Binaural signal detection, overall masking level, and masker interaural correlation: Revisiting the internal noise hypothesis

Leslie R. Bernstein and Constantine Trahiotis
Department of Neuroscience and Department of Surgery (Otolaryngology), University of Connecticut Health Center, Farmington, Connecticut 06030

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This study provides data concerning the characteristics of internal noise that limits binaural detection at 500 Hz under "pulsed" masking conditions and evaluates whether the parameters of such internal noise depend upon masker/signal duration. A single-interval adaptive procedure was employed to measure NoSπ detection thresholds as a joint function of the level of broadband masking noise and masker/signal duration. Sπ detection thresholds were also measured as a joint function of the interaural correlation of the masker and masker/signal duration. Findings include : (1) changes in Sπ thresholds taken either as a function of diotic masker level or as a function of masker interaural correlation are independent of masker/signal duration; (2) 500-Hz "quiet" So and Sπ thresholds yield a masking-level difference of −2.0; (3) reductions in thresholds with increasing duration are similar regardless of masker level. Analyses indicate: (1) the presence of stimulus-independent, interaurally-negatively-correlated, additive internal noise and stimulus-dependent internal noise having a level proportional to that of the external masker while being independent of masker/signal duration; (2) that NoSπ thresholds taken as a joint function of masker/signal duration and masker spectrum level are, quantitatively, well described by taking into account effects produced by the combination of internal and external noises.
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I. INTRODUCTION

Bernstein *et al.* (2006) recently reported the results of an investigation directed toward understanding how the detection of 500-Hz tonal signals masked by broadband noise and presented in the NoSπ configuration depends upon the relative durations of the temporally overlapping signals and maskers. In an attempt to account for some of their findings, Bernstein *et al.* (2006) showed that detectability was highly correlated with duration-dependent variations in activity expected to occur within and across auditory filters putatively involved in the processing of the stimuli. What remained elusive was how such variations in filter activity could be incorporated within a quantitative model in order to account for the results. Following Bernstein *et al.*'s (2006) discussion, it appears that in order to construct such a model, one would first need to characterize the parameters of the "internal noise" that limits binaural detection. Specifically, one would need to know whether and to what degree those parameters change with masker/signal duration. To our knowledge, such information concerning internal noise was not available. Therefore, one purpose of this study was to gather new behavioral data that would help to provide the required information. Another purpose was to gather additional data concerning the parameters (i.e., level, interaural correlation) of internal noise that limits binaural detection at 500 Hz.

In order to understand the design of the experiments, it is necessary to begin with a discussion of what is meant by "internal noise". We follow a host of "monaural" and "binaural" investigations in conceptualizing the totality of internal noise as arising from two different sources. The first source is characterized as being additive and serving as a "noise floor" that determines absolute threshold (e.g., Diercks and Jeffress, 1962; Watson *et al.* 1972; McFadden, 1968; Yost, 1988; Breebaart *et al.*, 2001). McFadden (1968 p. 218) described this type of internal noise as follows:

> It is assumed that in the auditory channel serving each ear there is some ongoing neural activity, the statistical characteristics of which are identical to the neural activity produced by the external noise source. The level of this additional activity is presumed to be relatively constant and independent of the external noise. The correlation between the internal noise and the external noise is assumed to be zero… In other words, the internal noise proposed here is analogous to having added additional noise sources externally. Indeed, it may be that part of this "internal noise" is due to the physiological noise measured in the external ear canal by Shaw and Piercy (1962).

It should be emphasized that the characteristics of this additive component of internal noise (e.g., it's level and its interaural correlation) are considered to be independent of the parameters of the external stimuli (Diercks and Jeffress, 1962; McFadden, 1968; Yost, 1988).

The second source of internal noise is characterized as directly limiting auditory processing or coding, per se. This component of internal noise has been studied in monaural hearing (e.g., Green, 1960; Spiegel and Green, 1981; Raab and Goldberg, 1975) and in binaural hearing. In the case of binaural hearing, this component of internal noise has been conceptualized in more than one way: either as a degradation of the information in the stimulus available to the binaural processor (e.g., Durlach, 1972; van der Heijden and Trahiotis, 1997, 1998) or as a degradation resulting from errors in the binaural processor itself (e.g., van der Heijden and Trahiotis, 1998; Breebaart *et al.*, 2001). An intuitive understanding of why this type of internal noise is necessary to account for binaural detection can be gained by considering the consequences of errorless binaural processing. Errorless binaural processing would, for stimuli presented in the NoSπ configuration, result in elimination of all of the external noise. Consequently, thresholds of detection would be identical to those for Sπ signals presented in the quiet, *regardless of the level of the external masker*. This is so because errorless binaural processing would lead to detection thresholds limited only by the first source of internal noise discussed above. The large amount of masking measured with typical levels of signals and maskers in the NoSπ configuration, however, requires the postulation of this second, processing-based, source of internal noise. It should be emphasized that the processing-based component of internal noise is explicitly considered to be dependent on the parameters of the external stimuli. Therefore, based on the properties of the two potential sources that compose the total internal noise that limits binaural detection, one would expect that any dependency of the total internal noise with the level and/or duration of the external stimuli would involve the second, stimulus-dependent source of internal noise.

We now return to the context of accounting for NoSπ detection thresholds at 500 Hz measured with pulsed and temporally overlapping signals and maskers. Recall that it was suggested that a potentially important, but missing, ingredient was information concerning whether and to what degree parameters of the total internal noise change with the duration of the stimuli. In monaural experiments concerning intensity discrimination, it has been shown that stimulus-dependent processing-based internal noise does, indeed, vary with the duration of the stimuli (e.g., Raab and Goldberg, 1975). A search of the binaural literature, however, revealed no experiments relating internal noise and duration. With regard to the stimulus-independent, additive source of internal noise, Watson *et al.* (1972) provided estimates of the level of that noise at 500 Hz for monaural detection. We were unable, however, to identify any experiments concerning binaural detection reporting estimates of the level (and interaural correlation) of additive internal noise at 500 Hz. This study reports new data that help shed light on the characteristics of both the stimulus-independent and stimulus-dependent components of internal noise that serve to limit binaural detection at 500 Hz.

The experiments were conducted using an approach that paralleled the one adopted by McFadden (1968). Detection of interaurally phase-reversed (Sπ) 500-Hz tonal signals masked by broadband noise was measured while varying the spectrum level of a diotic broadband noise masker. In a second experiment, thresholds for an Sπ signal were measured while varying the interaural correlation of a high-level broadband noise masker. In both experiments, thresholds of detection were measured while parametrically varying masker/signal durations over a large range. It will be seen that theoretical analyses of the new data, taken together with thresholds of detection for 500-Hz Sπ and So signals in "the quiet," suggest that binaural detection is limited by (1) a *stimulus-independent*, additive internal noise that is slightly *negatively* interaurally correlated and (2) a *stimulus-dependent* internal noise that affects detection differentially with changes in the level of the stimuli but not with changes in duration.

II. PROCEDURE

Detection thresholds were measured for 500-Hz tonal signals using the same single-interval adaptive matrix procedure described and evaluated by Kaernbach (1990). The procedure was employed and validated by comparison with a standard, "fixed-level" single-interval procedure by Bernstein *et al.* (2006) in their study of binaural detection with pulsed signals and maskers. Each trial consisted of a 500-ms warning interval followed by a single observation interval during which a visual display on a computer monitor marked the potential occurrence of the signal. "Non-signal" trials and "signal" trials were presented randomly with equal *a priori* probability. Correct-answer feedback was provided via the computer monitor for 400 ms after the listener responded, followed by a 400-ms pause before the beginning of the next trial. The procedure was used to target 75% correct performance. As discussed by Kaernbach (1990, p. 2649), this required the level of the signal to be reduced by one step-size unit after each "hit," increased by one step-size unit after each "miss," increased by two step-size units after each "false alarm," and left unchanged after each "correct rejection." In order to minimize the errors of estimation of threshold, the step-size was initially 2 dB and was reduced to 1 dB after the first two "reversals," a run was terminated after 16 reversals, and threshold was defined as the average level of the signal across the last 12 reversals (see Kaernbach, 1990, Fig. 6, p. 2651).

In one set of conditions, referred to as the "masker-level" conditions, 500-Hz Sπ tonal signals were presented against a background of diotic broadband noise (bandwidth 100–3000 Hz). Seven spectrum levels of the masker were employed that ranged from −10 to +50 dB SPL in 10 dB steps. Signals and maskers were gated on and off simultaneously using 5-ms $\cos^2$ ramps. The total durations of the stimuli (including the ramps) were 10, 20, 40, 80, 160, or 320 ms. Detection thresholds were also measured in the absence of the masking noise (i.e., in the quiet) for both Sπ and So 500-Hz tonal signals.

In another set of conditions, referred to as the "masker-correlation" conditions, Sπ tonal signals were, again, presented against a background of broadband noise (bandwidth 100–3000 Hz) utilizing the same set of masker/signal durations specified above. In this set of conditions, the spectrum level of the masker was fixed at 50 dB SPL and the interaural correlation of the masker took on values of 1.0, 0.997, 0.992, 0.97, 0.87, 0.5, 0.2, or −1.0. Such values have been shown by van der Heijden and Trahiotis (1998) to allow one to characterize relatively precisely the function relating thresholds of detection to the interaural correlation of the masker.

The desired values of interaural correlation were produced by appropriate "mixtures" of pairs of independent Gaussian noise, one diotic and one interaurally phase-reversed (van der Heijden and Trahioits, 1997).

All stimuli were generated digitally with a sampling rate of 20 kHz via a custom software library (MLSIG) running within MATLAB©, were converted to analog form via a TDT PD1, and were low-passed filtered at 8.5 kHz (TDT FLT1) before being presented via matched TDH-39 earphones to listeners seated in individual single-walled IAC chambers. Noise and signal waveforms were each selected randomly from within their own 2-s-long buffers that were generated anew prior to each adaptive run. The relative levels of the stimuli and their rise-decay ramps were controlled via software and the absolute levels of the stimuli were determined by programmable attenuators (TDT PA4) in a manner that maximized the use of the 16-bit range of the digital-to-analog converters.

Four young adults (one male and three female) with audiometrically normal hearing served as listeners. Thresholds were obtained in the masker-correlation conditions for all but the masker interaural correlations of 0.2 and −1.0. Then, thresholds were measured in the masker-level conditions. Thresholds for the masker interaural correlation of 0.2 were collected following completion of the masker-level conditions. Those thresholds were collected along with re-tests of the masker interaural correlation of 0.97 to check for stability of overall performance. Performance was found to be stable in that only small (typically within 1 dB) and unsystematic changes in threshold were observed. Finally, thresholds for a masker interaural correlation of −1.0 were collected.

For both the masker-correlation and masker-level conditions, thresholds were measured using blocks of conditions during which the masker/signal duration was held constant. For the masker-correlation conditions, a masker/signal duration was chosen at random and single estimates of threshold were collected by visiting values of the masker interaural correlation in random order. Then, those same values of masker interaural correlation were visited twice more, once in reverse order and once more in the original order. This yielded three estimates of threshold for each masker interaural correlation at a particular value of masker/signal duration. Then, a new value of duration was chosen and the process was repeated. Once all of the values of duration and masker interaural correlation had been exhausted, all conditions were visited again, but in reverse order. This resulted in the collection of six estimates of threshold for each combination of masker/signal duration and masker interaural correlation. A similar scheme was employed to measure thresholds in the masker-level conditions. For those conditions, however, the initial ordering (i.e., before the ordering was reversed) of both masker/signal duration and of masker-level was ascending (i.e., from lowest to highest value). The same ordering of conditions was used for all four listeners.

Estimates of "final" thresholds for each listener were calculated by first omitting the lowest and highest of the six estimates of threshold for each stimulus condition and then computing the mean of the remaining four. In the masking-level conditions, for 6 of the 54 conditions, the standard deviation of the final thresholds for one listener exceeded 3 dB. In those instances, additional measures of threshold were obtained substituting the new measures one-for-one with the "oldest" measures until the four estimates of threshold yielded a standard deviation of less than 3 dB. This required the measurement of no more than three additional thresholds.

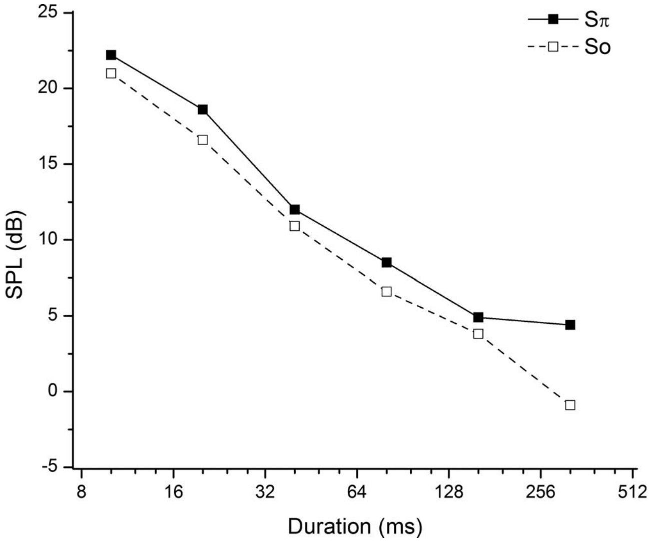

FIG. 1. So and Sπ detection thresholds (dB SPL) obtained in "the quiet" as a function of the duration of the signal. The data represent the thresholds averaged across four listeners. The average standard error of the mean across the 12 points displayed was 2.5 dB.

III. RESULTS AND DISCUSSION

Figure 1 displays the signal levels, averaged across the four listeners, required to reach threshold when 500-Hz So and Sπ tones were each presented in the absence of any external masker (i.e., in the quiet). In order to foster visual clarity, error bars are not displayed. The average standard error of the mean across the 12 points displayed was 2.5 dB. Note that, for all six durations tested, thresholds were found to be *lower* in the So configuration than in the Sπ configuration. This outcome is highly statistically significant by the sign-test ($p=0.016$). Important for our purposes, the data reflect an average masking-level difference (MLD) of −2.0 dB (So threshold minus Sπ threshold).

The finding of a negative MLD was quite perplexing in light of the positive MLD between So and Sπ thresholds reported by Diercks and Jeffress (1962) and the positive MLD reported by McFadden (1968) between So and Sm thresholds for tonal signals presented in the quiet. It is the case, however, that neither Diercks and Jeffress (1962) nor McFadden (1968) included measurement of So and Sπ quiet thresholds using 500-Hz tonal signals. Diercks and Jeffress (1962) measured quiet thresholds for 250-Hz tonal signals in Sm, So, and Sπ configurations and found that the values of the thresholds decreased in that same order. McFadden (1968) measured the quiet thresholds for 400-Hz tonal signals with only Sm and Sπ signals and, like Diercks and Jeffress (1962), found that the former yielded higher thresh-

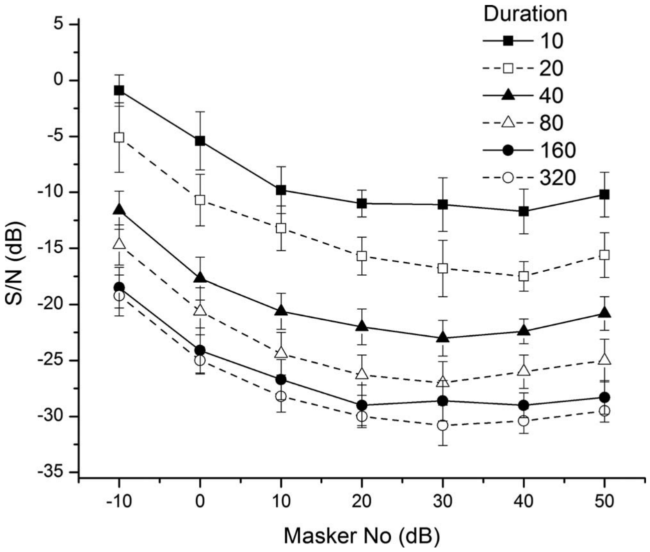

FIG. 2. NoSπ threshold S/N (in dB) plotted as a function of the spectrum level of the broadband (100–3000 Hz) Gaussian noise masker. The data represent the thresholds averaged across four listeners. Error bars represent ±1 standard error of the mean. The parameter of the plot is the masker/signal duration.

olds than the latter, yielding a positive MLD. Importantly, Lakey (1976) did employ 500-Hz tonal signals and measured quiet thresholds in Sm, Sπ, and So conditions. Consistent with the two earlier studies, Lakey (1976) measured higher thresholds in the Sm condition than in the Sπ condition. Nonetheless, Lakey (1976) found an MLD of about −3 dB between So and Sπ thresholds at 500 Hz. This finding is consistent with the −2.0 dB MLD we measured using the same stimulus conditions.

Taking all of this into account, it appears that the only potential inconsistency among the four studies is the small positive MLD between So and Sπ conditions found by Diercks and Jeffress (1962) at 250 Hz. In order to verify that finding, we measured So and Sπ quiet thresholds at 250 Hz with the same listeners and procedures utilized in the main experiment. The results, averaged across all six durations and four listeners, revealed a positive MLD of about 1.3 dB, essentially replicating the 0.9-dB MLD obtained by Diercks and Jeffress (1962). Thus, it appears that whether one measures positive or negative MLDs in the quiet can depend both upon the monaural reference condition one adopts (i.e., So or Sm) and the frequency of the signal one chooses.[1]

Figure 2 displays the signal-to-noise (S/N) ratio required to reach NoSπ detection threshold as a function of the spectrum level of the broadband (100–3000 Hz) masking noise, again averaged across the four listeners. The error bars represent ±1 standard error of the mean. The parameter of the plot is the masker/signal duration. Visual inspection suggests two main trends in the data. First, detection thresholds are inversely related to masker/signal duration. This outcome replicates the results of previous studies employing "pulsed" signals and maskers (e.g., Robinson and Trahiotis, 1972; Kohlrausch, 1986; Bernstein and Trahiotis, 1997; Bernstein *et al.*, 2006). Second, for each duration, threshold S/Ns are relatively constant for spectrum levels of the masker greater than or equal to 20 dB. In contrast, for all durations, threshold S/N *increases* by about 10 dB as the level of the masking noise is *reduced* from 20 dB to −10 dB. This outcome is consistent qualitatively, but not quantitatively, with the results obtained by McFadden (1968) in the study that motivated this work. Examination of Fig. 4 of McFadden (1968) reveals that his listeners' NoSπ thresholds increased by approximately 17 dB over this same range of spectrum levels of the masker. Furthermore, McFadden's (1968) figure shows that thresholds began to increase once the spectrum level of the masker was below 35 dB. We will return to this issue in Sec. IV F.

The data in Fig. 2 were subjected to a two-factor (six durations × seven masker levels) within-subjects analysis of variance. The error terms for the main effects and for the interactions were the interaction of the particular main effect (or the particular interaction) with the subject "factor" (Keppel, 1973). In addition to testing for significant effects, the proportions of variance accounted for (ω^2) were determined for each significant main effect and interaction (Hays, 1973).

Consistent with visual inspection of the data, the main effect of duration was significant (assuming an α of 0.05) $[F(5,15)=150.7,\ p<0.001]$ and accounted for 66% of the variability of the data. This significant main effect reflects the fact that, on average, thresholds were lower for longer stimuli. The main effect of masker level was also significant $[F(6,18)=91.3,\ p<0.001]$ and accounted for 20% of the variability in the data. This significant main effect reflects the fact that, on average, thresholds increased with decreases in the level of the masker. Also in accord with the essentially parallel, nonoverlapping appearance of the curves in Fig. 2 is the fact that the interaction of duration and masker level was not significant $[F(30,90)=0.76,\ p=0.81]$. Thus, the main effects of duration and masker level can be interpreted as being independent of each other.

Figure 3 displays the S/Ns ratios required to reach NoSπ detection threshold as a function of the interaural correlation, ρ, of the relatively high-level (spectrum level=50 dB) broadband (100–3000 Hz) masking noise. The scaling of the abscissa has been expanded for the largest values of ρ in order to preclude overlapping of thresholds that could obscure the patterning of the data. The data depicted are averages calculated across the four listeners and the error bars represent ±1 standard error of the mean. The parameter of the plot is the masker/signal duration. As was the case for the data depicted in Fig. 2, threshold S/N is inversely related to masker/signal duration. For all durations, thresholds remained essentially constant as the interaural correlation of the noise was decreased from 1.0 (NoSπ) to 0.97, then increased substantially as the interaural correlation of the noise was decreased from 0.97 toward 0.2, and changed very little when the interaural correlation of the noise was decreased further to −1.0 (NπSπ). The changes in threshold S/N produced by changes in ρ are consistent in kind and amount with those reported by Robinson and Jeffress (1963) and van der Heijden and Trahiotis (1997) for long-duration 500-Hz tones masked by continuous broadband noise.

The data in Fig. 3 were subjected to the same type of within-subjects analysis of variance described earlier. For these data the two-factor analysis was composed of 48 total

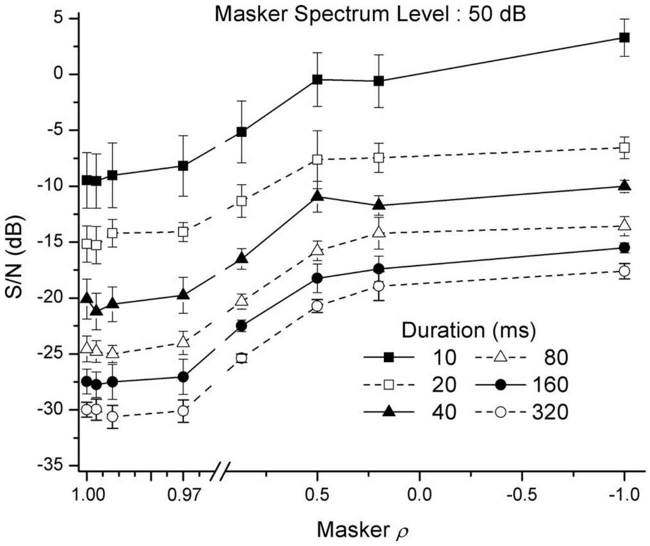

FIG. 3. NoSπ threshold S/N (in dB) plotted as a function of the interaural correlation of the broadband (100–3000 Hz) Gaussian noise masker. The scaling of the abscissa has been expanded for the largest values of ρ in order to preclude overlapping of thresholds that could obscure the patterning of the data. The data represent the thresholds averaged across four listeners. Error bars represent ±1 standard error of the mean. The parameter of the plot is the masker/signal duration.

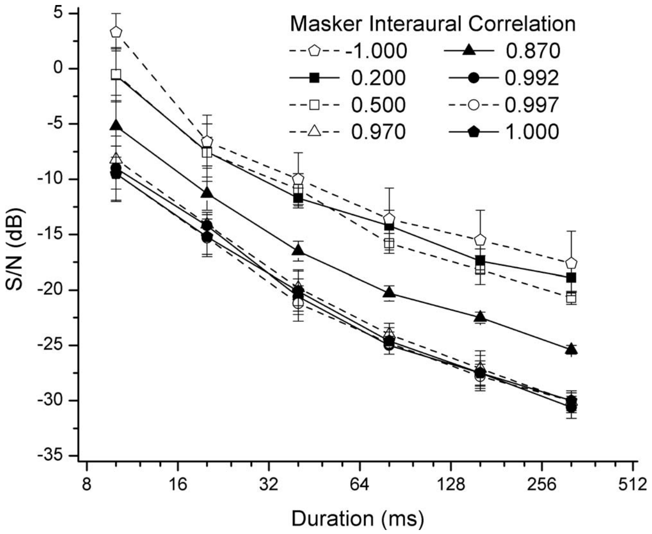

FIG. 4. A replotting of the data in Fig. 3. Threshold S/N (in dB) is plotted as a function of masker/signal duration. The parameter of the plot is the interaural correlation of the masker.

conditions (six durations × eight masker interaural correlations). The main effect of duration was significant (assuming an α of 0.05) $[F(5,15)=121.5,\ p<0.001]$ and accounted for 64% of the variability of the data. This significant main effect reflects the fact that, on average, thresholds were lower for longer stimuli. The main effect of masker interaural correlation was also significant $[F(7,21)=198.4,\ p<0.001]$ and accounted for 27% of the variability in the data. This significant main effect reflects the fact that, on average, thresholds increased with decreases in the interaural correlation of the masker. The interaction of duration and masker interaural correlation was not significant $[F(35,105)=1.4,\ p=0.11]$. This is consistent with the essentially parallel, nonoverlapping appearance of the curves. Thus, statistically, the main effects of masker/signal duration and masker interaural correlation can be interpreted as being independent of each other. These new data are especially interesting because they indicate that the increases in Sπ threshold that have been measured while decreasing masker/signal duration in experiments employing pulsed diotic maskers (e.g., McFadden, 1968; Robinson and Trahiotis, 1972; Bernstein and Trahiotis, 1999; Bernstein *et al.*, 2006) occur regardless of the interaural correlation of the pulsed masker. This aspect of the data can be appreciated in a more direct manner via Fig. 4 in which the thresholds in Fig. 3 have been re-plotted as "temporal integration functions" with duration along the abscissa and masker interaural correlation as the parameter.

The findings of no interaction between masker/signal duration and masker level and no interaction between masker/signal duration and masker interaural correlation are important. Taken together with the assumption of a low-level, stimulus-independent source of internal noise, those two findings mean that the parameters of the stimulus-dependent source of internal noise do not vary with masker/signal duration. Thus, the data of Figs. 2 and 3 and the postulation of both stimulus-independent and stimulus-dependent components of internal noise suggest that the parameters of the "total" internal noise that limits binaural detection are independent of masker/signal duration.

IV. CHARACTERIZING THE INTERNAL NOISE

We now consider how the data in Figs. 1–3 reveal the influence of the two components of internal noise discussed earlier.

A. Evidence for a stimulus-dependent high-level source of internal noise

Recall that if binaural processing were errorless, then the levels of Sπ signals required for detection in the presence of a diotic masker would be identical to those for Sπ signals presented in the quiet. Those "quiet" thresholds are conceived of as being determined by the level of a stimulus-independent, additive internal noise discussed earlier. Taking the 160-ms-long Sπ signal as the example, note that its threshold of detection in the quiet is 3.8 dB SPL (see Fig. 1). Now, consider the levels of this signal that were required for detection when it was masked by the four highest levels of the *external* noise. Conversion of the values of threshold in Fig. 2 from S/N to signal-SPL reveals that when the spectrum level of the external masker was 20, 30, 40, or 50 dB, the level of the Sπ signal required for detection was 25.6, 36.0, 45.6, or 56.3 dB SPL, respectively. Those thresholds (1) are clearly well above the one measured in the quiet and (2) increase in proportion to the level of the external masker. These two features of the data are consistent with the notion discussed above that binaural detection is limited additionally by a source of internal noise having a level proportional to the level of the external masker (e.g., Green, 1960; Spiegel and Green, 1981).

B. Evidence for a stimulus-independent, additive source of internal noise

The finding that threshold S/N increased as the spectrum level of the diotic masking noise was reduced below 20 dB is consistent with the presence of a relatively low-level, additive internal noise that acts in conjunction with the external noise (e.g., McFadden, 1968; Yost, 1988). According to this view, at relatively low levels of the external masking noise, say for spectrum levels below 20 dB, the relative level of the additive internal noise is large enough so that it adds appreciably to the amount of masking produced by the external noise. Note that, the threshold values of S/N in Fig. 2 were calculated only on the basis of the power of the external masking noise. Therefore, any additional amounts of masking produced by the low-level, additive internal noise are manifest as increases in the S/N. Those additional amounts of masking could, conceivably, arise in two different manners. First, the internal noise, when combined with the external noise would result in an "effective" masker having a power greater than that of the external noise alone. Second, the internal noise, when combined with the external noise could result in an "effective" masker having an interaural correlation that is less than 1.0 (the interaural correlation of the diotic external masker). This would occur if the interaural correlation of the additive internal noise were, itself, less than 1.0.

C. Quantifying the level and interaural correlation of the stimulus-independent, additive internal noise

The data presented in Figs. 1–3 permit one to estimate both the interaural correlation and the level of the stimulus-independent, additive internal noise that affects binaural detection at 500 Hz. An estimate of its interaural correlation can be made using the average MLD of −2.0 dB obtained from the So versus Sπ quiet thresholds shown in Fig. 1. That negative MLD is, by hypothesis, the difference between NρSo and NρSπ thresholds, where Nρ represents the additive *internal* noise. Our MLD of −2.0 dB can be used to estimate ρ by consulting the data from Fig. 3 of Robinson and Jeffress (1963). They measured MLDs for So or Sπ 500-Hz tones masked by broadband noise at each of several values of interaural correlation ranging between −1.0 and 1.0. The spectrum level of their masking noise was 50 dB, a level high enough to "swamp out" effects produced by the presumably much lower-level stimulus-independent component of internal noise. Making the empirically sound assumption that Robinson and Jeffress' NoSo thresholds were equivalent to their NπSπ thresholds (see Egan *et al.*, 1969), subtracting their So-based MLDs from their Sπ-based MLDs is equivalent to the subtraction:

$$(\mathrm{NoSo} - \mathrm{N}\rho\mathrm{S}\pi) - (\mathrm{NoSo} - \mathrm{N}\rho\mathrm{So}). \tag{1}$$

This quantity reduces to NρSo−NρSπ where Nρ now represents the *external* masking noise. Making the further assumption that the effective interaural correlation of the masker, rather than its source (be it internal or external) determines the MLD, one can use the data of Robinson and Jeffress (1963) to determine what value of masker interaural correlation yields an MLD of −2.0 dB between So and Sπ thresholds. In order to estimate the interaural correlation of the stimulus-independent, additive internal noise following this logic, fits were made to the MLDs (NoSo−NρSπ and NoSo−NρSo) obtained by Robinson and Jeffress (1963) using the procedure and equations described by van der Heijden and Trahiotis (1997). Subtracting the fitted functions indicated that an interaural correlation of the masker of −0.27 produced an MLD of −2.0. Therefore, taking into account the MLD we measured in the quiet along with reasonable interpretations and generalizations of Robinson and Jeffress' data (1963), the interaural correlation of the internal noise based on our data at 500 Hz is estimated to be −0.27. It seems worth mentioning that estimating the value of the interaural correlation of internal noise at 500 Hz in the same way but by using Lakey's (1976) So versus Sπ MLD of −2.7 dB yields a value of −0.36. That estimate is very similar to the one we derived (−0.27) on the basis of our own data.

Having estimated the interaural correlation of the stimulus-independent internal noise, the next step was to estimate its level. Recall that the data in Fig. 2 indicated that threshold S/Ns increased as the spectrum level of the masker was decreased below 20 dB. This was taken as evidence that reducing the level of the external noise resulted in a greater relative contribution of the stimulus-independent, additive internal noise to the masking of the signal. Recall that the greater relative contribution of such an internal noise to the masking of the signal could come about in two distinct manners. First, adding its negatively-interaurally-correlated power to the diotic external masker would serve to reduce the interaural correlation of the effective masker to a value below 1.0. As shown in Fig. 3, reducing the interaural correlation of a high-level diotic masker results in increases in Sπ thresholds. Second, the addition of the stimulus-independent internal noise would increase masking by increasing the overall level of the effective masker.

In order to estimate the parameters of the stimulus-independent internal noise, an iterative process was employed that simultaneously took into account both its interaural correlation and its level. Specifically, for any particular level of the external masker, say −10 dB, a value of the level of the stimulus-independent internal noise was chosen, say −14 dB. Then, using the estimated value of the interaural correlation of the internal noise (−0.27), the *effective* interaural correlation of the combined stimulus-independent internal and external sources of noise was calculated as the weighted average of the interaural correlations of the two sources, where the weighting represents the proportional power of each source with respect to the total power of the effective masking noise:

$$\rho_{effective} = \frac{P_{\mathrm{int}} * \rho_{\mathrm{int}} + P_{\mathrm{ext}} * \rho_{\mathrm{ext}}}{P_{\mathrm{int}} + P_{\mathrm{ext}}}, \tag{2}$$

where P_{int} and P_{ext} represent the powers of the internal and external noises, respectively, and ρ_{int} and ρ_{ext} represent the interaural correlation of the internal and external noises, respectively.

TABLE I. For each spectrum level of the broadband (100–3000 Hz) diotic external noise masker (columns 1 and 2), the table lists the parameters of the internal noise computed by the analyses (columns 3 and 4). Based on the assumption that the external and internal noises are combined, the last two columns list, respectively, the increase in effective power produced by the addition of the internal noise to the external noise and the effective interaural correlation of the combined external and internal noises. (NM: not measurable.)

External noise spectrum level (dB)	External noise ρ	Internal noise ρ	Internal noise spectrum level (dB)	Added power (dB)	Effective ρ
−10	1.00	−0.27	−13.7	1.5	0.62
0	1.00	−0.27	−10.5	0.4	0.90
10	1.00	−0.27	−7.6	0.1	0.98
20	1.00	−0.27	NM[a]	NM[a]	1.00
30	1.00	−0.27	NM[a]	NM[a]	1.00
40	1.00	−0.27	NM[a]	NM[a]	1.00
50	1.00	−0.27	NM[a]	NM[a]	1.00

[a] NM: not measurable

The value of *effective* interaural correlation ($\rho_{\text{effective}}$) was entered into six independent equations, one equation for each masker/signal duration. Each equation represented the best-fit two-term exponential function relating the threshold S/N to masker interaural correlation for that masker/signal duration (i.e., the data in Fig. 3). The fits were made separately for each duration in order to provide precise interpolation between values of masker correlation used in the experiment and to capture the vertical positioning of the data in the figure. Two-term exponential functions provided excellent fits in that values of r^2 relating the functions and the data were always 0.99 or greater and rms errors were, at most, 0.75 dB being typically about 0.35 dB.

This procedure yielded six estimates of threshold, one for each masker/signal duration. These six estimates of threshold were then increased by the increment in total power that would result from adding the assumed level of internal noise (in this example, −14 dB) to the level of the external noise (in this example, −10 dB). These "revised" estimates of threshold were then compared to the actual thresholds obtained at the level of the external noise under consideration (here, −10 dB). The procedure was repeated making changes to the estimate of the level of the internal noise until the variance accounted for between the predicted and obtained thresholds was maximized.[2] The entire process was carried out separately for each of the seven levels of the masker tested. Under the reasonable assumption that threshold S/N remains constant for a given "effective" masker interaural correlation regardless of the level of the external masker, the seven individual estimates of the level of the stimulus-independent internal would be expected to be constant.

To summarize, the quiet thresholds were used in conjunction with the data of Robinson and Jeffress (1963) to estimate the interaural correlation of the stimulus-independent, additive internal noise. Then, for each spectrum level of the external masker employed (1) a "test" value of the spectrum level of the stimulus-independent additive internal noise was chosen; (2) that test value was used to calculate the "effective" interaural correlation of the combined external and internal noise; (3) that computed effective interaural correlation was used with the data of Fig. 3 to derive "predicted" values of threshold S/N; (4) those "predicted" values of S/N were adjusted to account for the increase in the power that would result from adding the "test" level of internal noise to the external noise; (5) the adjusted predicted values of S/N were compared to the obtained threshold values of S/N in Fig. 2; (6) the procedure was repeated with new "test" values of the spectrum level of internal noise until the amount of variance accounted for in the data of Fig. 2 was maximized.

The left-most two columns of Table I indicate the respective levels of the external noise and its interaural correlation. The third column indicates the interaural correlation of the stimulus-independent internal noise, which was derived from the So and Sπ quiet thresholds. The last three columns contain the results of the iterative procedure described above: estimates of the spectrum level of the stimulus-independent internal noise, estimates of the increase in power resulting from its addition to the external noise, and estimates of the "effective" interaural correlation of combined internal and external noise.

The next two columns show that, while the presence of the stimulus-independent, internal noise would add very little to the level of the external masking noise, it would have a substantial effect on the "effective" interaural correlation of the masker. For example, for an external noise level of −10 dB, the internal noise would add only 1.5 dB to the level of the external masker but would reduce the effective correlation to 0.62. Thus, it seems inescapable that the approximately 10-dB increase in threshold S/N observed when the spectrum level of the masker was reduced from about 20 to −10 dB (see Fig. 2), results almost entirely from the decrease in the effective masker interaural correlation. The several rows in the table containing the entry "NM" indicate cases in which the relative level of the external noise was so high as to preclude measurement of any effects stemming from the addition of the internal noise. Consistent with that, note that the effective interaural correlation of the combined external and internal noises is estimated to be 1.00 for spectrum levels of the external masker ranging from 20 to 50 dB.

Let us focus on the top three rows of the table, cases in which the levels of the external noise were low enough for the stimulus-independent, additive internal noise to be able to exert a measurable influence. Note that the estimates of the level of the stimulus-independent internal noise are not constant. Rather, they increase from −13.7 to −7.6 dB as the level of the external noise increases from −10 to +10 dB. Two possibilities regarding this outcome come to mind. First, it could be the case that the "actual" spectrum level of this component of internal noise is about −10 dB and the increasing estimates result from errors of measurement of the detection thresholds that underlie the analysis. Alternatively, it could be the case that the increasing estimates of the level of the stimulus-independent internal noise are not the result of measurement error. To understand how this could be so, first recall from the analysis in Sec. IV A that the NoSπ thresholds in Fig. 2 obtained at the four highest levels of the external noise appear to be consistent with the notion that the level of the stimulus-dependent component of internal noise increases in a dB-for-dB fashion with the level of the external masker. Such dB-for-dB increases would result in the measurement of constant threshold S/N, independent of the level of the external masker. Now, let us hypothesize that the level of the stimulus-dependent component of internal noise increases with the level of the external masker at a slightly greater rate than dB-for-dB, say, 10.1 dB per 10 dB. Note that this is tantamount to hypothesizing that threshold S/Ns would increase slightly with the level of the external masker. If that were the case, then our iterative procedure, which (1) assumes that threshold S/N is constant for a given effective masker interaural correlation regardless of the level of the external masker and (2) only estimates the level of the stimulus-independent component of internal noise, would err by ascribing small increases above dB-for-dB masking to an increase in the level of the stimulus-independent, additive component of internal noise.

When the relative level of the stimulus-independent component is substantially less than the level of the external masker, even slightly greater than dB-for-dB masking would result in a substantial increase in the estimate of its level. For example, consider the approximately 3 dB increases in the estimates of the level of the stimulus independent internal noise shown in Table I that occur when the level of the external masker was increased by 10 dB. How much masking above dB-for-dB would the stimulus-dependent component have to produce in order for the iterative procedure to (erroneously) assign such 3-dB increases to the stimulus-independent additive component? One can determine this by comparing the increment in power produced by the levels of the stimulus-independent component returned by the iterative procedure to estimates made assuming that the spectrum level of the stimulus-independent component was fixed at −13.7 dB. That is the value derived for an external noise spectrum level of −10 dB. Such calculations were made and revealed that, on average, a rate of masking of the stimulus-dependent component of only about 10.1 dB per 10 dB would yield the observed 3-dB increases in the assumed level of the stimulus-independent component. In fact, Fig. 4 (p. 1042) of Reed and Bilger (1973) shows that monaural thresholds of detection for a 500-Hz signal, increased by approximately 10.15 dB for increases of 10-dB of the spectrum level of the masker. Data obtained by Reed and Bilger with other signal frequencies ranging from 1 to 8 kHz show consistent and even larger increases in growth of masking with increases in the spectrum level of the masker. In our view, this apparent consistency between Reed and Bilger's (1973) findings and our theoretical account is intriguing, but not sufficient for deciding what factor or factors underlie the increasing estimates of the level of the stimulus-independent, additive noise derived from our analysis (Table I). Clearly the effects of interest are very small and very precise measurements would be required to settle the issues.

D. An alternative way to estimate of the level of the stimulus-independent, additive internal noise

One of the reviewers of an earlier version of this report pointed out that the level of the stimulus-independent, additive internal noise could also be estimated by using the Sπ thresholds obtained in the quiet (Fig. 1) in conjunction with the S/Ns measured as a function of the interaural correlation of the masker having a spectrum level of 50 dB (Fig. 3). Following that reviewer's suggestion, we used the six functions fitted to the data in Fig. 3 (described in Sec. IV C) to derive, for each masker/signal duration, the threshold S/N corresponding to a masker interaural correlation of −0.27. That is the value of the interaural correlation that was estimated for the stimulus-independent, additive internal noise. The six values of threshold S/N were used to find the spectrum level of the (internal) noise corresponding to each of the six threshold SPL values obtained when the Sπ signals were presented in the quiet. The average value of the six estimates of the spectrum level of the stimulus-independent additive internal noise was found to be −11.8 dB and the standard deviation of those estimates was 1.3 dB. This estimate of the spectrum level of the additive internal noise is remarkably close to the value of −10.6 dB, which is the average of the estimates shown in Table I, which were obtained using the more complex procedure. It should be stressed that this alternative, simpler procedure for estimating the level of the additive internal noise assumes that threshold S/N are constant, independent of whether the effective masker is the low-level stimulus-independent additive internal noise, higher-level external noise, or both. Said differently, this procedure leaves no room to observe any potential departures from dB-for-dB masking that might call into question the assumption that threshold S/N is constant for a given effective interaural correlation of the masker, independent of the overall level of the masker.

Our inclination is to leave open the question of which of the two methods for estimating the level of the stimulus-independent, additive internal noise is preferable. The more simple method is parsimonious but is constrained by fewer of the empirical thresholds and uses the quiet Sπ thresholds both to estimate the interaural correlation of the additive internal noise and its level. The more complex procedure employs the quiet Sπ thresholds only to estimate the interaural correlation of the additive internal noise and relies on all of the data in Figs. 2 and 3 to derive estimates of the level of the additive internal noise. In our view, the similarity of the estimates of the level of the stimulus-independent, additive internal noise using the two procedures is the important out-

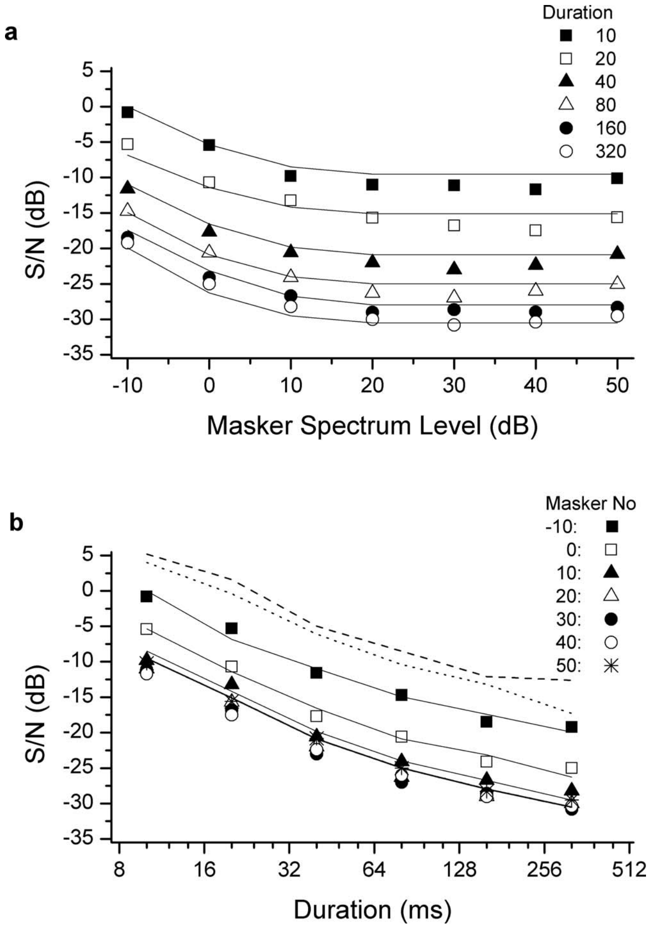

FIG. 5. Panels a and b contain a re-plotting of the data (symbols) depicted in Figs. 2 and 3, respectively. The predictions of the data derived from an iterative computational procedure (see text) are indicated by the solid lines. The parameter of the plot in each panel is the masker/signal duration. The dotted and dashed lines in panel b represent the So and Sπ quiet thresholds, respectively, replotted from Fig. 1.

come because it can stand independently of whether future research verifies the very small departure of dB-for-dB masking that may be inferred from the more complex analysis.

E. Predictions of the NoSπ thresholds

Panel a of Fig. 5 contains a replotting of the thresholds shown in Fig. 2 (symbols). The lines represent predictions of those data obtained via the procedure described above in Secs. IV A–IV C. Visually, the predictions capture quite well the trends in the data; quantitatively, the predictions account for 98% of the variability in the data. Panel b of Fig. 5 displays the same data (symbols) and predictions (solid lines) as those in panel a, but replotted as a function of masker/signal duration with external masker level as the parameter. The dashed and dotted lines will be discussed below.

Panel b more directly illustrates that our quantitative analyses provide an accurate description of how detection thresholds vary as a function of masker/signal duration over a 60-dB range of the level of the external masker. The accuracy of the predictions validates the primary assumption within the iterative procedure used to make the predictions, namely, that both the interaural correlation and the level of the stimulus-independent, additive component of internal noise can be considered to be constant as a function of duration. The validity of this assumption was tested further by employing the same estimation procedure described above separately for data obtained at each masker/signal duration when the spectrum level of the external masker was −10 dB. This yielded six new paired estimates of the interaural correlation and level of the stimulus-independent additive internal noise. Importantly, the deviations between the values of the individual estimates made at each duration and their mean were both unsystematic and small (being on average 0.11 for the estimates of interaural correlation and 0.90 dB for the estimates of spectrum level). This outcome attests to the validity of our primary assumption.

The dotted and dashed lines in panel b of Fig. 5 represent the So and Sπ quiet thresholds, respectively, replotted from Fig. 1. Their absolute vertical positioning is arbitrary but fulfills the purpose of showing that changes in So and Sπ quiet thresholds measured as a function of signal duration, parallel changes in Sπ masked thresholds measured as a function of common masker/signal duration. This suggests that the mechanism(s) mediating improvements in efficiency of detection with duration (e.g., “temporal integration” “multiple looks”) do not interact with the level of the effective masker, be it principally external, principally internal, or a combination of the two.

F. Quiet Sπ thresholds versus low-level noise-masked Sπ thresholds

Recall from Sec. III that McFadden’s (1968) listeners’ thresholds increased in signal-to-noise by approximately 17 dB when the spectrum level of the external masker was reduced from +20 to −10 dB. In contrast, over the same range of masker levels, our thresholds increased by only about 10 dB. In addition, while McFadden’s listeners’ thresholds began to increase once the spectrum level of the masker was below 35 dB, our listeners’ thresholds did not increase until the level of the masker was reduced to below 20 dB.

In an attempt to reconcile these differences, we calculated the signal levels in dB SPL corresponding to the NoSπ thresholds shown in McFadden’s (1968) Fig. 4 and plotted them along with the signal levels in dB SPL corresponding to our NoSπ thresholds obtained at a duration of 320 ms. Despite several differences in detail between the two studies, we found that the levels of the signal required for detection across the two studies were within 2.5 dB of each other for masker spectrum levels of about 15 dB and higher. When the spectrum level of the masker was decreased to values below 15 dB, however, the threshold signal levels calculated from McFadden’s (1968) data decreased much less steeply than did those calculated from our data. For masker spectrum levels of −5 and −15 dB, the SPL of the signal required by McFadden’s (1968) listeners was about 13 and 12 dB, respectively. For masker spectrum levels of 0 and −10 dB, the level of the signal required by our listeners was about 10 and 5 dB SPL, respectively. This 5 dB SPL threshold is within

1 dB of the quiet threshold we measured and equal to the 5 dB SPL quiet threshold reported by McFadden (1968).

Thus, adding an external noise at a spectrum level of −10 dB SPL produced no masking of the Sπ signal for our listeners. This outcome is expected if one assumes a stimulus-independent, additive internal noise having a spectrum level of about −14 dB (consistent with Table I). Adding a diotic external masker with a spectrum level of −10 to such internal noise would increase the power of the effective masker (external plus internal) by about 5 dB. Importantly for binaural detection, however, adding the diotic noise at this level would increase the interaural correlation of the effective masker from its value of −0.27 for internal noise alone to about 0.64. According to the data in Fig. 3, an equivalent change in interaural correlation of a masker would lead to about a 4 dB reduction in the level of the signal required to reach threshold. Thus, the potential 5-dB increase in masking produced by adding the power of the external masker at spectrum level of −10 would be expected to be essentially counteracted by the 4-dB reduction in masking produced by the increase in interaural correlation of the effective masker that it produces. Taking all of this into account, we cannot offer an explanation for the fact that adding an external noise at a spectrum level of −15 dB SPL produced 7 dB of masking for McFadden's (1968) listeners while adding a higher level of external noise (a spectrum level of −10 dB) produced no masking for our listeners.[3]

V. SUMMARY AND CONCLUSIONS

Binaural detection thresholds at 500 Hz were obtained as a joint function of masker/signal duration and external masker level and as a joint function of masker/signal duration and masker interaural correlation. The primary empirical findings were: (1) changes in Sπ thresholds as a function of the level of a diotic masker are independent of (i.e., do not interact with) masker/signal duration; (2) changes in Sπ thresholds as a function of the interaural correlation of the masker also do not interact with masker/signal duration; (3) So and Sπ thresholds measured at 500 Hz in the quiet reveal an MLD of −2.0 (So threshold minus Sπ threshold) that is essentially independent of signal duration; (4) improvements in efficiency of detection with increasing duration are similar regardless of the level of the effective masker be it principally external, principally internal, or a combination of the two. Analyses of the data support the following conclusions: (1) two components of internal noise appear to limit binaural detection: a stimulus-independent, relatively low-level, additive noise that is slightly negatively interaurally correlated and a stimulus-dependent noise having a magnitude that is proportional to the level of the external masker while being independent of masker/signal duration; (2) the stimulus-independent internal noise appears to exert its influence primarily by diluting the effective interaural correlation of the diotic external masker; (3) the patterning of NoSπ thresholds taken as a joint function of masker/signal duration and the spectrum level of the external masker is, quantitatively, well described by taking into account effects produced by the combination of internal and external noises.

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[1] The manner in which the sign and magnitude of the MLD depend upon the frequency of the signal is beyond the scope of this study but is currently under investigation in our laboratory.

[2] The formula used to compute the percentage of the variance for which our predicted values of threshold accounted was $100\times(1-[\Sigma(O_i-P_i)^2]/[\Sigma(O_i-\bar{O})^2])$ where O_i and P_i represent individual observed and predicted values of threshold, respectively, and $\bar{O}$ represents the mean of the observed values of threshold.

[3] The signal levels in dB SPL that we calculated were based on McFadden's (1968) Fig. 4. They are not consistent with the values of SPL McFadden (1968) reported in his Fig. 3. For example, Fig. 4 indicates that with a masker spectrum level of 45 dB, McFadden (1968) measured an NoSπ threshold of about −4 dB, expressed in terms of E/No. That value is consistent with the ones commonly reported for such stimulus conditions (e.g., Egan *et al.*, 1969). By our calculations, given that the duration of the signal was 250 ms, the level of the signal required for detection in that condition would be 47 dB SPL. The value read from Fig. 3, however, is about 41 dB SPL. It appears that all of the values of SPL for the *masked thresholds* in Fig. 3 were calculated based on the E/No values in Fig. 4, but without taking the duration of the signal into account. The quiet thresholds in Fig. 3, which do not appear in Fig. 4, appear to be accurate and are within 1 dB of those measured in our study.

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