Weber's fraction for the intensity of pure tones presented binaurally*

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The Weber fraction, $(I + \Delta I)/I$, was measured for pure tones which were presented either homophasically or antiphasically. For both stimuli, the Weber fraction was measured as a function of changes in the level of the standard tone and in the phase angle of addition between a test tone and the standard tone. The value, ΔI , in the Weber fraction was defined as that difference between the level of the test-plus-standard and the level of the standard (I) which was required for the listener to discriminate a difference between the standard and the test-plus-standard. In the homophasic case, the Weber fraction remained constant for changes in the phase angle of addition, whereas in the antiphasic condition, the Weber fraction decreased for increasing values of the phase angle of addition. For both the homophasic and antiphasic conditions and at all values of the phase angle of addition, the Weber fraction remained a constant as the value of the standard was varied. These results are in agreement with those obtained in studies involving noise masking, lateralization, and the monaural Weber fraction.

The classical data of Knudsen (1923) and Riesz (1928) have generally been accepted as indicating the form of the Weber fraction, $(I + \Delta I)/I$, for the intensity of pure tones. Tones presented monaurally above a sensation level (SL) of approximately 40 dB lead to a nearly constant Weber fraction of 0.8 dB.

In recent years, some investigators have been studying pure-tone intensity discrimination for binaural listening conditions. Jeffress et al (1956), Wightman (1969), Hafer and Carrier (1970), and Robinson and Yost (1970) have reported that pure-tone intensity discrimination for dichotic conditions is different from that for diotic ones. In these investigations, a test tone was added to a standard tone. In the antiphasic case (S_π), the test was added to the standard at one ear but subtracted (added at 180 deg) at the other ear, whereas in the homophasic case (S_0), the test was added to the standard identically at both ears. In both cases, the standard and the test were of the same frequency, duration, and rise-decay time. Figures 1a and 1b depict the vector diagrams representing these two conditions. The amplitudes of the standard, test, and resultant waveforms are represented by I , I_T , and R , respectively. The angle, α , is the phase angle of addition between

the standard and the test; θ is the interaural phase angle.

Two terms $[(I + \Delta I)/I]$ and I_T/I have been used to describe an O's ability to discriminate between presentations of the test-plus-standard and presentations of the standard, where $\Delta I = R - I$. In Fig. 1, the values of I , I_T , and R are in terms of pressure; thus, so is ΔI . The value, I_T/I , is equivalent to a signal-to-masker ratio, where I_T is the amplitude of the signal and I , the amplitude of the

masker. The signal-to-masker notation was used by the investigators who studied pure-tone intensity discrimination for binaural listening conditions. The level of the standard was not varied in their studies, but it will be varied in this investigation. Thus, this paradigm is closely aligned to the study of the Weber fraction. From the time of Riesz (1928), the value of $(I + \Delta I)/I$ which is required for detection has been used as the Weber fraction. Therefore, the value of $(I + \Delta I)/I$ required for detection will be the dependent variable in this experiment.

In the S_π condition (Fig. 1b), there may be an interaural amplitude difference ($R_L - R_R$), an interaural phase or temporal difference (θ or $\theta/2\pi f$, where f is the frequency of the tone), or both, depending on the phase angle of addition. In the S_0 condition (Fig. 1a), however, there are no interaural differences in the waveforms arriving at the ears. Since no interaural differences are present in the S_0 condition, discrimination is assumed to be based on the monaural intensive difference between the test-plus-standard and the standard. The monaural intensive difference is ΔI . Thus, in the S_0 condition, the Weber fraction, $(I + \Delta I)/I$, should remain a constant as a function of changes in the phase angle of addition. Also, the Weber fraction should remain at about 0.8 dB when the level

Fig. 1. The vector diagrams for the S_0 condition (Panel A) and the S_π condition (Panel B). The resultant amplitude (R) is a function of the amplitudes of the standard (I) and the test (I_T) and on the phase angle of addition (α). θ is the interaural phase angle present in the S_π condition.

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Fig. 2. The Weber fraction $(I + \Delta I)/I$ in decibels is shown as a function of α . Both the S_π and S_0 conditions are shown. The data are averaged over all six Os and the levels of the standard.

of the standard is changed, as the data of Riesz (1928) and Knudsen (1923) indicate. In the S_π condition, however, since there may be interactions between the monaural intensive cue, the interaural cues, and the intensity of the standard, neither the relationship between $(I + \Delta I)$ and α nor that between $(I + \Delta I)$ and I is easy to predict.

The data from earlier investigations showed that for a constant level of performance, $(I + \Delta I)$ remained constant in the S_0 condition when α was changed. However, in the S_π condition $(I + \Delta I)$ decreased for increases in α over the range of 0 to 90 deg. This difference in the Weber fraction for the S_π and S_0 conditions was interpreted as indicating that the interaural differences were being used as cues for detection in the S_π condition (Jeffress et al, 1956; Hafter & Carrier, 1970; Robinson & Yost, 1970). In these studies, the level of the standard was not varied, so that the constancy of $(I + \Delta I)/I$ was not tested.

This paper is concerned with measuring the Weber fraction when either the phase angle of addition or the level of the standard is varied. These relationships are studied for both the S_π and S_0 conditions. For this study, moderately high values of I (64, 70, 76 SPL) were chosen. Lower values were not used so that the problems of masking due to low-frequency internal noise could be avoided (Dolan & Robinson, 1967). The upper range was not extended so that auditory fatigue would not influence the results.

PROCEDURE

All data were obtained by using a two-alternative, temporal forced-choice (2ATFC) paradigm. The trial sequence consisted of a 512-msec

warning period, a 512-msec pause, a 150-msec observation interval, a 512-msec pause, a second 150-msec observation interval, a 1.536-sec response interval, and a 512-msec feedback interval. The warning period was marked for the listener by a light, and feedback lights indicated to the listener which interval contained the standard-plus-test. No lights marked the observation intervals.

During each 150-msec observation interval, a 128-msec 250-Hz standard tone was gated (a Grason-Stadler electronic switch, Model 829) with a 10-msec rise and decay time. The standard was presented in phase at the ears with an intensity of 64, 70, or 76 dB SPL. During one of the two observation intervals, a test signal of the same frequency, duration, and rise-decay time was added to the standard at one of the phase angles of addition (α): 0, 45, 90 deg. A Grason-Stadler phase shifter, Model E3520B, was used for this purpose. The standard-plus-test was presented either in the S_0 or in the S_π configuration (Fig. 1). The probability that the test was added to the standard in the first observation interval was equal to that for the second interval.

Six listeners (four females, two males) with clinically normal hearing participated in the experiment. They worked for approximately 1 h per day for 30 days. Each day consisted of one experimental session beginning with a 20-trial practice block in which the signal was elevated by 2 dB over the level used in the following block. After the practice block, four 80-trial blocks were run and then a 10-min rest period was given. The session ended with four 80-trial blocks. During each 80-trial block the intensity of the test remained the same. On any one day, the intensity of the standard, the phase angle of addition, and the interaural condition were held constant. Two levels of the test stimulus, separated by 4 dB, were used for each combination of interaural condition, phase angle of addition, and level of the standard. A minimum of 320 trials were run for each stimulus combination. For each level tested, a percent correct, $P(C)$, was obtained from the equation:

$$P(C) = [P(1 | I) + P(2 | II)]/2,$$

where $P(1 | I)$ is the proportion of times per 80-trial block the O correctly detected the test-plus-standard in the first interval. $P(2 | II)$ is the proportion of correct detections in the second interval. Two points on the psychometric function were thus obtained for each stimulus combination presented in the experiment.

Fig. 3. The Weber fraction $(I + \Delta I)/I$ in decibels is shown as a function of α . Both the S_π and S_0 conditions are shown. The data are averaged over the two Os who listened to the $\alpha = 45$ deg conditions and the levels of the standard.

All six Os listened to the S_0 and S_π conditions when the phase angle of addition was 0 and 90 deg. Two of these Os also listened to the S_0 and S_π conditions when the phase angle of addition was 45 deg.

During training on each interaural condition, the Os were told to use the feedback lights to help them learn to make decisions. For the S_0 conditions, they were instructed that their task would perhaps be to determine in which of the two intervals the tone sounded "louder." In the S_π conditions, they were told that their task could be to decide in which interval the tone sounded "off-center." In all S_π conditions, the ear which led in phase and had the greater amplitude was the right ear.

All phase angles were measured at the electrical inputs to the TDH-39 headphones. Interaural phase relations were measured by observing the Lissajous figure produced on an oscilloscope. Phase angles of addition were calibrated by measuring voltage changes at the headphones when the test was added to the standard.

For each O and for all conditions, a psychometric function of the form $d' = m(I_T/I)^k$ (Egan et al, 1969) was fitted to the two-point psychometric function obtained from data. In the equation, d' is a criterion-free measure of the O's performance and m and k are constants. The values of m and k leading to the best-fits were used to compute the values of $20 \log (I + \Delta I)/I$ required for $P(C)$ s of 90%, 75%, and 60%.

RESULTS AND DISCUSSION

The data are plotted in Figs. 2 and 3 as the Weber fraction vs the phase

Fig. 4. The Weber fraction $(I + \Delta I)/I$ in decibels is shown as a function of the level of the standard. The data for the S_0 condition were averaged over the values of α . These are the average data for all six Os.

angle of addition. Figure 2 represents the average data for the six Os who listened to the S_0 and S_π conditions when $\alpha = 0$ and 90 deg. Figure 3 shows the average data for the Os who also listened to the $\alpha = 45$ deg conditions. The data are averaged over Os and the three levels of the standard. These data show that the Weber fraction is independent of the phase angle of addition in the S_0 condition, but that it decreases in the S_π condition as the phase angle increases. These findings agree with those of Jeffress et al, Robinson and Yost, and the average data of Hafter and Carrier.¹

The data of Figs. 4 and 5 indicate that in Figs. 2 and 3, the averaging of the Weber fraction over levels of the masker was appropriate. That is, for each phase angle of addition and each binaural condition (S_0 and S_π), the Weber fraction remains a constant for the 12-dB change in the level of the standard. Since the Weber fraction in the S_0 condition was independent of the phase angle of addition, the data in Figs. 4 and 5 for the S_0 condition were averaged over the phase angle of addition. In this case, the Weber fraction stayed at 0.7 dB over the 12-dB range of I . This finding agrees very well with the value obtained by Knudsen and by Riesz. The Weber fraction for the S_π condition is shown for each value of the phase angle of addition.

Plots for the values of $20 \log (I + \Delta I)/I$ required for $P(C)$ s of 90% and 60% were compared to the plot of those values required for 75%. Since the forms of these three figures were similar, only the plots for a $P(C)$ of 75% are shown. In addition, the differences among the six Os were small. The Os varied slightly in their

absolute sensitivities, but the forms of the functions did not change over Os.

Therefore, the data from all four figures show that the Weber fraction is smaller in the S_π condition than in the S_0 condition, but in both conditions the Weber fraction remains constant for changes in the level of the standard.

The procedure for determining the Weber fraction, as described in this study, is similar to other experimental paradigms. Since the standard and test tones may be viewed as maskers and signals, the S_π condition is similar to the $No-S_\pi$ conditions studied in investigations of masking level differences (MLD, see Green & Henning, 1969). Dolan (1968) and McFadden (1968) studied the effect of masker level on the MLD when a tonal signal was masked by a wide-band Gaussian noise. The interaural configuration used in their studies was similar to the S_π condition described in this paper. Both investigators found that above a noise spectrum level of approximately 50 dB SPL, the signal-to-masker ratio remains constant in the S_π condition as the level of the masker is varied. Since a constant signal-to-masker ratio (I_T/I) is equivalent to a constant Weber fraction, the data involving noise maskers compares favorably with the data using tonal maskers.

The S_π condition is similar to a lateralization procedure as well. That is, the difference between the standard and the test-plus-standard may be discussed in terms of interaural differences. These interaural differences may result in the standard being lateralized in one place and the test-plus-standard in another. In fact, all Os reported using just such a shift in the lateral position in order to detect a difference between the standard and the test-plus-standard. The interaural temporal or intensive difference present in the test-plus-standard stimulus when O is performing at 75% in the 2ATFC task can be used as a measure of the interaural "just-noticeable shifts" (jns). An estimate of the jns for interaural intensity is obtained by computing the difference between R_L and R_R for the S_π condition at $\alpha = 0$ deg, when $P(C)$ equals 75%, since for $\alpha = 0$ deg, only an interaural intensive difference is present. At $\alpha = 90$ deg, the interaural angle, θ , is used to compute the interaural temporal jns, since, at $\alpha = 90$ deg there is only an interaural phase or time difference.

The interaural intensive jns averaged about 1.0 dB in this study, whereas the interaural temporal jns was about 70 microsec. Interaural intensive jns's of approximately 1 dB have been

Fig. 5. The Weber fraction $(I + \Delta I)/I$ in decibels is shown as a function of the level of the standard. The data for the S_0 condition were averaged over the values of α . These are the average data from the two Os who listened to the $\alpha = 45$ deg conditions.

found by many investigators (Hershkowitz & Durlach, 1969; Zwislocki & Feldman, 1956; Elfner & Perrott, 1967). The interaural temporal jns for low-frequency tones has been found to be between 12 and 25 microsec (Hershkowitz & Durlach, 1969; Mills, 1958; Klumpp & Eady, 1956). Hafter and Carrier (1970) have indicated that long-term practice factors are present for the $\alpha = 90$ deg condition. The interaural jns for the Os of this experiment might have been smaller if more time for practice had been given, but since the difference between 75 and 25 microsec for a 250-Hz tone is equivalent to approximately 4 deg, the discrepancy between the findings of this study and those of other investigators is relatively small.

There is agreement between the Weber fraction and lateralization procedures not only in terms of the magnitude of the jns's, but also in terms of the changes in the jns's as a function of changes in the level of the stimulus. Zwislocki and Feldman (1951) as well as Hershkowitz and Durlach (1969) found that for low-frequency tones, the jns for interaural time was independent of the level of the tones when the level was about 30 dB SL. Elfner and Perrott (1967) and Hershkowitz and Durlach (1969) reported that the jns for interaural time also remained nearly a constant for changes in the level of the stimulus.

In the present study, the Weber fraction for the S_π condition did not change as the level of the standard was varied. This is equivalent to stating

that the interaural differences did not vary as the level of the stimulus was changed. Therefore, excellent agreement exists between the results of this study and those of lateralization investigations.

So far, the discussion has been about conditions involving only one or the other of the two interaural differences. At $\alpha = 45$ deg in the $S\pi$ condition, there is both an interaural intensive difference ($R_L - R_R > 0$) and an interaural temporal difference ($\theta/2\pi f > 0$). For this condition, the ear which has the greater amplitude also leads in time. Therefore, both interaural differences agree, in that they both indicate that the lateral image is toward the same ear. In most lateralization studies involving a combination of the two interaural differences, the two differences are placed in opposition. In these studies, the lateral image is shifted from midline with an interaural intensive difference, and the O brings the image back to center by adjusting the interaural temporal difference. When the image is back to the midline, the ear which has the greater amplitude lags in time. The ratio of the interaural temporal difference to the interaural intensive difference is called "the trading ratio," expressed in microseconds per decibel. Deatherage and Hirsh (1959) and David, Guttman, and Van Bergeijk (1959) found that the trading ratio changed as a function of changes in intensity. Since the Weber fraction does not change in the $S\pi$ condition, the trading ratio, when computed for this study, does not change with varying intensity. In addition, the trading ratio obtained in this study was about 90-140 microsec/dB, which is much larger than the ratio normally found for low-frequency pure tones (Shaxby & Gage, 1932). In terms of the trading ratio, there is little agreement between the results obtained from lateralization studies and those involving the Weber fraction.

However, since the two interaural differences are in opposition in the lateralization studies but in agreement in this study, a comparison between the two procedures may not be appropriate. That is, the interaural differences of time and intensity may operate differently when they are in

opposition than when they are not. Hafter and Carrier (1970) found that this was, indeed, the case for the $S\pi$ condition. At $\alpha = 135$ deg the two differences are in opposition. Hafter and Carrier reported that the Weber fraction was much greater for the $\alpha = 135$ deg condition than for the $\alpha = 45$ deg condition. The data obtained in this study, when compared to data from "trading ratio studies," can also be interpreted as indicating that the two interaural cues operate differently in opposition than in agreement.

The data from three different paradigms investigating binaural processing are in good agreement. Hafter and Carrier (1970) and Hafter et al (1969) have argued that a single model of binaural processing based on a concept of lateralization can be used to describe the data from these three binaural procedures. They maintain that in all three procedures, the O uses the lateral position of the stimulus as the cue for detection. They also found agreement between measures of "just-noticeable shifts" computed for the noise masking and Weber fraction studies and those shifts obtained for lateralization studies. The data from this study, when compared to those of the noise masking and lateralization investigations, support the notion that all three procedures study the same type of processing.

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NOTE

1. A comparison between the Wightman data and those of Jeffress et al, Robinson and Yost, and Hafter and Carrier is presented in the Hafter and Carrier paper.

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