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MEASURING DIRECTIONAL MASKING IN A SOUND FIELD USING ADAPTIVE THRESHOLD PROCEDURES

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The accuracy of three adaptive threshold procedures for measuring directional masking was assessed in two experiments. For each experiment, detection of a target signal, located at either 0°, 90°, 180° or 270° azimuth was measured in the presence of a masker located at 0°, 90° or 180° azimuth. In Experiment 1, masked thresholds for ten normal hearing subjects were measured using the Bekesy Procedure and an Ascending Up-and-Down Procedure. In Experiment 2, masked thresholds for another group of ten normal hearing subjects were measured using the Bekesy Procedure and a Maximum Likelihood Procedure. Results confirmed the dependence of detection thresholds on the angular separation between the target and masker. In addition, threshold reliability depended on the location of the signal and the masker. No statistically significant differences were found in detection thresholds over repeated trials or between threshold procedures in Experiment 1 or 2.

1. Introduction

Within the last ten years, new technologies and techniques have been used to externalize earphone-presented sounds. Externalization is successful if the earphone-presented sounds appear to originate from locations outside of the head (i.e., at azimuths, elevations, and distances from the listener), similar to natural everyday listening. An externalized acoustic environment, which includes stationary or moving phantom sources, is commonly referred to as a three-dimensional (3D) audio display.

One new and exciting application of 3D audio displays is for enhancing multi-channel communication systems [8, 27, 28]. In traditional communication systems, operators may have the challenging assignment of monitoring many simultaneous auditory messages (sometimes up to six communications at one time) presented diotically through earphones. In diotic presentation, messages presented equally to both ears are perceived as originating within the operator's head. This type of presentation acoustically mixes the messages, making message extraction difficult.

If the messages are misunderstood, the resulting errors may cost time, equipment and even loss of life.

It the same multi-channel communication task is performed using a 3D audio display, the operator will perceive the messages as originating in the surrounding acoustic environment, at locations outside of the earphones. A 3D audio display spatially separates messages from one another, thereby making it easier for the operator to attend to any selected message. It is well documented that as a noise source is moved away from the location of a speech message, listeners can better detect, recognize or understand the message [e.g., 4, 6, 9, 10, 11, 13, 16, 18, 20, 23, 24, 29, 30, 34]. Similarly, researchers using more traditional signals (e.g., pure tones or narrow bands of noise) have reported that, as the angular separation between the masker and a target signal increases, detection performance improves [e.g., 11, 17, 32]. Given the advantages of spatially separated messages, strategic positioning of message directions in a 3D audio display may improve operator and system performance with multi-channel communications.

Proper positioning of message sources in a 3D audio display requires, however, an understanding of how multiple auditory signals interact in the environment. A typical listening environment is not only filled with many signals, but also with noises that interfere with our ability to monitor them. With a 3D audio display, messages have an apparent spatial location. Thus, messages that are not attended to can be though of as spatially-located maskers. Such maskers can singly, or in combination with background noise, mask sounds that carry information to the listener. Background noise differs from a spatially-located masker in that it appears to originate from no particular location, changes only occasionally in level and frequency, and is constantly present. Given that desired sounds, interfering messages, and background noise are present in a 3D audio display, the optimization of message spatial location, level, and content, under such conditions should be evaluated.

How should a 3D audio display be optimized? As a first approximation, the masking effect of a spatially-located masker on a target message could be established using some measure of detection. Frequently, detection of signals in noise is measured using adaptive procedures. An adaptive procedure is one in which the stimulus level on any one trial is determined by the response to the preceding stimulus level. Although adaptive procedures are known to be reliable and appropriate in threshold related studies, some adaptive procedures are time-consuming and inefficient. The purpose of the present study was to determine which adaptive threshold procedure should be used in evaluating multi-channel 3D audio displays. Specifically, the primary objective of the study was to determine which of three adaptive procedures (i.e., Bekesy Procedure, Ascending UP-and-Down Procedure, and Maximum Likelihood Procedure) was best for measuring the amount of masking by spatially-located directional masking in 3D audio displays. An ideal procedure should yield sufficiently repeatable detection thresholds in the shortest amount of time.

2. Methodology

2.1. Subjects

Twenty adults (aged 21 – 35) volunteered to participate in this study. Ten subjects participated in Experiment 1 and a different group of ten subject's participated in Experiment 2. All subjects had normal hearing (i.e., hearing thresholds 15 dB HL [1] or better in each ear from 250 through 8000 Hz, in octave steps), and bilaterally symmetrical hearing sensitivity (i.e., inter-aural sensitivity differences did not exceed 5 dB at any test frequency).

2.2. Instrumentation

A target signal and spatially-located masker were simultaneously presented to the subject by two independent loudspeakers representing signal (S) and noise (N). The different combinations of azimuth are shown in Fig. 1, where a letter-symbol directly in front of the head icon corresponds to a loudspeaker positioned at 0° azimuth. Letter symbols to the right and left correspond to a loudspeaker located at 90° and 270° azimuth, respectively. For example, in the second spatial configuration, the target signal was located directly in front of the subject at 0° azimuth, and the noise directly behind at 180° azimuth. Whenever the first spacial configuration was evaluated, both the target signal and the noise were presented through one loudspeaker located at 0° azimuth.

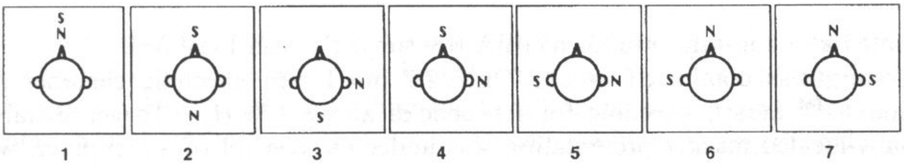


Fig. 1. The spatial configurations of the target signal and the spatially-located masker source. The first five configurations were used in experiment 1. All seven configurations were used in experiment 2.

The target was a single spondaic word (two-syllable compound words having equal stress on each syllable) from the CID W-1 standardized word list. Initially, a tape recording of the word was played from a cassette deck (Nakamichi, MR-1) through a graphic equalizer (General Radio, Model 1925) and digitally recorded and stored in a computer (Zenith 248, AT class, DSP-16, Ariel Corporation). The target word, 'Northwest', was selected for the following reasons. First, it is a simple representation of the target signal of interest in communication systems (i.e., speech). Second, the word is included in standardized recordings of word lists and can be easily available for use by any researcher. Third, of all the spondaic words in standardized recordings, Olsen and Matkin [25] reported that the two syllables in

'Northwest' are the most similar with respect to audibility. In summary, the major consideration in target signal selection was to identify a word that would reduce variability in test results, produce highly reliable threshold data, in require minimal training.

The spatially-located masker was a broadband signal approximating the long-term average speech spectrum [2]. The output from a noise generator (General Radio, Model 1825) was filtered to obtain the desired spectrum (Fig. 2) and always

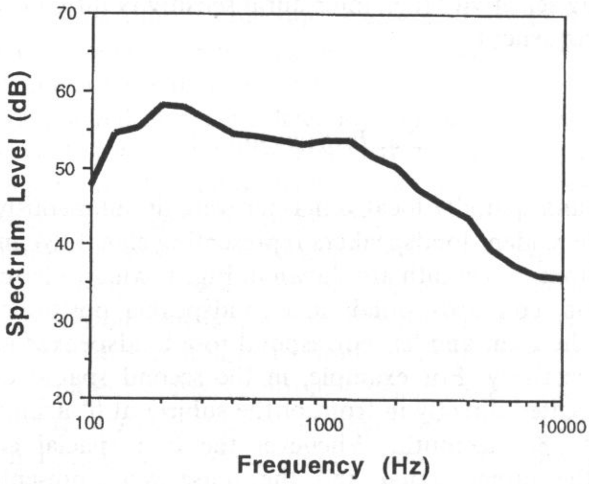


Fig. 2. The one-third octave sound pressure level spectrum of the masking noise used in this study.

presented at a constant level of 65 dBA (re: subject's head location).

Testing was conducted in a 2.7 m × 2.7 m × 1.9 m anechoic chamber (IAC Microdyne™ Series; anechoic for frequencies above 170 Hz). Target signal and spatially-located masker presentation was under the control of a computer, which directed the stimuli to two boom-mounted loudspeakers (Bose, 1180385A). The booms were suspended from the ceiling of the chamber and pivoted on the same axis, holding the loudspeakers at a uniform 1 m from the subject's head at ear level. Its design permitted independent movement of both loudspeakers anywhere on the circumference of the circle, in 1° steps, via computer-controlled stepper-motors (Arrick Robotics™). Four additional Bose loudspeakers were placed at fixed locations in the chamber and presented speech spectrum noise (65 dBA) to mask any audible motor or gear sounds that existed while the booms were in motion (Fig. 4). The output from all six loudspeakers was examined daily, using a 75 dBA pink noise signal that was presented sequentially through each louspeaker. Spectral outputs from the loudspeakers were compared in 1/3 octave bands and adjusted to be equal (within 2 dB) in the 200 to 9000 Hz range.

An acoustically-transparent cylindrical curtain (inside diameter of 1.75 m) kept the listeners from seeing any of the loudspeakers in the test chamber or the boom system overhead. A two-light display was located within the curtain at 0° azimuth and 1.2 m from the grated floor of the chamber. A white light was on continuously throughout the experiment to provide illumination inside the curtain (the chamber lights were turned off throughout testing). To mark listening intervals, a green light was illuminated by the control computer. Subjects provided threshold responses using either a hand switch or a response board, depending on the adaptive threshold procedure.

2.3. *Adaptive Threshold Procedures*

2.3.1. Bekesy Procedure. During the Bekesy tracking procedure, subjects used a hand-held resonse button to track their own detection thresholds. For each threshold measure, the green display light marked a 65 second listening interval. The target signal was initially presented at a level approximately 20 dB below the subject's actual masked threshold. With the presentation level changing at a rate of 5 dB/sec in 0.5 dB steps (this rate was found in a pilot experiment as optimal for the task), the intensity of the target signal was increased until the subject pressed the response button. Pressing the button caused the signal level to be attenuated. When the subject released the response button, the level of the target signal increased. Tracking of the target signal continued for 60 seconds beyond the first reversal on the tracing. Detection threshold was defined as the mean midpoint of several excursions during a 60 second tracking period [3, 5, 31]. The first reversal was excluded from the calculation of threshold because it increases the overall error of the threshold estimate [21, 36].

2.3.2. Ascending Up-and-Down Procedure. The Ascending Up-and-Down Procedure was adapted from the clinical methods of Hughson and Westlake [19] and Carhart and Jerger [7]. During this procedure the target signal was played once at each presentation level, rather than in a continuous manner as in the Bekesy Procedure. The initial presentation level of the target signal was at an intensity of about 10 dB below the subject's estimated masked threshold. Following this presentation, the target signal was presented in ascending 1-dB steps, until the subject responded. Once detected, its level was decreased by 10 dB and presented again in ascending 1-dB steps until the subject responded. Again, the green light marked listening intervals for subjects. Specifically, while the light was on (5 sec), a single presentation of the target signal occurred following a random time delay. Subjects were instructed to listen for the target signal and, when the light turned off, subjects were to press the response button if they heard something in addition to the spatially-located masker. The procedure continued until six ascending threshold responses were obtained. Detection thresholds was defined as the mean of the six ascending response levels [15].

2.3.3. Maximum Likelihood Procedure. The maximum likelihood procedure selected for this experiment was a PEST (Parameter Estimation by Sequential

Testing) Procedure incorporating maximum-likelihood principles [14, 22, 26, 33]. In all versions of PEST the results of previous trials are used to adjust the target signal level. However, the added maximum-likelihood principles determine the spread and threshold midpoint values that have the highest probability of being the best threshold estimate. Detection threshold can be chosen arbitrarily and in this case was chosen as the 50% detection point on a psychometric function.

To establish a detection threshold using this procedure, the target signal was presented to the subject 17 times, with the first two presentations defining the presentation level range (i.e., the first and second presentation of the target signal was at the highest and lowest level in the range of possible spread values, respectively. These presentations were not included in threshold calculation). Step sizes for the last 15 presentations of the target signal were determined by Maximum Likelihood Procedure rules [26], with the maximum step size limited to 20 dB, and a minimum of 1 dB.

During threshold determination, the green light on the display was used to indicate a listening interval. The "light on" condition marked an observation interval. The "light off" condition indicated a response interval. Subjects were instructed to respond by pressing either the left or right push-button on the response pad, indicating "No, I did not hear the target signal" or "Yes, I did hear the target signal", respectively. The masked detection threshold was established following the final 15 presentations of the target signal, with the last presentation level taken as the subject's detection threshold.

2.4. Procedure

2.4.1. General. Across all experiments the following procedure was used. The subject was seated on a custom-made, height-adjustable chair, which was bolted ot the floor of the anechoic chamber. While in a seated position, the chair was adjusted so that the ears of the subject were aligned with the centers of the boom-mounted loudspeakers. This arrangement allowed for the same center position to be used as a reference during the experiment. No restraints were used to keep the subject's head from moving during trials. Instead, two plomb-bobs were dropped from the roof of the curtain, 50 cm apart, directly in front of the subject. Subjects were instructed to visually align the two plomb-bobs during testing. In addition, head orientation was monitored by a head tracking electromagnetic device (Polhemus, 3-SPACE ISOTRAK). The device was mounted to the back of the subject's head using a Velcro™ strap that was wrapped around the subject's head at forehead level. Any target signal presentations that occurred during excessive head movement ($\geqslant 3°$) were discarded and repeated [12].

After the subject was positioned in the chamber, room lights were turned off and the white display light remained on for testing. The boom-mounted loudspeakers were rotated to one of the randomly selected spatial configurations (Fig. 1). Once the loudspeakers were in position, the spatially-located masker (65 dBA, measured at the

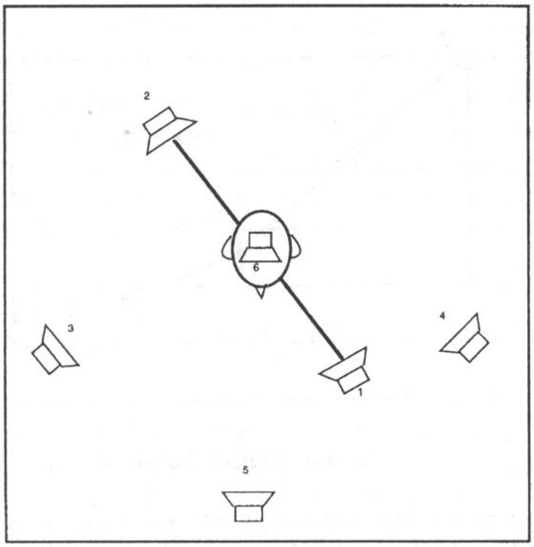


Fig. 3. Schematic of the experimental equipment and test chamber. Boom-loudspeakers are numbered *1* and *2*. Stationary loudspeakers are numbered *3*, *4*, *5* and *6*. Loudspeaker *6* was directly overhead.

subject's head position) was introduced and remained on until a detection threshold was established. The boom-mounted loudspeakers moved to the next randomly selected spatial configuration. To mask any apparatus-related noises, a 65 dBA speech-spectrum noise was delivered through the four stationary loudspeakers while the booms were in motion (Fig. 3).

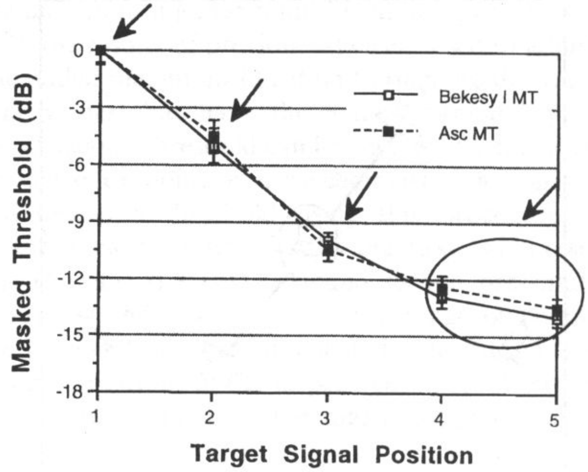
In Experiment 1, threshold estimates for a group of ten subjects were obtained using the Bekesy Procedure and the Ascending Up-and-Down Procedure for the first five spatial configurations shown in Fig. 1. Thresholds were repeated six times at each spatial configuration. One adaptive threshold procedure was used during one, 45-minute session while the other was used during a second 45-minute session. The order of adaptive threshold procedures was counterbalanced across subjects.

In Experiment 2, threshold estimates for the second group of ten subjects were obtained using the Bekesy Procedure and the Maximum Likelihood Procedure. All seven configurations shown in Fig. 1 were used. Two additional configurations were added to explore other masking possibilities. As in the first experiment, thresholds were obtained six times at each spatial configuration and for each test procedure, in two, 45-minute sessions. Again, the order of adaptive procedures was counterbalanced.

3. Results and Discussion

3.1. Experiment 1

Figure 4 presents the mean thresholds and standard error bars for the thresholds obtained in Experiment 1, using the Bekesy Procedure and the Ascending



zFig. 4. Experiment 1. Mean detection thresholds and standard error bars for both the Bekesy Procedure (Bekesy I MT) and the Ascending Up-and-Down Procedure (Asc MT).

Up-and-Down Procedure. The spatial configurations (Fig. 1) for the target signal and noise are presented along the abscissa. Masked threshold levels are represented along the ordinate, with 0 dB representing the threshold obtained when both the signal and noise were presented directly in front of the subject (spatial configuration 1). Since detection thresholds were always the poorest (highest) in this loudspeaker arrangement, spatial configuration 1 was used as a reference for which to compare the data obtained in other configurations. Error bars in Fig. 4 represent standard error of the mean.

Collected threshold data were analyzed using a three-way analysis of variance (ANOVA) with repeated measures [35]. The main effects included: adaptive procedure (Bekesy Procedure versus Ascending Up-and-Down Procedure), spatial configuration (1, 2, 3, 4, and 5), and trial (1, 2, 3, 4, 5, 6). A statistically significant difference was found for spatial configuration ([$F(4, 36)=1670.86$, $\mathbf{p}<0.0001$]). No statistically significant differences in threshold measures were found for the main effects of adaptive procedure and trial, and for any of the interactions ($\mathbf{p}>0.05$).

The Schéffè *post hoc* multiple comparison test was performed using appropriate error terms, to examine mean thresholds for each spatial configuration. At an alpha level of 0.05, four Schéffè groupings were found, as depicted by the arrows in Fig. 4 (mean thresholds within the circled area did not differe statistically),. The poorest detection thresholds occurred when the target and spatially-located masker occupied the same spatial position; that is, both S and N were presented at 0° azimuth (spatial configuration 1). In spatial configuration 2, a slight improvement was found in detection. The changes in perceived spectra of the target signal and spatially-located masker resulted in a 4 – 5 dB improvement in the detection threshold. When *both* the target signal and masker were located to the left or right of the median plane, improvements of as much as 10 to 14 dB in detection threshold were seen (spatial configuration 5). In these conditions, subjects were able to take advantage of all auditory spatial cues; changes to the pinna cues and interaural difference cues, together, provided listeners with information that significantly improved detection of the target. In summary, if the threshold obtained in the first spatial configuration is used as a reference, the maximum improvement in the mean detection threshold amounted to approximately 14 dB.

3.2. Experiment 2

To compare the Bekesy and Maximum Likelihood Procedures, a repeated measures ANOVA was conducted. The main effects included: adaptive procedure (Bekesy Procedure versus Maximum Likelihood Procedure), spatial configuration (1, 2, 3, 4, 5, 6 and 7), and trial (1, 2, 3, 4, 5, 6). A statistically significant difference was found for spatial configuration ([$F(9, 54) = 46037.73$, $\mathbf{p} < 0.0036$]). No statistically significant differences in mean detection thresholds were found for the main effects of adaptive procedure and trial, and for any interactions ($\mathbf{p} > 0.05$).

Figure 5 presents the mean thresholds and standard error bars obtained using the Bekesy Procedure and Maximum Likelihood Procedure. The spatial configurations for the target signal and spatially-located masker are numbered along the abscissa. Masked threshold level is represented along the ordinate of the figure. Error bars represent the standard error of the mean. The reported results are very similar to those found in the first experiment. The poorest detection performance occurred when the target and spatially-located masker were at the same position in space (i.e.,

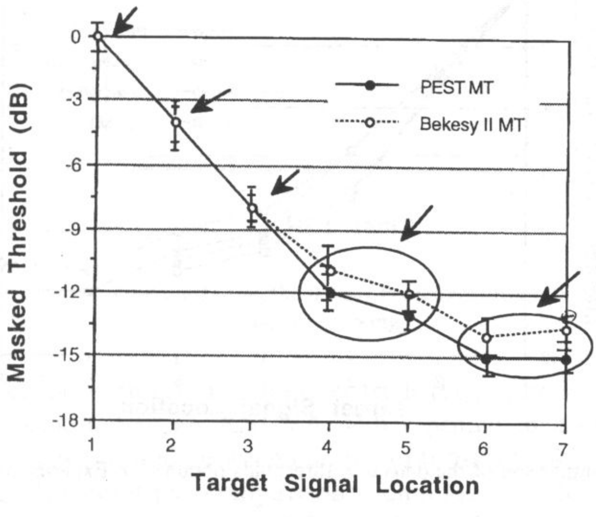


Fig. 5. Experiment 2. Mean detection thresholds and standard error bars for both the Bekesy Procedure (Bekesy II MT) and the Maximum Likelihood Procedure (Maximum Likelihood MT).

both S and N presented at 0° azimuth) and best performance resulted when one or both sound sources were off of the median plane, with the target being directed down the ear canal (i.e., positioned at either 90° azimuth of 270° azimuth).

To determine if statistically significant differences occurred between the mean thresholds at each spatial configuration, the Schéffè *post hoc* multiple comparison method was used. At an alpha level of 0.05, five Schéffè groupings were found, which are depicted by arrows in Fig. 5 (no statistically significant differences existed between mean thresholds within circled areas). Again, if the threshold obtained in the first spatial configuration is used as a reference, the maximum improvement in the detection threshold amounts to approximately 14–15 dB.

3.3. Comparison of Adaptive Threshold Procedures

The mean detection thresholds found in Experiment 1 and Experiment 2 using the Bekesy, Ascending UP-and-Down and Maximum Likelihood Procedure are illustrated in Fig. 6. Threshold means obtained using the Bekesy Procedure for Experiments 1 and 2 are represented in this figure as Bekesy I and Bekesy II, respectively. Using a mixed design structure, where one independent variable (Experiment) was a between-subject factor and one independent variable (spatial configuration) was a within-subject factor, an ANOVA with repeated measures was conducted. No systematic differences in threshold were found across adaptive threshold procedures ($p < 0.05$). Thus, for this particular task, no statistical or practical difference in detection threshold occurred between the Bekesy, Ascending Up-and-Down, or Maximum Likelihood Procedure.

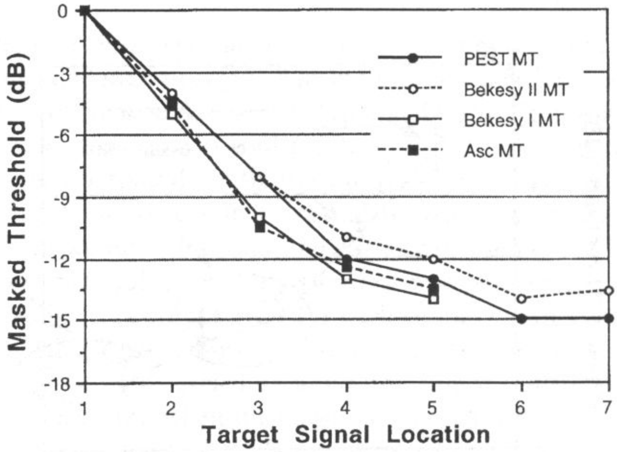


Fig. 6. Comparison of the detection thresholds obtained in Experiments 1 and 2.

At the end of each experiment, subjects were asked to comment on the adaptive threshold procedures. All subjects preferred the Bekesy Procedure for obtaining a detection threshold. The Ascending UP-and-Down and Maximum Likelihood Procedures were described as being taxing and stress producing. Moreover, all three procedures were reported as being time consuming. To evaluate this last comment, the Bekesy and Maximum Likelihood threshold data were studied in more detail. Specifically, detection thresholds were examined after 15, 30 and 60 seconds for the Bekesy Procedure, and after 3, 6, 8, 10, 12 and 15 trials for the Maximum Likelihood Procedure. (Data collection techniques would not allow for a break-down of the data from the Ascending Up-and-Down Procedure).

When Bekesy threshold data over time (i.e., after 15, 30 and 60 seconds) were subjected to an ANOVA with repeated measures, a statistically significant difference was found for the main effect of time [$F(2, 18) = 12.57$, $\mathbf{p} < 0.0112$)]. The Schéffè *post hoc* multiple comparison technique revealed that a detection threshold after 15 seconds was significantly different than thresholds after either 30 or 60 seconds. No significant difference in mean thresholds occurred between 30 and 60 seconds of tracking ($\mathbf{p} < 0.05$). Mean thresholds are shown in Fig. 7 for the three time periods. The results suggest that, for the directional masking experiment reported, a detection threshold after 30 seconds would not be statistically different from a threshold reported after 60 seconds; thus, the same detection threshold results could be found in half the amount of time.

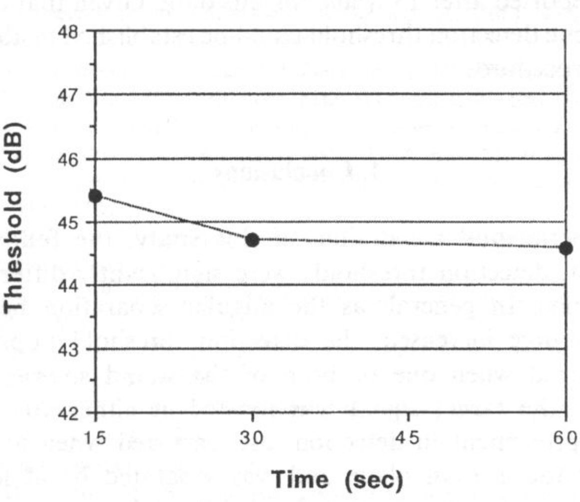


Fig. 7. Mean detection thresholds obtained using the Bekesy Procedure after 15 seconds, 30 seconds and 60 seconds of tracking.

Maximum Likelihood threshold data over trials (i.e., after 3, 6, 8, 10, 12, and 15 trials) were also subjected to an ANOVA with repeated measures. A statistically significant difference was found between number of trials [$F(5, 45) = 16.49$, $\mathbf{p} < 0.001$]. The Schéffè *post hoc* multiple comparison technique revealed that a detection threshold after 3 trials was significantly different than a detection threshold after 6, 8, 10, 12 or 15 trials. Mean threshold data are shown in Fig. 8. The results suggest that,

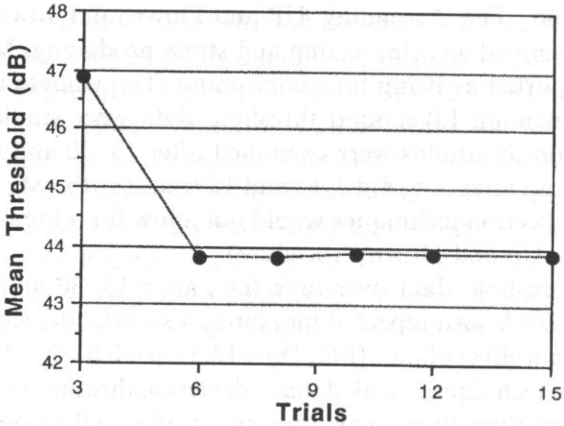


Fig. 8. Mean detection thresholds obtained with the Maximum Likelihood Procedure after 3, 6, 9, 12 and 15 trials.

for the directional masking experiment reported, a detection threshold obtained with the Maximum Likelihood Procedure after 6 trials would not be statistically different from a threshold reported after 15 trials, for this data. Given that each trial requires five seconds, the same detection threshold could be established in about half the time, as in the Bekesy Procedure.

4. Conclusions

Within the experimental constraints of this study, the following conclusions were reached. First, detection thresholds were significantly different at almost all spatial configurations. In general, as the angular separation between the target signal and noise source increased, the detection threshold improved. Maximum improvement occurred when one or both of the sound sources were off of the median plane, and the target signal was located at either 90° azimuth or 270° azimuth. Some improvement in detection also occurred when at least one source was located off of the median plane and was separated by at least 90° azimuth from the other source. Second, the results of this study support previous findings that, for a complex target presented together with a spatially-located masker, the changes in detection threshold can be as high as 15 dB depending on the spatial configuration of both sources [4, 7, 9, 10, 11, 13, 16, 18, 20, 23, 24, 29, 30, 35]. Third, although all three adaptive procedures yielded reasonably accurate results and render similar mean thresholds, subject satisfaction, and differences in administration time suggest that advantages might accrue from choosing the Bekesy Procedure for obtaining directional masking thresholds.

The measurement of directional masking should provide designers of multi-channel communication systems with a valuable tool for positioning messages in

3D audio displays. Specifically, the measurement of directional masking will help designers optimize the spatial locations and presentation levels of the messages so that background noise and directional maskers minimally affect message detection.

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