Where the action is: Weber fractions as a function of sound pressure at low frequencies

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Where the action is: Weber fractions as a function of sound pressure at low frequencies

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Weber fractions for sound intensity were measured for 70-, 100-, 200-, 1000-, and 10 000-Hz tone pulses at sound-pressure levels (SPLs) ranging from just above individual listeners' absolute thresholds to near their highest tolerable SPLs, using a two-alternative forced-choice adaptive staircase technique governed by a 1-up, 3-down rule. Results for four listeners with normal hearing and varying experience, despite individual differences in absolute values, showed Weber fractions that declined as sound pressure increased above threshold and asymptoted at intermediate SPLs. A power function with a negative exponent describes the data of the individual listeners better than a logarithmic function does. The absolute value of the exponent of the power function, which measures the curvature of the function, was largest at 70 Hz and declined with increasing frequency, similar to how exponents of power functions relating loudness judgments or simple reaction time to stimulus intensity differ with sound frequency.

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INTRODUCTION

Although the Weber fraction for sound intensity ($\Delta I/I$, $\Delta P/P$, or $\Delta E/E$)[1] had been investigated previously by others (see Knudsen, 1923), Riesz (1928) was the first to measure it, using the same listeners, over practically the entire frequency/intensity range available to humans. A striking aspect of Riesz's results, which has been largely ignored by later researchers, was the tendency for the increase of the Weber fraction near absolute threshold to differ for the various frequencies tested. The Weber fraction increased least with decreasing sound intensity (followed Weber's law best) for frequencies between 1000 and 4000 Hz, but increased more dramatically near threshold for lower frequencies and, to a lesser extent, for higher frequencies. Riesz (1928), following Knudsen (1923), fitted to his data a function of the form (Riesz expressed sound intensity in energy units, so the Weber fraction is $\Delta E/E$),

$$\Delta E/E = S_\infty + (S_0 - S_\infty)(E/E_0)^{-n}, \qquad (1)$$

where S_∞ is the value $\Delta E/E$ approaches at large E, S_0 is its value at absolute threshold (E_0), and n is a constant that depends on frequency. In Eq. (1) the factor $(S_0 - S_\infty)$ represents the extent of the departure from Weber's law ($\Delta E/E = k = S_\infty$) over the range of E values from absolute threshold to asymptote, and the exponent n reflects the steepness of the curve, relating $\Delta E/E$ to E/E_0, that describes how quickly this departure changes with increasing E. Riesz found that all three parameters, S_∞, S_0, and n, from the fitted versions of Eq. (1) decreased as frequency increased from 35 Hz to about 1000 Hz and then began to increase again for higher frequencies. In particular n had a value of about 0.45 at 35 Hz, 0.41 at 70 Hz, 0.36 at 200 Hz, and 0.28 at 1000 Hz. These differences in the steepness of the curve relating the Weber fraction to auditory intensity near threshold are reminiscent of the way power function exponents for magnitude estimations of loudness (n in $\mathrm{ME} = aP^n + b$, where P stands for sound pressure) are larger at frequencies below 400 Hz (Hellman and Zwislocki, 1968; Schneider *et al.*, 1972; Stevens, 1966; Ward, 1990). For example, Ward (1990) found exponents of about 0.68 for 65 Hz, 0.57 for 100 Hz, 0.55 for 200 Hz, and 0.42 for 1000 Hz. They are also reminiscent of the way exponents of Pieron's law for simple reaction times ($\mathrm{RT} = aP^n + b$) are larger at the same lower frequencies (Chocolle, 1945). One of the motives for the present study was to provide data that would enable us to explore this similarity further.

Riesz's (1928) study, which used the detection of beating of a pair of continuous tones to estimate Weber fractions, is still considered important and is still frequently cited. However, the modern preference is to measure Weber fractions for successive pulsed tones in an adaptive forced-choice paradigm. Using this paradigm, experimenters have not always found the same relation between Weber fraction and sound intensity that Riesz did (see, for example, Carlyon and Moore, 1984; Florentine *et al.*, 1987; Jesteadt and Wier, 1977; Rabinowitz *et al.*, 1976; McConville *et al.*, 1991). Instead, they have tended to find that the Weber fraction for pulsed tones decreases roughly linearly with dB of sound intensity (see, e.g., Fig. 4 of McConville *et al.*, 1991). However, modern studies have tended to concentrate on measuring Weber fractions (or other measures of auditory intensity resolution) at frequencies near the middle of the human audible range, especially at 1000 Hz where Riesz found the relation between sound intensity and Weber fraction to be the flattest, and have seldom investigated the region below 400 Hz where he found it to be more curved. The available summaries of the modern data concentrate on the pulsed tone data at 1000 Hz (e.g., Luce and Green, 1974; McConville *et al.*, 1991; Rabinowitz *et al.*, 1976). The most comprehensive of the modern pulsed tone studies, those of Florentine *et al.* (1987) and Jesteadt and Wier (1977), measured auditory intensity resolution at frequencies of 250 and 200 Hz, respectively, and higher. Therefore, the extent to which the available pulsed-tone data can be compared with Riesz's (1928) data for lower frequencies is limited. A second goal of the present study was to remedy this situation to some extent.

The present paper reports data on the relation of the Weber fraction (measured in units of sound-pressure amplitude, so $\Delta P/P$) to sound-pressure amplitude from near absolute threshold to near the highest tolerable pressure. We concentrated on frequencies lower than 400 Hz, "where the action is" in loudness and reaction time data, measuring Weber fractions at several SPLs for each of 70, 100, 200, 1000, and 10 000 Hz. In this paper, we also point out other rationales (than Riesz's) for describing the relation of the Weber fraction to sound intensity using a power function with a negative exponent (similar to Pieron's law), which resembles Weber's law at higher sound intensities but which captures the increase in the Weber fraction at lower intensities. We used a curve fitting technique to fit this function to our data and compare the results to Riesz's and others' data. A detailed comparison between the present Weber fraction data and data from the same listeners for loudness judgments and simple reaction times to sounds is reported in Ward and Davidson (in preparation).

I. METHOD

A. Apparatus and stimuli

A Hewlett–Packard Vectra ES/12 computer was used to control the timing and presentation of stimuli and to record responses from subjects. Auditory stimuli were delivered monotically through stereo headphones (Koss Pro-4AAA Plus) whose air-filled soft plastic ear cups fitted relatively tightly around listeners' ears and reduced energy leakage at low frequencies. Sound pressures were measured at the earphones, prior to conducting any of the experiments, with a precision sound meter (General Radio) and a custom-built artificial ear. Signals were created by a custom-built tone generator. Responses were entered by the listener on a standard computer keyboard. The listener was seated in a dimly lit acoustical chamber (Tracoustics RE-142C).

Stimuli consisted of 600-ms duration, sine wave signals at the following frequencies: 70, 100, 200, 1000, and 10 000 Hz. The rise and fall times were 2.5 ms. The stimulus set for each listener for each frequency was determined by first measuring the lower threshold for each listener. Threshold (in dB SPL+2 dB became the (preliminary) lowest SPL for each listener, except for 1000 Hz. Because of equipment limitations, the lowest usable SPL at 1000 Hz was 20 dB. This was higher than absolute threshold for all listeners (which was around 8–10 dB SPL under our conditions), and was the lowest SPL tested at 1000 Hz for all listeners. A preliminary stimulus set was selected by adding an increment successively to a listener's lowest SPL nine times to create a set of ten equally spaced stimuli (in terms of SPL). The increments (6, 7, 8, or 9 dB) were chosen so as to come as near as possible to but not to exceed the listener's tolerance SPL (as measured by informal test). Because of equipment limitations some of these SPLs were deleted or replaced with nearby SPLs and some additional SPLs, particularly near threshold, were sometimes added to the set tested. The final set of stimuli tested for each listener consisted of from 9 to 12 SPLs at each frequency, spread roughly equally over that listener's range of SPLs.

TABLE I. Absolute thresholds (dB *re*: 0.0002 dyn/cm^2) by frequency and listener.

Listener	70 Hz	100 Hz	200 Hz	1000 Hz[a]	10 000 Hz
B	43.3	36.7	29.3	20	29.3
C	40.3	35.4	25.3	20	36.7
K	43.3	29.3	23.3	20	25.3
S	43.3	29.3	23.3	20	25.3

[a]Lowest SPL tested, greater than absolute threshold.

B. Procedure

The lower auditory threshold was determined from an adaptive staircase, two-alternative forced-choice (2AFC) technique governed by a 1-up, 3-down rule (based on Levitt, 1971; see also Jesteadt, 1980; Kollmeier *et al.*, 1988; Taylor and Creelman, 1967). With the 1-up, 3-down rule the probability of obtaining a correct response at convergence is 0.794 (Green, 1990). The listener listened during two 600-ms intervals (indicated visually on a LED display placed on a table inside the chamber), and indicated which interval had been filled by a tone. The tone was assigned randomly to one of the two intervals, the other interval was silent. The auditory threshold was estimated by averaging SPLs at the final 12 reversal points obtained at the minimum step size for a single run. Absolute thresholds as determined by this technique are displayed in Table I for each listener at each frequency. Note that the values displayed for 1000 Hz are not thresholds but are the lowest SPLs used at that frequency.

A similar 1-up, 3-down adaptive staircase technique was used to measure Weber fractions ($\Delta P/P$). In the Weber fraction version, each of two 600-ms intervals contained a tone ($P \pm \Delta P$ or P), and the task was to specify which interval contained the more intense tone ($P+\Delta P$ for the A sequence and P for the B sequence). The Weber fraction runs were composed of two randomly interleaved sequences, each of which was required to reach a certain number of reversals for termination (e.g., Levitt, 1971). The starting comparison value for the A sequence was set at a pressure two to three initial step sizes larger than that of the standard tone, and that for the B sequence was set the same amount smaller (except near threshold, where such faint pressures would have been inaudible, the starting pressure for the B sequence was the same as that for the A). The difference threshold for each standard pressure at each frequency was estimated from the average of the pressure difference (ΔP) of the two tones in use at each of the final 16 reversal points from each run (8 from each sequence). Each listener served in from 45 to 60 Weber fraction runs depending on the number of SPLs tested for each frequency (one run per frequency-SPL combination). The order of the runs was randomized independently for each listener. Runs lasted from 5 to 14 min each.

C. Listeners

Four students from the University of British Columbia, including one of the authors (K, age 28), participated in the Weber fraction experiment (and also in loudness estimation and simple reaction time experiments, which are not reported here). Three were male and one was female—S (age 28) was a volunteer in the study, B (age 21) was already employed by the lab, and C (age 25), from the lab's observer pool, participated for pay. Also, S was the most experienced observer (over 6 years as researcher and observer in psychophysics).

D. Data analysis

1. Raw data

The Weber fractions ($\Delta P/P$) obtained for each of the four listeners for each SPL at each frequency are displayed in Fig. 1 as a function of pressure amplitude (dyn/cm^2) and SPL (dB). Ignore the curves for the present. Notice that for all listeners at all frequencies there is a tendency for the Weber fractions to be larger at the lower SPLs and to fall to a plateau for higher SPLs. Notice also that there are a few graphs (e.g., listener B at 70 Hz) in which one or more Weber fractions for particular SPLs are quite different from those for other nearby SPLs and are relatively far from the trend of the other points. We are convinced that at least some of this variability arose from peculiarities of individual runs such as momentary inattention or fatigue or a run of "good or "bad" guesses near differential threshold. This was confirmed by the fact that reruns of some of these points produced Weber fractions more similar to those at nearby SPLs and falling more nearly on the general trend of the other data at that frequency. Substituting the rerun points for the outliers would make some of the graphs appear to follow smoother curves [more similar to Riesz's (1928) curves]. Nonetheless, our analyses here are based on only the points shown, which represent for each frequency the first run at each SPL.

2. Primary data analysis

Equation (1), used by Riesz (1928) to describe his data, resembles Pieron's law for simple reaction times as a function of sound intensity in that both are three-parameter power functions with a negative exponent. A similar three-parameter power function, but with a positive exponent since loudness increases with sound intensity, has been suggested as the best-fitting form to use for magnitude estimations of loudnesses (e.g., Fagot and Stewart, 1964; Lochner and Burger, 1962). The absolute values of the exponents of all three functions have been found to vary in the same way as a function of frequency below about 400 Hz (see Introduction). In order to evaluate this relationship more fully (Ward and Davidson, in preparation), and in order to facilitate comparison with Reisz's (1928) data, we fitted a three-parameter power function to the data displayed in Fig. 1.

The particular equation we used was motivated by Norwich's (e.g., 1981, 1987) entropy theory of perception (cf. Lufti, 1989). The theory implements a conservation law approach to perception which limits but does not compete with mechanistic approaches (Ward, 1991). In this approach, it is assumed that perception occurs only when informational entropy is reduced (by information gain) and that the firing rate of a primary ganglion cell attached to a receptor that is exposed to a stimulus is proportional to the entropy experienced by the receptor-primary ganglion system with respect to that stimulus. From these assumptions, and some more technical ones, Norwich (e.g., 1981, 1987) derived the fundamental entropy equation:

$$H=\tfrac{1}{2}k\ln(1+\beta\mu^{n}/t), \tag{2}$$

where H is the receptor-ganglion system entropy, μ is the nominal stimulus intensity, t is the stimulus duration, and k, β, and n are constants. From Eq. (2), Norwich (1987) derived an expression for the Weber fraction ($\Delta\mu/\mu$) as a function of stimulus intensity that, with some further manipulation and assumptions, can be written as

$$\Delta\mu/\mu=c(\beta/t+\mu^{-n}), \tag{3}$$

where c is a constant. Equation (3) can be rewritten as

$$\Delta P/P=cP^{-n}+b, \tag{4}$$

where $b=c\beta/t$ and P (dyn/cm^2) has been substituted for μ. Equation (4) is identical in form to Pieron's law for simple reaction time as a function of stimulus intensity (simply substitute SRT for $\Delta P/P$). We fitted Eq. (4) to the data in Fig. 1.[2] In Eq. (4), the multiplicative constant c assumes a scaling role, interacting with the exponent n, to determine the curvature of the fitted curve. We had no *a priori* expectations as to what numerical value(s) the parameter c should take. Also, c is a composite of several more meaningful parameters of Norwich's (1987) original function, so in this context it is not easy to interpret. The additive constant b, however, is clearly interpretable as the limit of auditory intensity resolution for large intensity ($cP^{-n}\rightarrow 0$), similar to S_∞ in Eq. (1).

The curve-fitting program used (nonlinear curve-fitting algorithm from SYSTAT Inc.) was based on a simplex optimization routine (Nelder and Mead, 1965). Because of a trade-off between the c and n parameters in many of the unconstrained three-parameter fits, in which larger c compensated for smaller n and vice versa, and since n was the important parameter to estimate, we decided to constrain c. It was assumed that c would be unique to a given listener but should be constant across frequencies within a listener. Under this assumption, differences across frequencies between fitted exponents n would represent differences in the curvature of the Weber fraction–sound-pressure relationship, while differences between fitted additive constants b, would represent differences in the

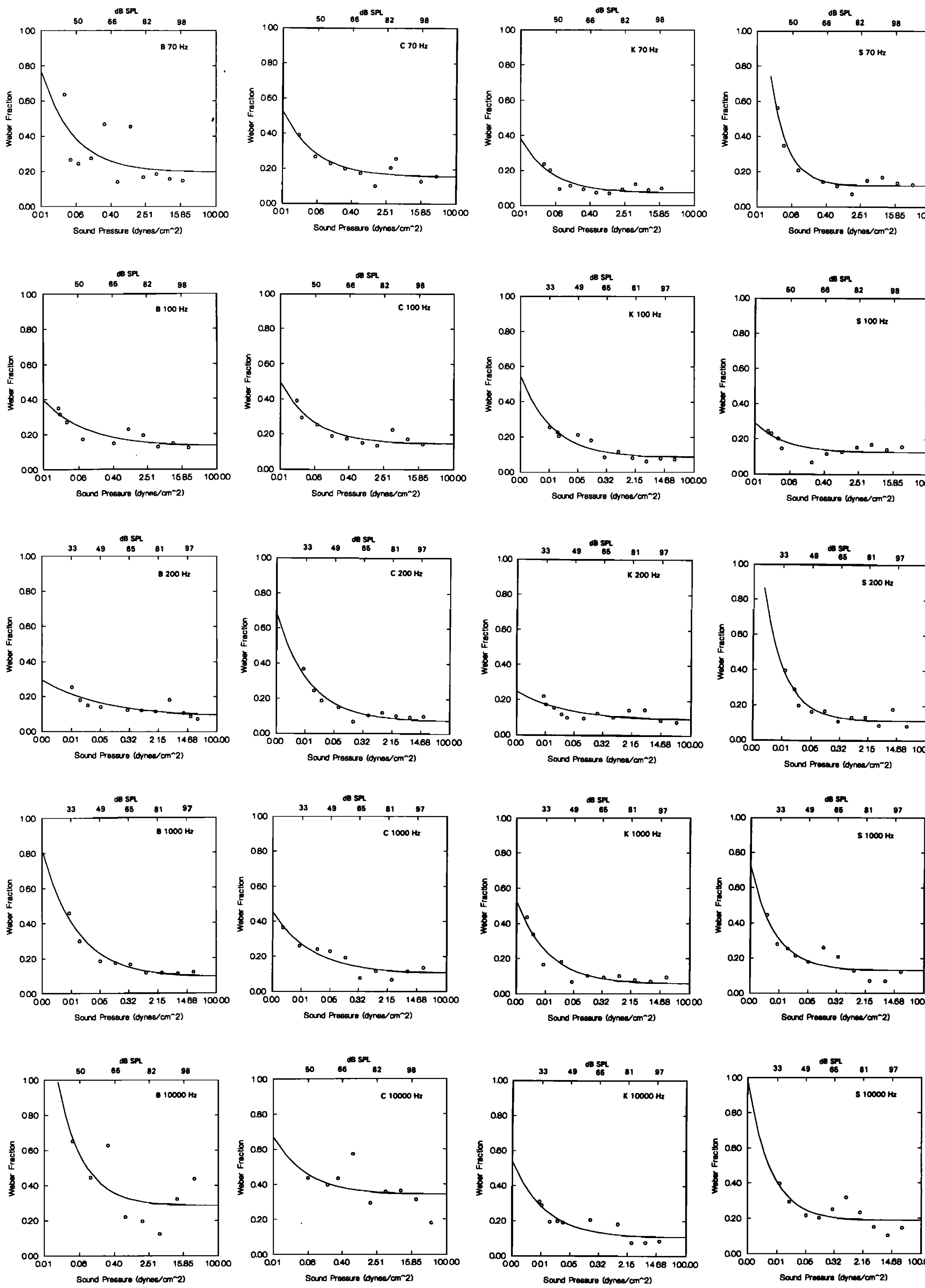

FIG. 1. Weber fractions plotted against log sound pressure (dyn/cm^2, dB SPL also indicated) for individual listeners at five frequencies. The plotted curves are versions of Eq. (4) with the parameter values listed in Table I for the individual listeners.

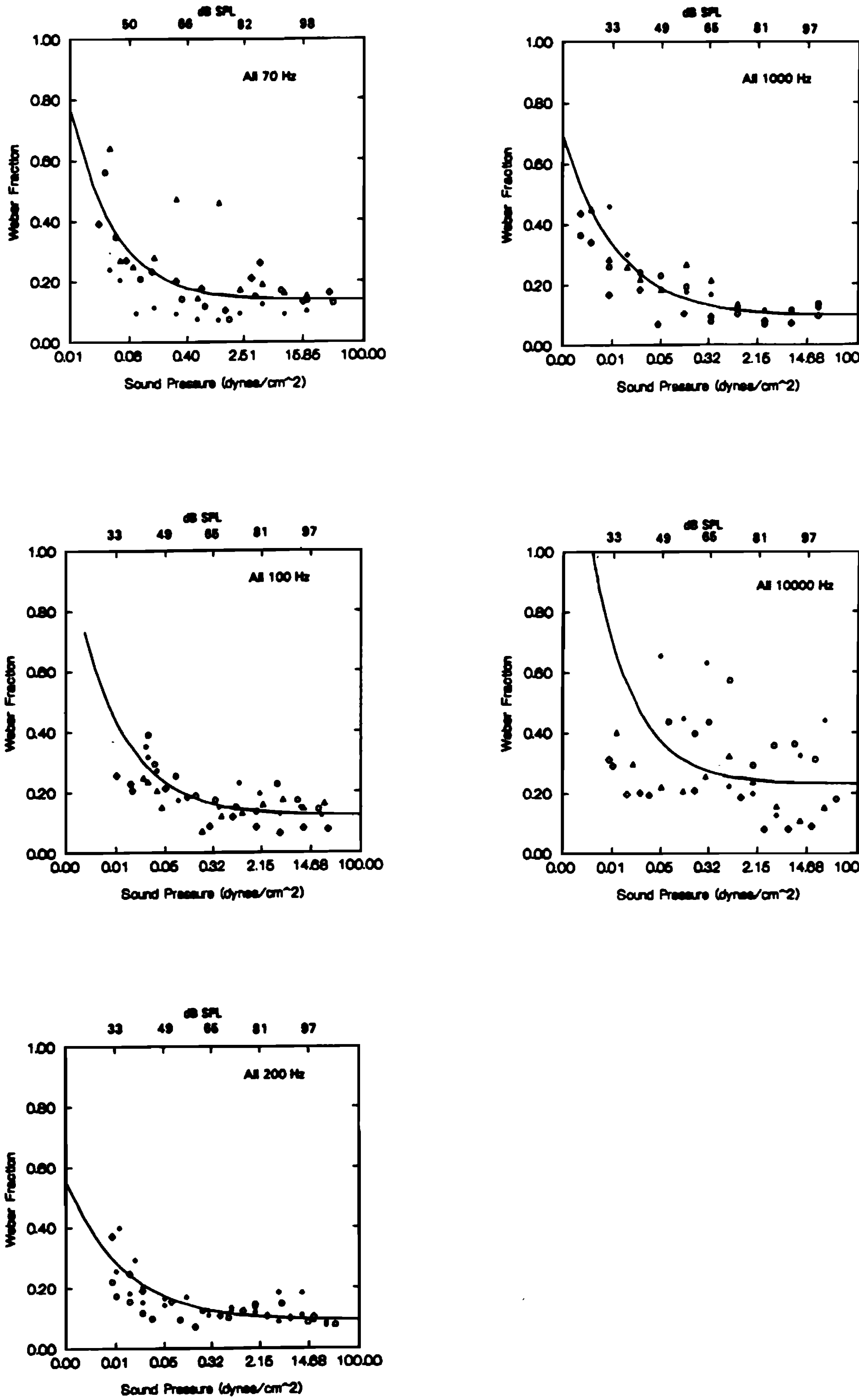

FIG. 2. Weber fractions plotted against log sound pressure (dyn/cm^2, dB SPL also indicated) for all listeners at five frequencies. The plotted curves are versions of Eq. (4) with parameter values listed in the "Ave" column of Table I.

TABLE II. Curve-fitting results [Eqs. (4) and (5)] for listeners B, C, K, and S.

Frequency	Parameter or r^2[a]	B	C	K	S	Ave
	c	0.0361	0.0245	0.017	0.0076	0.0213
70	n	0.601	0.592	0.629	1.127	0.737
	b	0.196	0.157	0.073	0.121	0.137
	$r^2(4)$	0.335	0.717	0.688	0.945	0.671
	$r^2(5)$	0.260	0.415	0.262	0.421	0.340
100	n	0.435	0.579	0.478	0.668	0.540
	b	0.129	0.145	0.086	0.127	0.122
	$r^2(4)$	0.784	0.832	0.843	0.509	0.742
	$r^2(5)$	0.644	0.503	0.837	0.082	0.516
200	n	0.255	0.466	0.323	0.740	0.446
	b	0.086	0.072	0.090	0.112	0.090
	$r^2(4)$	0.619	0.894	0.463	0.878	0.714
	$r^2(5)$	0.509	0.534	0.278	0.488	0.452
1000	n	0.436	0.386	0.481	0.631	0.484
	b	0.090	0.103	0.057	0.131	0.095
	$r^2(4)$	0.949	0.853	0.887	0.793	0.870
	$r^2(5)$	0.645	0.693	0.506	0.682	0.632
10 000	n	0.759	0.566	0.469	0.673	0.617
	b	0.285	0.340	0.107	0.188	0.230
	$r^2(4)$	0.480	0.208	0.774	0.560	0.506
	$r^2(5)$	0.176	0.407	0.763	0.554	0.475

[a] r^2 values adjusted for positivity (results in smaller values).

asymptotes.[3] To obtain the value of c for each listener, we chose a value that would give exponents in the range of exponents of power functions fitted to each listener's magnitude estimations of a similar set of SPLs (Ward and Davidson, in preparation). Thus, the version of Eq. (4) fitted to the data of each listener for each frequency contained a listener-unique value for c, and only b and n were free to vary, making this effectively a two-parameter fit. This technique gave stable fits to the data of all listeners at all frequencies, with (adjusted) r^2 only slightly lower than the far less stable fits obtained with all three parameters left free to vary. For comparison purposes, because the Weber fraction is often asserted to be linear with dB SPL, we also fitted a log-linear model to the data using ordinary least squares. The equation fitted was

$$\Delta P/P = w(\log P) + d, \tag{5}$$

where w and d are constants. It is fair to compare fits of this two-parameter function to those of Eq. (4) since we constrained c in Eq. (4). Thus our fits to Eq. (4) were also effectively made with only two free parameters.

Figure 1 displays the curve fits for Eq. (4) superimposed on the data of each listener. Figure 2 shows the data of all listeners plotted together along with the curves from Eq. (4) using average (across listeners) parameter values. It is clear that Eq. (4) provides acceptable characterizations of the data for all listeners with a few exceptions where the data are not clean (see also the values of adjusted r^2 in Table II). Moreover, it is also clear from Figs. 1 and 2 that Eq. (4) provides a better characterization of all of the data taken together than would a straight line (representing the logarithmic function in these semi-log plots), although straight lines would provide acceptable fits for some of the individual plots (e.g., 200 Hz for listeners B and K).

Table II gives the details of the constrained (c) and fitted (n and b) parameter values from Eq. (4) and the corresponding values for adjusted r^2 for each listener. Table II also lists the adjusted r^2 values from fits of Eq. (5) for comparison purposes. The value of adjusted r^2 for fits to Eq. (4) was higher than that for Eq. (5) in 19 of 20 cases (5 fits for each of 4 listeners), and the only reversal was for 10 000 Hz for listener C, where the data were quite noisy. Average adjusted r^2 for fits to Eq. (4) was 0.701 while that for fits to Eq. (5) was 0.483. Twelve of 20 fits of Eq. (4) had adjusted r^2 greater than 0.700, while only 2 of 20 fits of Eq. (5) had adjusted r^2 greater than 0.700. Equation (4) fits our data better than Eq. (5) does. The estimated exponents (n) from Eq. (4) are in the range of exponents obtained from power function fits to magnitude estimation of loudness data, as was determined by our choice of c values. Also, as we expected, but not arising from the constraints imposed on the curve fitting (see footnote 3), the exponents are larger for the lower frequencies, especially for 70 Hz, which had the largest exponent for every listener. For listener C, n decreased with increasing frequency up to 1000 Hz and then increased again for 10 000 Hz. For listener B, n decreased with increasing frequency up to 200 Hz, and then increased again for 1000 and 10 000 Hz. For listener K, n followed a similar pattern except that it decreased again at 10 000 Hz. For listener S, n decreased with increasing frequency only up to 100 Hz, increased somewhat for 200 Hz, decreased again for 1000 Hz, and finally increased again for 10 000 Hz. The average exponent decreased with frequency up to 200 Hz and then increased for 1000 Hz and again for 10 000 Hz.

II. DISCUSSION OF RESULTS

A. Weber fractions as a function of sound pressure

The data presented in Figs. 1 and 2 demonstrate that the trend is for Weber fractions ($\Delta P/P$) to decrease as standard sound pressure increases from near threshold, and to asymptote at a constant value (i.e., Weber's law holds over some range of SPLs). This is the relationship we would expect if the Weber fraction for pulsed tones measured by an adaptive staircase method behaved similarly to Riesz's (1928) classical data for Weber fractions measured from the detection of beats, although our curves are more variable than his, being those of individual listeners. Our results differ from those in the more recent literature, however, in that they indicate a power function relationship between Weber fraction for pulsed tones and sound intensity instead of a logarithmic relation (Weber fraction linear with dB SPL). It seems that particularly large Weber fractions near absolute threshold are responsible for the greater curvature of the Weber fraction versus log sound-pressure plots in our data, although Weber fractions do not seem to approach the same value at threshold (see footnote 3). This indicates the importance of tailoring to the individual listener the set of SPLs for which Weber fractions are measured, especially of measuring the absolute threshold and including several standard SPLs in that vicinity.

There is little indication in our data of the increase in Weber fraction at the highest SPLs that McConville *et al.* (1991) speculated might be true of auditory intensity resolution as it is of Weber fractions at high stimulus intensities in other modalities such as taste. Thus Eq. (4), which is the simplest form of the relation between Weber fraction and sound pressure derivable from Norwich's (1981,1987) entropy theory of perception, appears adequately to characterize auditory intensity resolution as a function of sound intensity at all frequencies.

B. Weber fractions as a function of frequency

As can be seen in Table I, there is a more pronounced increase in the magnitude of the Weber fraction near absolute threshold (indicated by a larger exponent, n) at 70 and 100 Hz than at 200 and 1000 Hz. At 10 000 Hz the exponent is also larger than at 1000 Hz. This basic pattern is observable for each listener (with the exceptions noted earlier). The effect of frequency on exponent was statistically significant ($F_{4,12}=3.66$, $p=0.036$, Huynh–Feldt correction for sphericity violation). Thus we observed for the relation of individual listeners' Weber fractions to sound pressure the same trend of larger exponents at lower frequencies that has been found for magnitude estimations of loudness and for simple reaction times to sound stimuli. This result lends credence both to the fitting of equations like Eq. (4) to such data, and to Norwich's entropy theory of perception from which it can be derived. However, at present it is not possible to derive from the entropy theory an expression that predicts the value n should take for each frequency. Most speculations about why n should vary in this way, e.g., those for low-frequency recruitment of loudness (cf. Lochner and Burger, 1962; Stevens, 1966), are based on the fact that absolute thresholds are substantially larger for pure tones at frequencies less than 1000 Hz and are also somewhat larger for frequencies higher than 5000 Hz, while highest tolerable limits do not change as much. This results in a decreasing dynamic range as frequency moves away from the 1000- to 5000-Hz region. One argument based on dynamic range assumes that the stimulus range used in loudness experiments is a constant proportion of dynamic range. Also, if data are described by a simple power function ($\mathrm{ME}=aP^n$), $n=\log$ response range/log stimulus range (Teghtsoonian, 1971). Thus a constant response range matched to stimulus ranges that are smaller for lower frequencies could lead to the larger values of n at low frequencies observed in magnitude estimations of loudness. However, it is not so easy to see why dynamic range should affect simple reaction times or Weber fractions.

III. CONCLUSIONS

The present results seem to indicate that at least under our pulsed tone conditions, the Weber fraction is related to sound pressure by a power function similar to that used by Riesz (1928) to describe his data obtained using the method of beats. This function is also similar in form to the power functions used to describe simple reaction times and magnitude estimations as a function of sound intensity. This case can be made strongly for the lower frequencies used in this study but is less strong for the highest frequency (10 000 Hz).

Furthermore, the exponent governing the Weber fraction power function is largest for frequencies less than 200 Hz. The majority of the work done in the modeling of auditory intensity resolution has focused on the Weber fraction–sound intensity relationship within a given frequency (usually 1000 Hz), or, if the frequency dependency is considered, on accounting for intensity resolution at frequencies above 200 Hz, (e.g., Florentine *et al.*, 1987) Our data suggest that a major, and neglected, area of interest should be the low-frequency, low-intensity region. The dramatically larger Weber fractions in this region compared with the higher frequency/intensity regions implies that there may be something fundamental missing from the current models of auditory intensity resolution. A conservation law approach does make some progress toward explaining why a similar pattern is observed for intensity resolution, simple reaction time to sound, and loudness (measured by magnitude estimation) (Ward and Davidson, in preparation), but does not reveal the specific auditory mechanisms responsible for this convergence. Only mechanistic models, such as those discussed by Florentine *et al.* (1987), can do that. One interesting possibility is that the broader excitation patterns caused by lower frequency tones are more difficult to discriminate from each other at near-threshold intensities because they are more easily obscured by random fluctuations than are the narrower excitation patterns caused by higher frequency tones.

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[1]In this paper, the words "sound intensity" refer to the general intensive dimension of sound, which is usually measured in units of power per unit area (intensity I, W/cm^2), or in units of force per unit area or pressure amplitude (P, dyn/cm^2). We express sound intensities as dB SPL [dB $\mathrm{SPL}=20\log(P/0.0002)$] where convenient, except that we use pressure amplitude units (P,dyn/cm^2) in curve fitting in order to make exponents comparable to those reported in the scaling and reaction time literatures. Because we are fitting curves to Weber fraction data, we express Weber fractions as $\Delta P/P$, where P is the pressure amplitude at which ΔP, the differential threshold, was measured. The results are similar when sound intensities are expressed in units of power per unit area except that the values for Weber fractions and exponents are different.

[2]McConville *et al.* (1991) fitted more complicated equations to similar data (1000 Hz only) because of the tendency for the Weber fraction to rise again for higher stimulus intensities for modalities other than audition. The more complicated expressions show this rise at higher stimulus intensities. However, their data, and those of others, including our own, show little evidence of an increase in the Weber fraction at higher audi-

tory intensities. Therefore, we chose to fit the simpler one of the expressions implied by entropy theory.

[3]A reviewer commented that if c is constrained and b varies little across frequencies, then n would simply reflect the sound intensity at which $\Delta P/P$ reaches some large value, e.g., 1. In other words, if $\Delta P/P_{\mathrm{th}}=k = cP_{\mathrm{th}}^{-n} + b$, then $n=-\log[(k-b)/c]\log(P_{\mathrm{th}})=k'/\log(P_{\mathrm{th}})$. However, as Fig. 1 shows, neither b nor the value of $\Delta P/P_{\mathrm{th}}$ seem to be very constant across frequencies. Moreover, as frequency decreases, absolute threshold increases, which in this analysis implies that n should be smaller at low frequencies. As this is exactly the opposite of what we expected, and of what we found, this interpretation of n is not viable.

Carlyon, R. P., and Moore, B. C. J. (**1984**). "Intensity discrimination: A severe departure from Weber's law," J. Acoust. Soc. Am. **67**, 1469–1376.

Chocolle, R. (**1945**). "Variations des temps de reaction auditifs en fonction de l'intensité à divers frequences," Année Psychol. **41**, 65–124.

Fagot, R. F., and Stewart, M. R. (**1964**). "An experimental comparison of stimulus and response translated power functions for brightness," Percept. Psychophys. **3**, 297–305.

Florentine, M., Buus, S., and Mason, C. R. (**1987**). "Level discrimination as a function of level for tones from 0.25 to 16 Hz," J. Acoust. Soc. Am. **81**, 1528–1541.

Green, D. M. (**1990**). "Stimulus selection in adaptive psychophysical procedures," J. Acoust. Soc. Am. **87**, 2662–2674.

Hellman, R. P., and Zwislocki, J. J. (**1968**). "Loudness determination at low sound frequencies," J. Acoust. Soc. Am. **43**, 60–64.

Jesteadt, W. (**1980**). "An adaptive procedure for subjective judgments," Percept. Psychophys. **28**, 85–88.

Jesteadt, W., and Wier, C. C. (**1977**). "Comparison of monaural and binaural discrimination of intensity and frequency," J. Acoust. Soc. Am. **61**, 1599–1603.

Knudsen, V. O. (**1923**). "Sensibility of the ear to small differences of intensity and frequency," Phys. Rev. **21**, 84–102.

Kollmeier, B., Gilkey, R. H., and Sieben, U. K. (**1988**). "Adaptive staircase techniques in psychoacoustics: A comparison of human data and a mathematical model," J. Acoust. Soc. Am. **83**, 1852–1862.

Levitt, H. (**1971**). "Transformed up–down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Lochner, J. P. A., and Burger, J. F. (**1962**). "Pure-tone loudness relations," J. Acoust. Soc. Am. **34**, 576–581.

Luce, R. D., and Green, D. M. (**1974**). "Neural coding and psychophysical discrimination," J. Acoust. Soc. Am. **56**, 1554–1564.

Lufti, R. A. (**1989**). "Informational processing of complex sound. I: Intensity discrimination," J. Acoust. Soc. Am. **86**, 934–944.

McConville, K. M. V., Norwich, K. H., and Abel, S. M. (**1991**). "Application of the entropy theory of perception to auditory intensity discrimination," Int. J. Biomed. Comput. **27**, 157–173.

Nelder, J. A., and Mead, R. (**1965**). "A simplex method for function minimization," Comput. J. **7**, 308–313.

Norwich, K. H. (**1981**). "The magical number seven: Making a 'bit' of 'sense.' " Percept. Psychophys. **29**, 409–422.

Norwich, K. H. (**1987**). "On the theory of Weber fractions," Percept. Psychophys. **42**, 286–298.

Rabinowitz, W. M., Lim, J. S., Braida, L. D., and Durlach, N. I. (**1976**). "Intensity perception: VI. Summary of recent data on deviations from Weber's law for 1000-Hz tone pulses," J. Acoust. Soc. Am. **59**, 1506–1509.

Riesz, R. R. (**1928**). "Differential intensity sensitivity of the ear for pure tones," Phys. Rev. **31**, 867–875.

Schneider, B. A., Wright, A. A., Edelheit, W., Hock, P., and Humphrey, C. (**1972**). "Equal loudness contours derived from sensory magnitude judgments," J. Acoust. Soc. Am. **51**, 1951–1959.

Stevens, S. S. (**1966**). "Power group transformations under glare, masking, and recruitment," J. Acoust. Soc. Am. **39**, 725–735.

Taylor, M. M., and Creelman, C. D. (**1967**). "PEST: Efficient estimates on probability functions," J. Acoust. Soc. Am. **41**, 782–787.

Teghtsoonian, R. (**1971**). "On the exponents in Stevens' law and the constant in Ekman's law," Psych. Rev. **78**, 71–80.

Ward, L. M. (**1990**). "Critical bands and mixed-frequency scaling: sequential dependencies, equal-loudness contours, and power function exponents," Percept. Psychophys. **47**, 551–562.

Ward, L. M., and Davidson, K. P. (**in preparation**). "Exponent convergence in Norwich's conservation law for psychophysics: Simple reaction time, Weber fractions and loudness," unpublished manuscript, 47 pp.