second set of tones (110, 220, 330 Hz) yielded changes in masked thresholds that, on average, were in good agreement with the Statistical Summation Model. However, intersubject variability was large and prohibited a definitive conclusion regarding the concern that tone spacing was inadequate.

Several conclusions can be drawn from the results of the three experiments. All of the experiments showed that the masked thresholds of sounds with multiple (two or three) equally-detectable low frequency tones were lower than those of the single tones. It is clear that audibility is enhanced by the presence of signals in multiple auditory filters. This finding is consistent with most previous research conducted at higher frequencies. In contrast with previous research, test subjects were, on average, able to detect multitone sounds at lower levels than those predicted using the SSM. Analyses that included Monte Carlo simulations showed that normally distributed errors in the single tone thresholds will result in biased estimates of the thresholds of multitone sounds. This phenomenon is likely responsible for at least a substantial fraction of the deviation of measurements from predictions. Other factors that were examined that might explain lower-than-predicted masked thresholds were difference tones that create temporal fluctuations that potentially provide additional auditory cues, and inadequate frequency separation between tones that allows two tones to be perceived using a single auditory filter. However, neither of these factors were shown to be responsible for the observed differences between measured and predicted thresholds of multitone sounds.

7 Acknowledgments

The authors thank Sanford Fidell and Richard Horonjeff for helpful discussions regarding test methods, test designs, and analyses. Matthew Boucher provided helpful comments on a draft of this document. The Monte Carlo simulation code described in Experiment B is courtesy of Richard Horonjeff. The execution of the tests was enabled by Regina Johns, Erin Thomas and Matthew Hayes.

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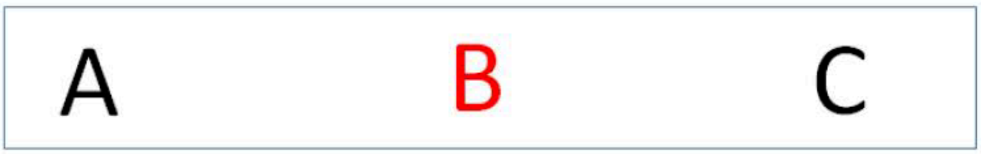
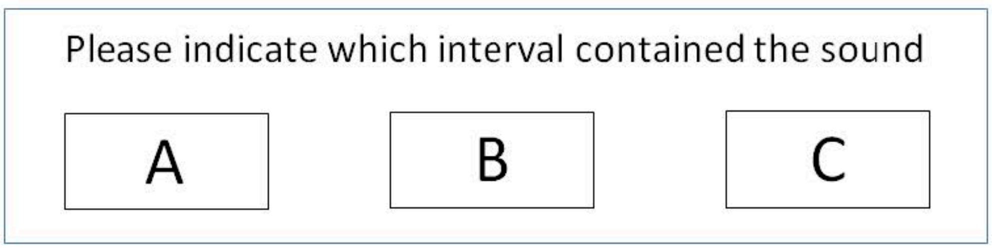
Appendix A   Test Instructions and Informed Consent Form

Test Instructions

This study is designed to investigate human capability to detect sounds. This test consists of three sessions, each of which lasts between 15 and 20 minutes. During each test session, you will be presented with many test trials. Each trial will involve 3 time intervals (A, B and C) during which you may or may not hear a sound. The screen on your tablet will display the letters A, B, and C in black. These letters will turn red, in order, to indicate each time interval as it occurs. The figure below shows as an example of how the screen will appear during time interval "B." Among these three sounds <u>one</u> will include an additional sound.



Following the three time intervals, you will be shown a screen on your table that looks like:



Please touch the box that contains the letter of the interval that contained the sound. After you have made your selection, the tablet will show another screen indicating whether or not your selection was correct. This process will be repeated throughout the test session many times.

Before starting the actual test, we will play some sample sounds so you can hear the types of sounds that we are asking you to listen for. You will then complete a practice session in which you answer these questions while the Test Director is with you in the room. This will let you become familiar with using the tablet computer to indicate your responses and allow you to ask any questions you may have about the test.

Thank you for your help with this investigation.

Human Subjects Informed Consent Statement

Principal Investigators/Phone:

Federal regulations require researchers to obtain signed consent for participation in research involving human subjects. After reading the information and the Statement of Consent below, if you wish to consent, please indicate so by signing this form. Also initial each of the previous pages (pages 1-3) of the form in the spaced provided at the bottom of the pages.

I. Statement of Procedure:

Thank you for your interest in this research. By this time you have had the experimental rationale and procedures discussed with you in detail. You will find a summary of the major aspects below, including the risks and benefits of participating. Please feel free to ask any questions about the procedures at any time. Carefully read the information provided below. IF YOU WISH TO PARTICIPATE in this study, please sign your name and date the form in the space provided. Also please initial each page. Any information you provide will be maintained in strict confidence to protect your privacy.

II. I understand that:

- This is a research experiment.
- I will be participating in an experiment designed to evaluate the characteristics of noise.
- This study will be performed in the Exterior Effects Room, Building 1208, at NASA Langley Research Center.
- Audiograms will be taken before and after the test, and I will be informed whether I meet the program requirements.
- Noise exposure monitoring at the test facility will confirm that the noise exposure to test subjects is limited to levels that comply with NASA Noise Exposure Requirements (NPD 1800.1 c, 4.8.3.3, Table 1) and the allowable limits defined by the Occupational Safety and Health Administration (OSHA) regulations associated with this research testing.
- I will receive instructions and training on the task I am to perform. I will be allowed time to familiarize myself with the task prior to starting the experiment.
- During the course of the experiment, I will provide my assessment of the sounds I hear using a tablet computer.
- I have been briefed on the reasonable risks involved with the testing procedures. I will adhere to the safety requirements as specified by the Principal Investigator, and I will obey any and all regulations.
- The duration of my participation will require approximately 3 hours of my time including hearing tests at the start and the end of the test. There may be up to 6 sessions in the test, each lasting about 20 minutes. I will be given a break between sessions. In each session I will be presented with sets of sounds and asked to evaluate their differences. Each set will last about 5 seconds.
- Federal representatives are eligible to review research records for the purposes of protecting human subjects.
- I may contact the Principal Investigator listed at the beginning of this document if I have any questions regarding this experiment before or after my participation.

Page 1 of 4

III. Compensation

There are no costs associated with participating in this study. If I am not a U.S. Federal Government civil servant, and if the results of the initial hearing test I take confirms my eligibility to participate as a test subject, I will be compensated by receiving $75 for each day of my participation. I will not receive a separate reimbursement for travel.

I understand that:

- If I am a NASA civil servant, I am participating in the research in my official capacity. I understand that "official capacity" means that my supervisor is aware of my participation as a test subject in this research, and has approved of my participation in my official capacity. If I am injured during the course of this research, I am eligible for compensation through the Federal Workers Compensation System. For additional information, I may contact the NASA Shared Services Center at (XXX) XXX-XXXX.
- If I am a non-civil servant volunteer injured as a result of participating in the research, I am eligible to file a claim under the Federal Tort Claims Act by filing Standard Form 95. For additional information, I may contact the LaRC Office of the Chief Counsel at (XXX) XXX-XXXX.
- If I am a NASA contractor employee participating in the research as part of official duties as approved by my appropriate contractor manager, in the event of injury, I may be eligible for workers compensation. I may contact my company's human resources office for additional information.
- If I am not a NASA civil servant or NASA contractor participating in this research in my official employment capacity, I am participating as a subject through the NASA XXXX contract with YYYY Corp, and, in the event of injury, insurance coverage is provided to me as a research subject volunteer under the NASA XXXX contract. For additional information, I may contact X.YYYY at (XXX) XXX-XXXX.

IV. Potential Risks

- There is minimal risk associated with participation in this study other than that associated with or encountered in everyday life, however, I may request to stop the experiment at any time. A pre-test and post-test audiogram is performed to verify that no change in hearing ability has resulted from the test.
- In the unlikely event that I am injured or otherwise experience discomfort while at NASA Langley, I may visit the on-site Occupational Health Clinic. The Clinic has hours of operation from 7:00 a.m. to 3:30 p.m. The clinic number is (XXX) XXX-XXXX. Emergency medical personnel and ambulance service is also available within a mile of the test facility to transport me to nearby health care providers.
- If I have questions about the research and my rights should I experience any injury, I may contact the Principal Investigator listed at the beginning of this document.
- I will hear noises no greater than those experienced on a daily basis from heavy traffic or other sources. I will experience a maximum A-weighted sound level of no more than 95 decibels (dBA). A noisy home vacuum cleaner or lawn mower will normally equal the 95 dBA level. A automatic volume limiter system will automatically stop playback in the unlikely event that signals exceed a safe level.

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V. Potential Benefits

I understand that:

- Except for being able to assist NASA and receiving information about my hearing ability, I will derive no direct benefit from participation in this study. I may request copies of the screening and test day audiograms, however these will be made available only after review by the audiologist and may take up to 30 days to process.
- The results of my participation may advance the development of a new simulation tool that will allow the assessment of human response to aircraft sounds.

VI. Confidentiality

- The test will be monitored on closed circuit television and audio intercom, and this visual and audio monitoring data will not be recorded. Some personal data may be collected, but my name will not be associated with these collected data.
- Any information obtained about me from the research will be kept strictly confidential. Data from the research could be used in reports, presentations, or publications, but I will not be identified.
- Records of my participation will be kept confidential by encoding them with subject identification numbers. There will be approximately 40 individuals participating in the test.
- Any research data stored electronically will not be confidential, but I will not be personally identified in any event. The results of the hearing tests will be kept confidential, maintained in the files associated with this research, and stored in a secured location.
- I understand that any public release of data obtained from my participation in this study will be done in a manner that does not associate me with the data.

VII. Voluntary Participation

I understand that taking part in this study is voluntary. I may withdraw from participating or be asked to withdraw from participating at any time. Such a decision will not result in any penalty or loss of benefits to which I may otherwise be entitled.

VIII. Safety

As a voluntary test subject participating in this research, I understand that:

- NASA is committed to ensuring my safety, health, and welfare plus the safety and health of all others involved with this research.
- I should report any accident, injury, illness, and changes in my health condition, hazards, safety concerns, or health concerns to the Principal Investigator listed at the beginning of this document. If I am unable to reach the above named individuals or am not satisfied with the response I receive, I should contact the LaRC Safety Office at (XXX) XXX-XXXX or the Chairperson of the LaRC Institutional Review Board, Mr. Y.XXXX, at (XXX) XXX-XXXX.
- If I detect any unsafe condition that presents an imminent danger to me, or others, I have the right and authority to stop the activity or test. In such cases the Principal Investigator and associated research personnel will comply with my direction, stop the activity, and take action to address the imminent danger.

IX. Statement of Consent:

- I certify that I have read and fully understand the explanation of procedures, benefits, and risks associated with the research herein, and I agree to participate in the research described herein. My participation is given voluntarily and without coercion or undue influence, and I also voluntarily consent to sharing the data collected during my test session, as long as my identity is not disclosed. I understand that I may discontinue participation at any time. I have been provided a copy of this consent statement. If I have any questions or modifications to this consent statement, they are written below.

______________________	______________________
Participant Signature	Witness Signature
______________________	______________________
Participant Name	Witness Name
______________________	NASA Langley Research Center
Participant Address	Witness Address
______________________	Hampton, VA 23681
Participant City, State, & ZIP	Witness City, State, & ZIP
______________________	
Participant Age	
______________________	
Participant Phone Number	
______________________	______________________
Date	Date

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c) Stephenson, James H.

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14. ABSTRACT
This study examined the audibility of multiple tones ranging from 55 - 330 Hz placed in distinct auditory channels in the presence of broadband noise. The experiments measured the change in masked threshold for two and three-tone signals relative to the level of the equally-detectable single tones. The measured changes in masked threshold generally exceeded predictions made using the Statistical Summation Model (SSM). It was concluded that audibility is enhanced by the presence of signals in multiple auditory filters. The deviation from predictions is partly due to errors in the determination of single tone masked thresholds yielding biased estimates of the thresholds of multi-tone signals.

15. SUBJECT TERMS
Low Frequency Auditory Filters

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