INTERAURAL INTENSITY DIFFERENCE LIMEN

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I. The Problem

This study was designed to examine intensity discrimination under *dichotic* intensity conditions. The measure may be termed the *interaural intensity difference limen* (DL $(i)_{int}$). The DL$(i)_{int}$ can be interpreted in two ways—as differential sensitivity and as sound-localization discrimination. As a phenomenon of differential sensitivity, it was investigated as a function of frequency and level. To determine the relation of the dichotic DL$(i)_{int}$ to other measures of intensity discrimination, it was compared with *monotic* (signal to one ear) and *diotic* (identical signal to both ears) conditions, which yield the *monaural intensity difference limen* (DL$(i)_{mon}$) and the *binaural intensity difference limen* (DL$(i)_{bin}$) respectively. As a phenomenon of sound localization, the DL$(i)_{int}$ was studied as a function of two additional variables—interaural phase and apparent azimuth.

The DL$(i)_{int}$ has been studied variously but incompletely. In 1936, Upton[21] examined it as a function of level at one frequency. Later, Mills[12] looked at it as a function of frequency at one level. It has been studied as a function of apparent azimuth at low- and mid-range frequencies.[1,5] But no investigation has systematized the DL$(i)_{int}$ as a function of level, frequency, and apparent azimuth. Also, the diversity of results and methods found in previous DL(i) studies[2,3,8,10,14] suggests the need for an empirical comparison of the DL$(i)_{mon}$, DL$(i)_{bin}$, and DL$(i)_{int}$ using an equivalent method. Finally, for completeness, an interaural phase relation of 180° was included to determine whether phase affects intensity discrimination as it does the perceived image.

Predicted Results

Effect of Level. The DL$(i)_{mon}$ is small and stable at levels well above threshold, but at levels

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slightly above threshold it is much larger[6,13]. It was expected that the DL$(i)_{int}$ would behave similarly.

Effect of Frequency. In sound-field localization studies, (1) phase (or time) cues dominate the low-frequency range, (2) localization ability is poor in the middle range, and (3) actual intensity differences are large in the high-freqency range[11,16]. None of these findings suggests a strong basis for assuming any large variation in intensity discrimination throughout the range. However, Ford's[4] report of better localization at 2000 Hz than at 200 Hz suggests that the effect of frequency on the DL$(i)_{int}$ might resemble the effects reported by Riesz[14] for the DL$(i)_{mon}$. Thus it was suspected that the DL$(i)_{int}$ might be smaller in the mid-range than at lower or higher frequencies.

Effect of Phase. Since usable temporal information from pure-tone signals is restricted to frequencies below 1500 Hz[7,17,18,25], it was predicted that no phase effect would be demonstrated above that frequency. Also, since the dichotic intensity condition in the present study can be assumed to measure a minimum shift in localization from a centered sound image, the dichotic phase condition could increase the size of the DL$(i)_{int}$ at low frequencies.

Apparent Azimuth. Stenger[15], suggesting a test to detect simulated unilateral hearing loss, reported that when tones from two matched tuning forks are presented to a subject with one tone louder (nearer its ear) than the other, the subject does not perceive the softer (farther) fork at all. Therefore, a tone simultaneously presented to both ears suggests a perceived or apparent azimuth related to the intensity difference between ears. Investigating the Stenger effect as a test of malingering, Taylor[19] verified the laterization effect; but the data suggest that, if the intensity of the tone is *gradually* changed at one ear, sophisticated subjects are able to use intensity localization cues to simulate deafness successfully despite the test.
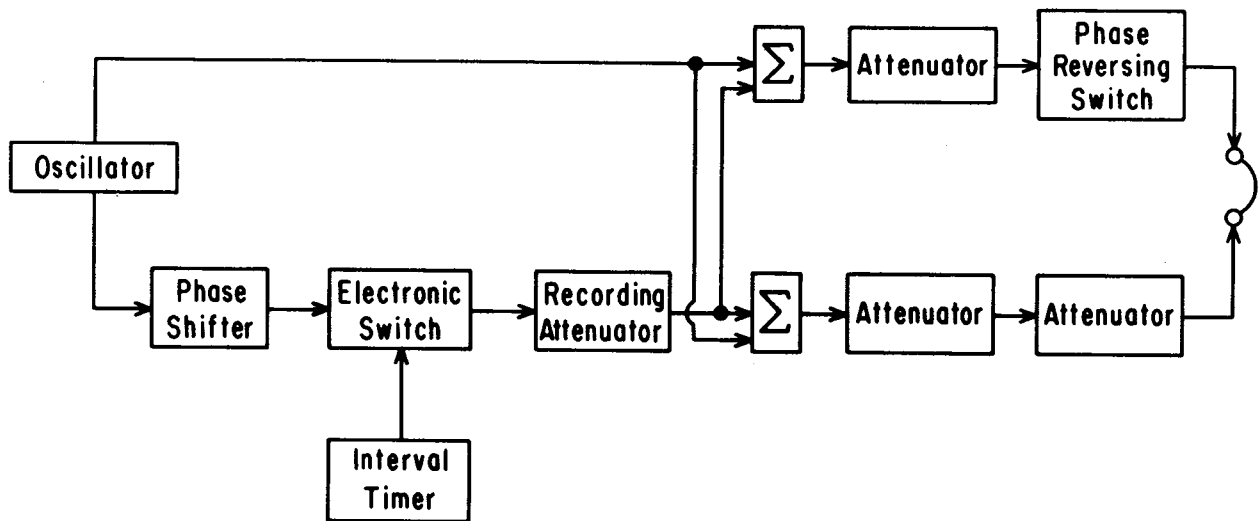
FIGURE 1. Simplified block diagram of apparatus.

In 1935, Gage[5] reported the effect on the $DL(i)_{mon}$ of simultaneously introducing a tone of the same frequency at a different level to the opposite ear. Such a condition satisfies our definition of an apparent-azimuth study of the $DL(i)_{int}$. Using a tone with varying intensity in one ear and the same tone but with constant intensity in the other, Gage found that the $DL(i)_{int}$ is larger when the constant-intensity signal is greater than the varying-intensity signal and smaller when the constant-intensity signal is smaller. In a similar study, Chocholle[1] reported an increase in the size of the $DL(i)_{int}$ with a concurrent increase in the constant signal. Data from the present study were expected to show similar trends.

II. Method

Instrumentation

Figure 1 presents a simplified block diagram of the apparatus used. Three intensity conditions of stimulation—dichotic, diotic, and monotic —were provided.

Each of three test frequencies—250, 2000, and 6000 Hz—was produced by a Hewlett-Packard 201–CR audio oscillator. The tone from the oscillator was split into two channels. One channel was split and fed through two mixers: one part of this split signal was combined with the signal in the opposite channel to become the varying signal and one part remained as the constant signal. This constant signal went next to a Hewlett-Packard 350–D attenuator set, then to a phase-reversing switch, then to one of a matched

pair of Telephonics TDH–39 earphones with NAF 48490–1 cushions. In the other channel, the tone was first fed to a Grason-Stadler E3520B phase shifter, which compensated for unwanted shifts in relative phase between the constant and varying signals. The tone proceeded to a Grason-Stadler electronic switch, model E3382B, which was activated by a Grason-Stadler 471–1 interval timer. The electronic switch was set for a rise-decay time of approximately 50 msec, and the interval times was set to gate the signal in a 0.5 sec on, 0.5 sec off cycle. The gated signal was fed to a Grason-Stadler recording attenuator, E4554A, with a rate-of-change of 1 dB/sec, then to a mixer where it was combined with the tone split from the opposite channel. Alternate half-seconds, the varying signal from the mixer was equal to the constant signal in the opposite channel in frequency, phase, and intensity; then for the other 0.5 sec, the two signals differed in intensity. The varying signal proceeded to a Hewlett-Packard 350–D attenuator. This attenuator and the 350–D attenuator in the constant-signal channel controlled the overall signal levels. A Daven T–326–F attenuator with a 2.0 dB range in 0.1 dB steps was placed between the 350–D attenuator and the remaining TDH–39 earphone to correct for differences in acoustic output between the channels. The earphones were matched for phase with a special coupler: the actual acoustic phase difference was less than 2° for any of the test frequencies.

For the diotic intensity condition, with the varying signal delivered to both earphones, the

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gated signal coming from the recording attenuator and the constant signal from the opposite channel were both fed to both mixers. For the monotic intensity condition, the mixed constant and varying signal was delivered to one earphone, but no signal went to the other.

Stimulus

Range of Intensity. Although previous studies specified the intensities at which discriminations were made in terms of sensation levels[1,12,21], the fact that more parameters were included in the present study dictated a fixed physical reference —hearing level (HL) was chosen. Since the subject population and the conditions of testing were similar to those used for the ISO standard, it was selected as the reference.

Three levels, 20, 35, and 50 dB HL, comprised the *baseline* levels of the experiment. Apparent azimuth and $\triangle I$ the intensity increment) were calculated from these baseline levels.

Range of Frequency. Three frequencies were selected to represent the low, middle, and high portions of the human auditory range: 250, 2000, and 6000 Hz.

Apparent Azimuth. The $DL(i)_{int}$ was examined for situations in which the reference portion of the duty cycle appeared to be off center and for situations in which the varying signal was either more or less intense than the constant signal. The constant signal was presented at 20, 25, 30, 35, 40, 45, and 50 dB HL. With the varying signal to one ear at a baseline of 20 dB HL, the range of the constant signal presented to the contralateral ear provided differences between the two signals from 0 to +30 dB. With the varying signal at a baseline of 35 dB HL, the differencse ranged from −15 to +15 dB, and with the varying signal at a baseline of 50 dB HL, the range of differences was from −30 to 0 dB.

Phase. All signals in the dichotic and diotic intensity conditions were presented at both 0° and 180° interaural phase.

Subjects

The subjects were five men between the ages of 18 and 27. None had a history of ear pathology and all had an air-conduction threshold of 15 dB HL (ISO) or better between 250 and 8000 Hz.

Procedure

Subjects were instructed to listen for rhythmic changes in a steady tone. They were told that the changes might sound like fluctuations in loudness or changes in the position of the sound. They indicated when they heard the fluctuations by pressing a switch; they released the switch when the signal grew steady again. Each subject received an initial practice period of at least 2 hours and was given a 15-min practice period before each session.

Air-conduction thresholds were obtained before each session. If the 15–dB HL criterion was exceeded, the subject was rescheduled.

Ninety-six random presentations at one frequency constituted one set of trials. The monotic trials were presented randomly to the left and to the right ear. The dichotic trials were presented randomly with the varying signal in the left ear and the constant signal in the right, and with the varying signal in the right ear and the constant signal in the left. Each set was presented on two occasions of each frequency, making a total of 576 trials per subject.

Response

The subject's response was observed, via the tracing of the recording attenuator, until the tracing was stable for 4 maximum and 4 minimum excursions. This procedure provided approximately 4600 data points per subject. Stimulation was not continued for more than 3 min per task.

The arithmetic mean of the 4 maximum and 4 minimum scores provided the average decibel difference between the gated and steady tones that made up the varying signal. This number was then converted to $\triangle I$ in decibels with the help of the table provided by Tobias.[20]

III. Result

Data

A t test was performed on the paired data (left ear—right ear) for the monotic condition, and another t test was performed on the paired data for the dichotic condition. No significant differences were found. A t test was used to compare the two complete samples of data for all subjects. No significant differences were found between the replications. Therefore, the scores presented in the tables (and the data points in the graphs) are averaged for ears and for replications as well as for subjects. Four analyses of variance were run.
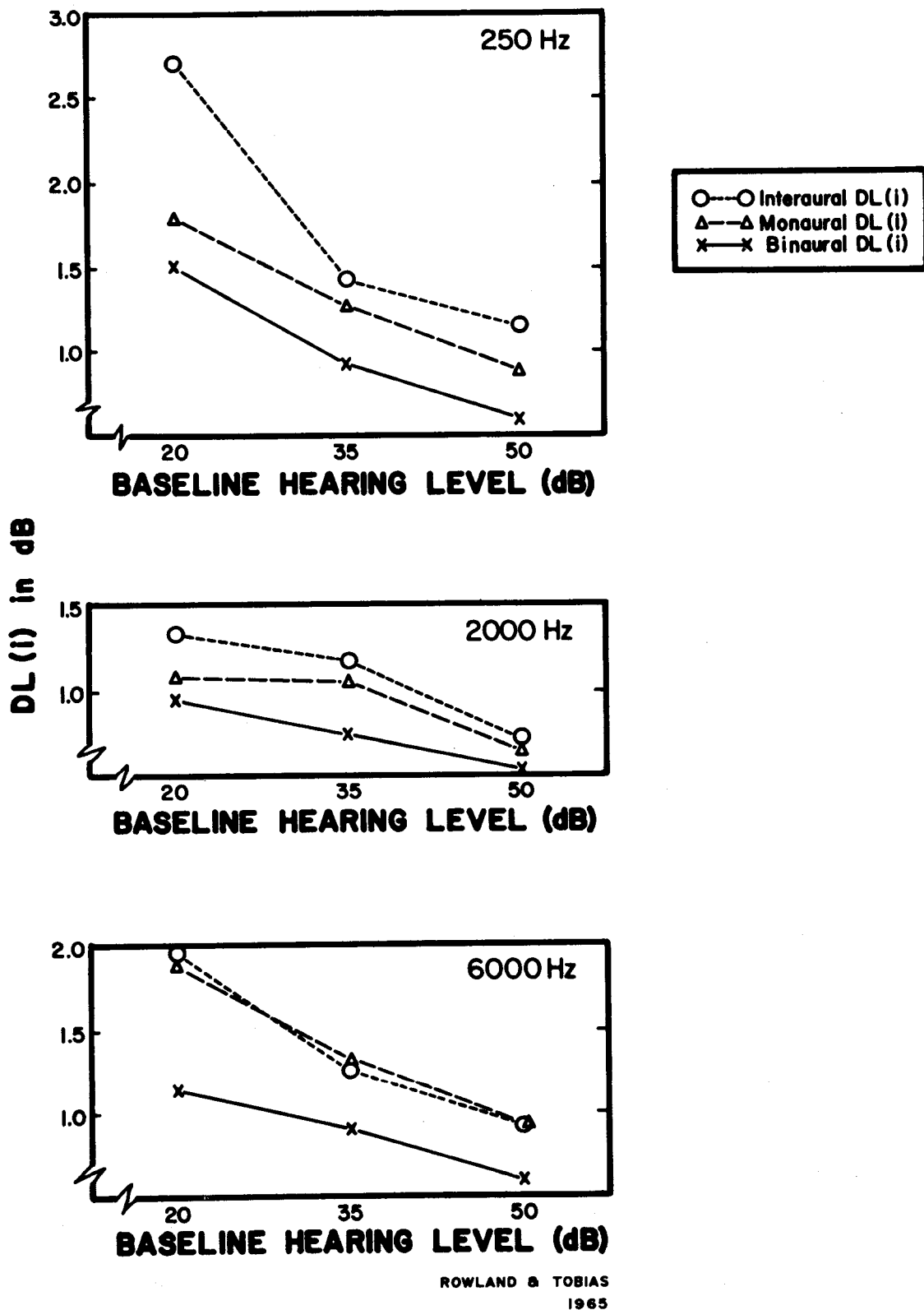
FIGURE 2. Comparison of the monaural, binaural, and interaural DL(i) as a function of hearing level and frequency.

Comparison of the Intensity Difference Limens

Effect of Condition. Table 1 and Fig. 2 show that the values obtained under dichotic conditions are larger than those of the monotic condition except for 6000 Hz at 35 dB HL. The diotic $DL(i)$ is consistently the smallest. Differences between conditions are significant ($p<.01$).

TABLE 1. Mean $DL(i)$ values (in dB) for 3 stimulus conditions at 3 levels and at 3 frequencies

Frequency (Hz)	Hearing Level (dB)	Condition		
		Dichotic	Monotic	Diotic
	20	2.70	1.80	1.51
250	35	1.44	1.28	0.93
	50	1.15	0.88	0.60
	20	1.33	1.08	0.95
2000	35	1.17	1.06	0.75
	50	0.72	0.65	0.53
	20	1.95	1.88	1.14
6000	35	1.25	1.32	0.90
	50	0.92	0.93	0.60

Effect of Level. The largest scores are obtained at the lowest level (20 dB HL); the smallest are at the highest level (50 dB HL) (Fig. 2). This tendency of the $DL(i)$ to decrease with an increase in level is significant ($p<.01$).

Effect of Frequency. The values in Table 1 and the curves in Fig. 2 show the $DL(i)$ to be smaller at 2000 Hz than at 250 and 6000 Hz. The level of significance of the main effect for frequency did not support this trend ($p<.10$). However, the interaction of condition and frequency suggested an effect related to condition ($p<.05$). A separate analysis of the simple main effects for frequency[24] produced the following levels of significance for each condition: dichotic ($p<.01$), monotic ($p<.01$), and diotic ($p<.05$).

Phase

Significant phase effects ($p<.05$) were obtained for only one group of tasks—the 20 dB baseline data for apparent azimuth. Predictably, the analysis of simple effects of phase for each frequency (see the first graph of Fig. 2) shows the effect to be limited to 250 Hz ($p<.01$). The $DL(i)_{int}$ obtained under a condition of 180° interaural phase relation is smaller than the $DL(i)_{int}$ obtained under a 0° interaural phase condition when the constant signal and varying signal are presented at the same level. However,

as the constant signal is increased relative to the varying signal, the $DL(i)_{int}$ for 180° interaural phase increases in size until it is equal to the $DL(i)_{int}$ for 0° interaural phase, when the constant and varying signals are 30 dB apart.
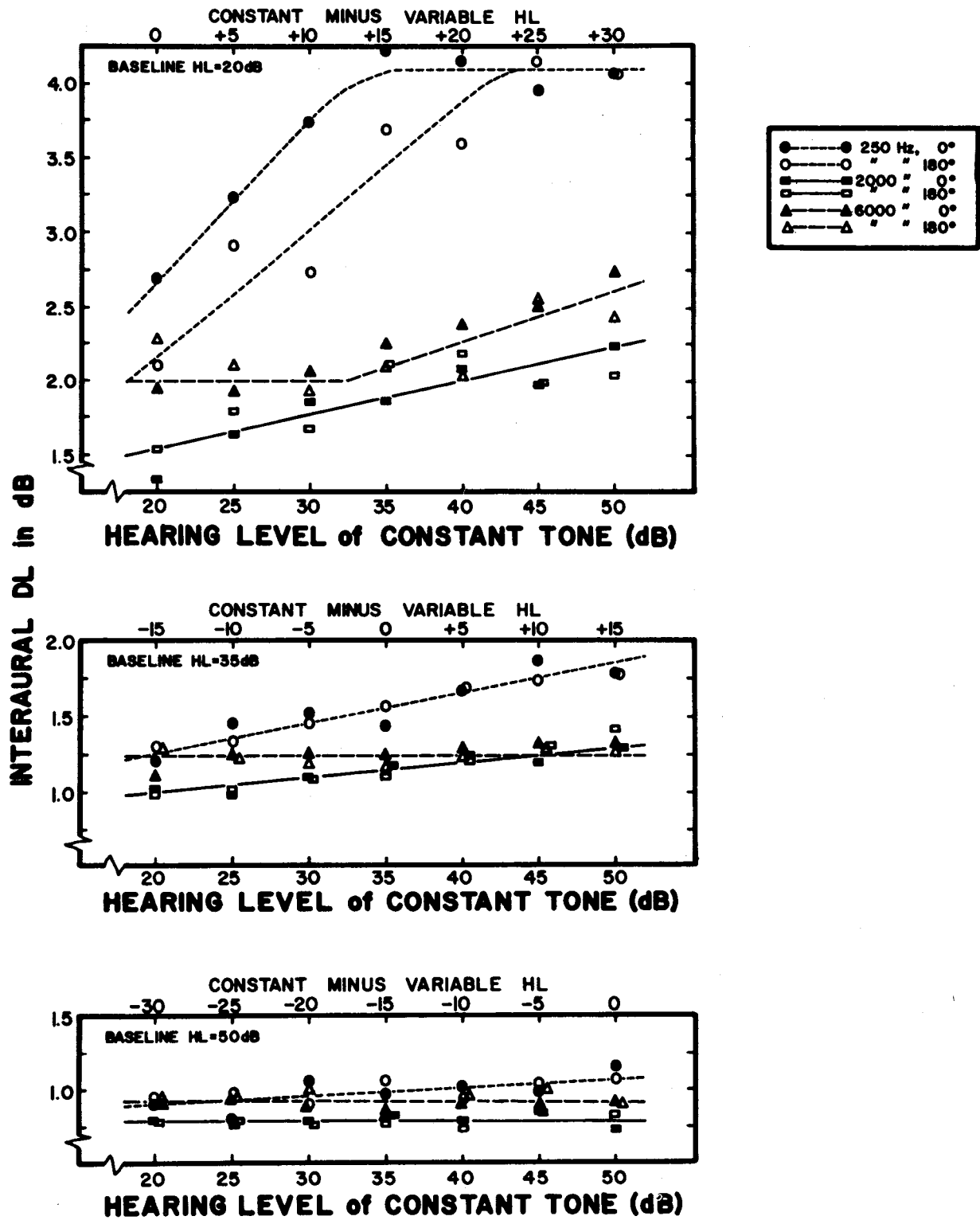
Apparent Azimuth

Baseline of 20 dB HL. The results for 20–dB baseline portion of the study are presented in Table 2; graphic representation of the results for all 3 baseline levels is found in Fig. 3. As the intensity of the constant signal is increased relative to the variable signal, the size of the $DL(i)_{int}$ increases. The function becomes asymptotic for 250 Hz when the difference reaches 15 dB. The method of moving averages produces a rather smooth curve for the line representing 250 Hz. However, an inspection of the data points shows a peak when the difference is 15 dB, followed by a slight decline. This "ripple" in the data, although less exaggerated, is like the ones reported by Gage.[5] The effect is least at 6000 Hz. The differences for the effect of difference level (apparent azimuth) are significant ($p<.01$).

TABLE 2. Mean $DL(i)_{int}$ values (in db) for decibel differences between the constant and variable (20–db baseline) intensities for 3 frequencies (250, 2000, and 6000 Hz) and for 2 interaural phase conditions (0° and 180°)

Difference Decibel	Phase	Frequency		
		250 Hz	2000 Hz	6000 Hz
0	0°	2.70	1.33	1.95
	180°	2.10	1.54	2.28
+5	0°	3.23	1.64	1.93
	180°	2.92	1.79	2.11
+10	0°	3.73	1.85	2.07
	180°	2.74	1.66	1.94
+15	0°	4.23	1.86	2.25
	180°	3.69	2.11	2.10
+20	0°	4.15	2.08	2.38
	180°	3.59	2.18	2.04
+25	0°	3.95	1.96	2.31
	180°	4.15	1.99	2.56
+30	0°	4.07	2.23	2.73
	180°	4.06	2.03	2.44

Baseline of 35 db HL. The results for the 35–dB baseline portion of the study are presented in

CONSTANT MINUS VARIABLE HL

BASELINE HL=20dB

BASELINE HL=35dB

BASELINE HL=50dB

INTERAURAL DL in dB

HEARING LEVEL of CONSTANT TONE (dB)

250 Hz, 0°
" " 180°
2000 " 0°
" " 180°
6000 " 0°
" " 180°

FIGURE 3. The interaural (DL(i) as a function of phase, frequency, and apparent azimuth.

Table 3. The second graph of Fig. 3 shows that, as the constant signal is increased from -15 dB to $+15$ dB relative to the varying signal, the size of the DL$(i)_{int}$ increases most at 250 Hz and least at 6000 Hz. Of all the variables, only the overall effect of difference level is significant $(p < .01)$.

TABLE 3. Mean DL$(i)_{int}$ values (in dB) for decibel differences between the constant and variable (35-dB baseline) intensities for 3 frequencies (250, 2000, and 6000 Hz) and for 2 interaural phase conditions (0° and 180°)

Difference Decibel	Phase	Frequency		
		250 Hz	2000 Hz	6000 Hz
-15	0°	1.25	1.02	1.11
	180°	1.30	0.98	1.29
-10	0°	1.45	0.99	1.25
	180°	1.33	1.01	1.22
-5	0°	1.51	1.10	1.26
	180°	1.45	1.08	1.18
0	0°	1.44	1.17	1.25
	180°	1.56	1.10	1.17
$+5$	0°	1.66	1.24	1.28
	180°	1.69	1.20	1.23
$+10$	0°	1.86	1.19	1.32
	180°	1.73	1.30	1.27
$+15$	0°	1.78	1.29	1.32
	180°	1.78	1.41	1.26

Base line of 50 dB HL. The results for the 50-dB baseline portion of the study are presented in Table 4. The data in Table 4 and the third graph of Fig. 3 (for the 50-dB baseline) show a very slight change in size of the DL$(i)_{int}$ as the constant signal increases relative to the varying signal. This change is not significant. No significant effects were demonstrated for the other variables.

IV. Discussion

The major conclusion to be drawn from these experiments is that intensity discrimination under dichotic conditions differs sufficiently from discrimination under monotic and diotic conditions to warrant its differentiation as the *interaural intensity difference limen.* Had the DL$(i)_{mon}$ and the DL$(i)_{bin}$, Gage's[5] and Cho-cholle's[1] earlier descriptions of it as simply a DL$(i)_{mon}$ in the presence of a contralateral sound of equal frequency would have seemed more

TABLE 4. Mean DL$(i)_{int}$ values (in dB) for decibel differences between the constant and variable (50-dB baseline) intensities for three frequencies (250, 2000, and 6000 Hz) and for 2 interaural phase conditions (0° and 180°)

Decibel Difference	Phase	Frequency		
		250 Hz	2000 Hz	6000 Hz
-30	0°	0.90	0.79	0.91
	180°	0.95	0.78	0.94
-25	0°	0.80	0.76	0.94
	180°	0.98	0.79	0.94
-20	0°	1.06	0.78	0.89
	180°	0.90	0.78	1.00
-15	0°	0.97	0.82	0.82
	180°	1.07	0.77	0.86
-10	0°	1.01	0.78	0.91
	180°	0.94	0.73	0.96
-5	0°	0.98	0.85	0.91
	180°	1.04	0.84	1.00
0	0°	1.15	0.72	0.92
	180°	1.06	0.83	0.90

logical. However, the difference between the DL$(i)_{int}$ and the DL$(i)_{mon}$ at 250 Hz, and their eventual equivalence at 6000 Hz, indicate an independent nature.

The differential response to frequency is what might be expected of a system that need not depend upon intensity differences alone for localization cues at lower frequencies.

Although the previous reports of Churcher, King, and Davies[2] and of Upton and Holway[22, 23] show that intensity discrimination under diotic conditions is superior to discrimination under monotic conditions, our finding that this difference is significant is worth noting. Figure 4 provides a comparison of the present study's 250-Hz data with the data for 800 Hz from Churcher, King, and Davies.

The prediction that the DL$(i)_{int}$ would decrease as overall level was increased is clearly demonstrated by the data. The predicted "leveling off" effect of the increasing intensity is less definite, but the tendency is there.

The predicted increases in the DL$(i)_{int}$ with relative increases in the constant signal were verified. Our data are similar to Gage's[5] and Cho-

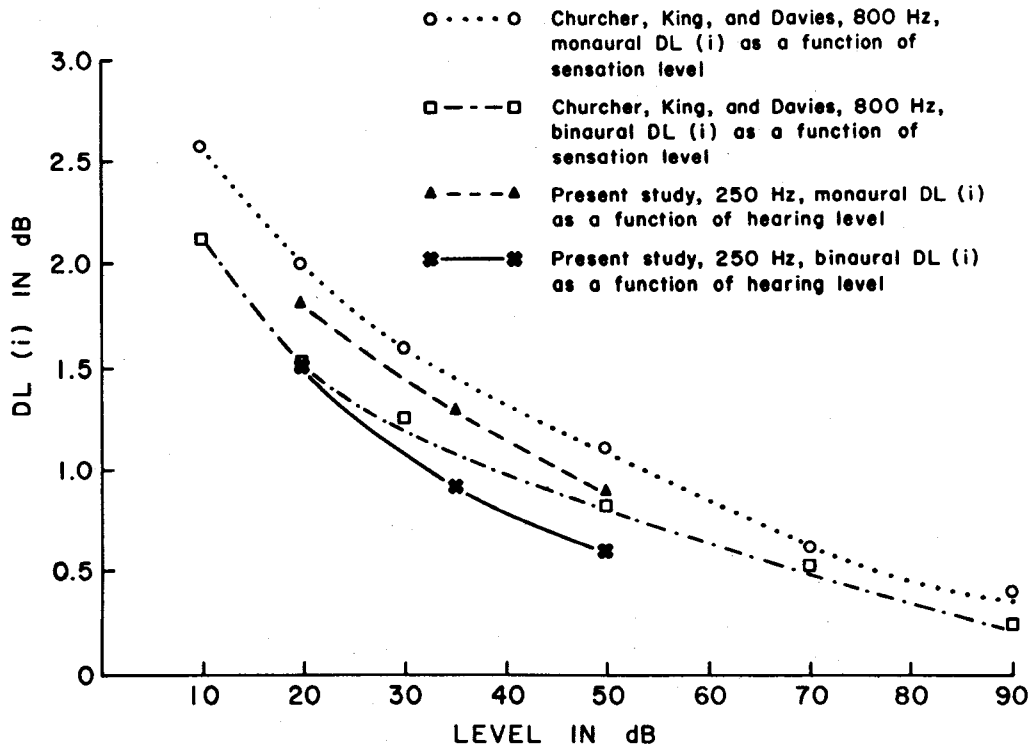FIGURE 4. Comparison of monaural and binaural DL (i) of present study with monaural and binaural DL(i) from Churcher, King, and Davies[2].
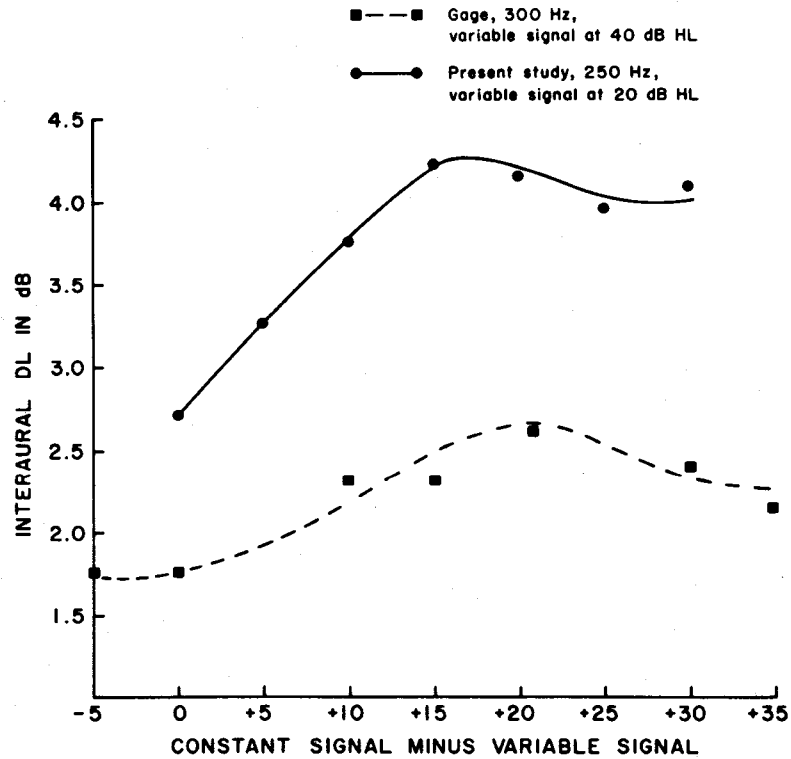

FIGURE 5. Comparison of low-frequency interaural DL(i) of present study with low-frequency interaural DL(i) from Gage[5]

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cholle's[1] (Figs. 5 and 6), even including Gage's "ripple" at the low frequency.

Phase effects were not found at the two higher frequencies, just as was predicted. The assumption that phase might have more effect on a locali- zation task such as the $DL(i)_{int}$ than on a non- localization binaural task such as the $DL(i)_{bin}$ is reflected in the data. The decrease in the $DL(i)_{int}$ for the 180° interaural phase relation is the reverse of the prediction.
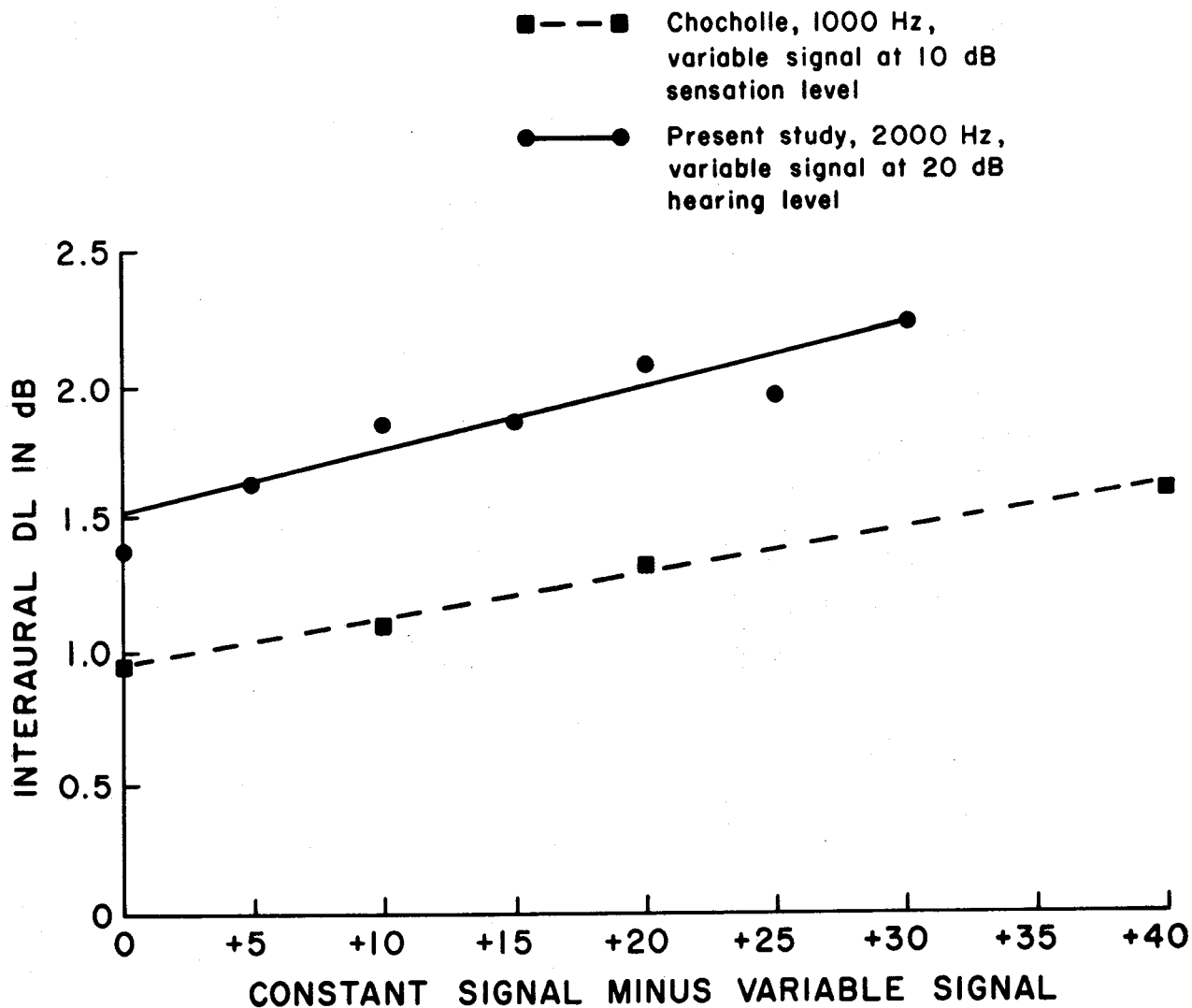

FIGURE 6. Comparison of mid-frequency interaural DL(i) of present study with interaural DL(i) from Chocholle[1].

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