The intensity-difference limen for 6.5 kHz: An even more severe departure from Weber's law

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Intensity-difference limens (DLs) were obtained for tones of 6.5 kHz over levels of 30–90 dB SPL. The tones had Gaussian-shaped envelopes whose duration was expressed as equivalent rectangular duration D , that of a rectangle enclosing the same area as the envelope. D ranged from 0.314 to 30 msec. DL behaviors such as the “severe departure from Weber's law,” the “midlevel hump,” or the “midduration hump”—that is, a rise in the DL over a range of short durations—were identified using trend analysis. The DL versus level followed a “severe departure” that increased as duration dropped to $D \approx 1$ –2 msec. That midlevel hump then fell with further shortening of the tone pip, producing a mid-duration hump. Materials for this article may be accessed through the Psychonomic Society's Norms, Stimuli, and Data archive, at www.psychonomic.org/archive.

This article reports the threshold for the change in the RMS sound pressure level in decibels, the intensity-difference limen (DL), as a function of level and of duration for very brief 6.5-kHz tone pips. To minimize the product of the tone's duration and its spectrum, it was shaped with a Gaussian envelope, which also restricts the energy spectrum to a single, prominent lobe centered at the tone's frequency (Gabor, 1946). The envelopes were reduced to zero at ± 4 standard deviations (σ), giving durations of 8σ . Most of the energy occurs within a much shorter span of time, however. This has inspired alternate duration measures. A convenient theory-based duration is that of the rectangular envelope that encloses the same area as the Gaussian envelope (Baer, Moore, & Glasberg, 1999; Baer, Moore, & Marriage, 2001), called D , the “equivalent rectangular duration.” Originally, this meant the duration of a square-gated stimulus that had the same level and energy as the waveform of interest, whatever its shape (Dallos & Olsen, 1964). Here $D = \sigma\sqrt{2\pi}$, so that $8\sigma \approx 3.19D$ (Nizami, Reimer, & Jesteadt, 2001).

EXPERIMENT 1

Method

Subjects

The listeners (average age 19) were 3 men, J.D., J.S., and T.C., and 2 women, E.M. and S.S., all paid student volunteers from Creighton University. None had experience as psychophysical listeners. All were told of the method but not the expectations of the study. Quiet thresholds in either ear were ≤ 20 dB SPL for 0.5-, 1-, and 4-kHz tones having plateau durations of 200 msec.

Thomas Creutz provided crucial hardware and software support and Hongyang Tan developed the data collection into Excel. Numerous helpful insights were provided by Chris Plack and three anonymous reviewers. Work was partly supported by a grant to Walt Jesteadt and by the Boys Town National Research Hospital core center. Address correspondence to L. Nizami, 1312 Grayson Place, Decatur, GA 30030 (e-mail: nizamii2@aol.com).

Apparatus and Stimuli

Signals were generated digitally at a sampling rate of 50 kHz, using an array processor (TDT AP2), and passed through 16-bit digital-to-analog converters (TDT DD1). One channel of the DD1 produced the pedestal waveform, beginning at a positive-going zero crossing; the other channel produced the increment waveform, in quadrature. Each was low-pass filtered at 20 kHz (TDT FT-6) and attenuated (TDT PA4); then the two were combined (TDT SM3), passed through a headphone buffer (TDT HB6) and a remote passive attenuator inside the double-walled soundproof chamber, and finally presented through a Sennheiser HD 250 Linear II headphone. All listeners used their left ears. Since parallel use of attenuators, summers, and headphone buffers allowed four simultaneous listeners, subjects were assigned to permanent groups.

Tone pips were made by multiplying 6.5-kHz carrier tones by Gaussians. Reported levels were carrier levels.

Procedure

Estimation of DLs. DLs were estimated using two-interval two-alternative forced choice adaptive tracking (Levitt, 1971). Each track was a block of 50 trials. The pedestal and the increment were of the same length, had Gaussian envelopes, and appeared simultaneously when in the same interval. The increment started 15–20 dB higher than the (fixed) level of the pedestal, letting the subjects adjust to the task through a series of correct choices. Occasionally, due to equipment limitations, the separation was only 10 dB, but the subjects' performance was unaffected, as follows. Listeners can lapse into reverie, impairing performance. To discourage such behavior, the subjects were reminded that the experimenter, using a computer monitor, was following their responses trial by trial. Persistent loss of attention could therefore be caught and the subject discreetly informed. DLs were gathered in sets of 2–4; the subjects were shown a record of their last track in each set and became adept at assessing their own performance (after Nizami et al., 2001; Nizami, Reimer, & Jesteadt, 2002). No change in tracking behavior was evident with lower starting levels.

Blocks of trials started out with 4-dB steps in the increment, reduced to 2 dB after the fourth reversal. The latter reversal levels were averaged to estimate the threshold level of the increment, from which

$$DL = 10 \log_{10} \left(1 + \frac{\Delta I}{I} \right),$$

where

$$\frac{\Delta I}{I} = \frac{10^{\text{Threshold level}/10}}{10^{\text{Pedestal level}/10}}.$$

Learning effects were absent (Nizami et al., 2001, 2002).

The subjects observed a 16-character message window at the top of a hand-held keypad. Each trial began with an asterisk, to indicate imminent stimuli. After 400 msec, the first stimulus interval began, as did the stimuli. The interval was followed by 600 msec of quiet, then the second stimulus interval. The intervals lasted 50 msec, except when the tone pip's actual duration was >50 msec ($D = 15.67$ msec), for which the intervals were 100 msec. Using a corresponding button, subjects chose the interval that they believed contained the increment. A few seconds were required. The last subject's response initiated a 500-msec pause before the next trial.

Choice of stimuli. Tone pip durations, in presented order, were $D = 1.25, 10.03, 2.51, 20.06, 0.627,$ and 0.314 msec. Between $D = 0.627$ msec and $D = 0.314$ msec, testing was done for tones having 25-msec plateaus and 5-msec cosine-squared ramps (Carlyon & Moore, 1984).

To train, the subjects did one block at each of 90, 60, and 30 dB SPL, in that order, for $D = 1.25$ msec. By the end of the third block, the subjects had grasped the adaptive-tracking procedure and were performing within expected limits (see Nizami et al., 2001, 2002), as evident from self-reports and trial-by-trial monitoring. The subjects then did two blocks for each pedestal level, moving from a level of 30 dB SPL to a level of 90 dB SPL in steps of 10 dB.

To obtain quiet thresholds, two blocks without pedestals were inserted between 40 and 50 dB SPL.

The above test was then run in reverse and the whole cycle was then repeated, yielding eight estimates of quiet threshold and eight estimates of the DL for each pedestal. For each condition and subject, an arithmetic mean and a standard deviation were calculated. Testing recommenced with the next D .

Data Analysis

DLs were examined using univariate ANOVA for repeated measures, a within-subjects design, using the SPSS routine. Effects deemed significant represent $p < .05$, the traditional criterion. The F examined for significance was obtained under the Huynh–Feldt correction, a stricter criterion (Howell, 1997, p. 466; Keppel & Wickens, 2004, p. 378) than the sphericity condition typically assumed. The DLs were examined across subjects using two-way ANOVAs; one-way ANOVAs across subjects were then done to examine trend (see “Trend Analysis,” below). In the ANOVAs across subjects, each input was the average of the 8 DLs obtained from each subject for each included level and/or duration. The error term was always an interaction of the treatment effect (whether a main effect or an interaction) with the subjects.

Not all subjects were able to produce DLs in all stimulus conditions. The pedestal had to be more than 5 dB above the quiet threshold, a criterion broad enough to represent a psychometric function whose 70.7%-correct point could be estimated with confidence using adaptive tracking, as established by careful monitoring of subjects' performances in similar experiments (Nizami et al., 2001, 2002). To avoid missing values, which otherwise requires special corrections that would complicate interpretation, the various ANOVAs covered only the conditions for which all subjects could produce DLs. The ANOVAs across subjects therefore may not have used all of the levels and durations for which any given subject produced usable DLs, allowing significant effects within individuals to be missed. Accordingly, two-way and one-way ANOVAs were done subject by subject for all available DLs. Eight DLs—that is, the 8 replications done by each subject—were used for each level and/or duration. The error term was always the interaction of the treatment effect with the replications done by the subject.

Trend Analysis

ANOVA provides a means of testing specific hypotheses about the dependence of the DL on level and duration. First, that dependence can be briefly summarized. For 100- to 600-msec tones, and for tones as brief as 15 msec specifically at 1 kHz, there is a general

decline in DL with level, the “near miss to Weber's law” (e.g., McGill & Goldberg, 1968), where Weber's law means a constant DL with level. The near miss is not universal. For 20- to 30-msec tones having a frequency of 6.5 kHz, the DL rises at moderate levels, the “severe departure from Weber's law” (Carlyon & Beveridge, 1993; Carlyon & Moore, 1984, 1986). This rise is frequency dependent; the DLs for the 500-msec tones of Jesteadt, Wier, and Green (1977) show a subtle midlevel rise that progressively enlarges as frequency increases from 2 to 8 kHz. For the 500-msec, 8- to 10-kHz tones of Florentine, Buus, and Mason (1987), the midlevel rise is clear.

Nizami and Schneider (1994) found a midlevel rise in the DLs for a 2-kHz Gaussian-shaped tone pip having a duration of $D = 1.25$ msec and having levels of 30–90 dB SPL. Nizami et al. (2001, 2002) elected to call this rise a “midlevel hump” because it was found for a much shorter tone of a much lower frequency than the “severe departure.” Nizami et al. (2001) repeated the study, for durations of $D = 1.25, 2.51,$ and 10.03 msec. For D s of 1.25 and 2.51 msec there were midlevel humps, but $D = 10.03$ msec produced the near miss to Weber's law. Nizami et al. (2002), using only $D = 2.51$ msec, again found the midlevel hump.¹

The DL does not rise indefinitely as the Gaussian-shaped tone is shortened. Nizami et al. (2001) plotted the DL versus the duration of the tone pips for the levels of 40, 50, and 70 dB SPL. The DL rose significantly at $D = 2.51$ msec, a feature they dubbed the “midduration hump.” Midduration humps for very brief Gaussian-shaped tone pips are evident elsewhere (Baer et al., 1999; van Schijndel, Houtgast, & Festen, 1999).

The literature thus provides several hypotheses to be tested: the near miss to Weber's law, a linear trend (that is, a line of nonzero slope); and the “severe departure from Weber's law,” the midlevel hump, and the midduration hump, all quadratic trends. Trends were identified using trend analysis within one-way ANOVAs. Trend analysis reveals significant patterns, even without main effects; but it only indicates a significant trend, not whether the trend is an increase or a decrease over any given range of durations or levels. The latter can be intuited from visual inspection of the plotted DLs, but firm inference requires knowing which of the DLs mutually differ significantly, done using pairwise comparisons (Nizami et al., 2001).

Trend analyses require unique multiplicative coefficients, which are supplied in the SPSS routine under the assumption of equally spaced conditions. Because the present D s were not equally spaced, the coefficients had to be calculated using algorithms from Keppel (1982) entered onto a spreadsheet.

Results

Quiet Thresholds and Excluded Increment Thresholds

Table 1 lists quiet thresholds. Table 3, which may be accessed in the Psychonomic Society online archive, lists increment thresholds that were excluded, based on those quiet thresholds.

DLs

Figure 1 shows the DLs subject by subject. Note the strong individual differences, as found elsewhere for DLs for very brief Gaussian-shaped tone pips when using forced choice adaptive tracking (Baer et al., 1999; Baer et al., 2001; Nizami et al., 2001; van Schijndel et al., 1999). Figure 2 shows the DLs averaged across subjects. With the abscissa in dB SPL, the plots rise at moderate levels, but each plot peaks at a different level. Using sensation level (SL) scales brings those peaks into alignment, an effect noted for Gaussian-shaped 2-kHz tones (Nizami et al., 2001). This phenomenon is explained in the Discussion, below.

Table 1
Quiet Thresholds for the Tone Pips Used in Experiments 1 and 2

Subject	Duration (in msec)											
	0.1	0.2	0.314	0.627	1	1.25	2	2.51	8.78	10.03	20.1	30
Experiment 1												
E.M.	—	—	36.46	34.41	—	33.24	—	28.02	—	23.15	21.54	17.94
J.D.	—	—	29.48	25.4	—	26.37	—	23.84	—	17.57	15.31	8.85
J.S.	—	—	33.30	23.92	—	29.14	—	20.92	—	17.06	18.03	12.11
S.S.	—	—	28.62	25.16	—	23.63	—	20.65	—	16.13	10.97	12.06
T.C.	—	—	37.71	36.42	—	34.55	—	34.29	—	28.68	24.16	22.67
Mean±SD	—	—	33.11±3.63	29.06±5.25	—	29.38±4.09	—	25.54±5.12	—	20.52±4.76	16.90±4.3	14.73±5.52
Experiment 2												
E.F.	39.54	37.87	—	—	33.62	—	31.62	—	23.60	—	—	—
E.G.	42.89	38.77	—	—	34.89	—	26.89	—	28.97	—	—	—
K.B.	40.46	36.52	—	—	29.16	—	25.16	—	18.36	—	—	—
M.P.	51.09	46.07	—	—	42.96	—	41.95	—	39.32	—	—	—
Mean±SD	43.5±5.26	39.81±4.28	—	—	35.16±5.75	—	31.41±7.54	—	27.56±8.96	—	—	—

Note—Levels are in dB SPL and durations are in milliseconds in equivalent rectangular duration (see the introduction). Duration of 30 msec refers to the tone pip used by Carlyon and Moore (1984; see the present p. 1108, "Choice of stimuli").

ANOVAs for DLs Pooled Across Subjects

Not all subjects produced DLs for pedestal levels of 30 and 40 dB SPL, and so the DLs used in the two-way ANOVA across subjects were those for combinations of duration and level for levels ≥ 50 dB SPL. Level proved significant [$F(4,16) = 18.417, p < .001$]; that is, Weber's law is not obeyed at 6.5 kHz for levels of 50–90 dB SPL and durations of $D = 0.314$ –30 msec. Duration was significant [$F(6,24) = 2.892, p < .05$] and there was a significant interaction of level and duration [$F(24,96) = 2.798, p < .001$], altogether suggesting that the deviation from Weber's law, whatever its form, is duration dependent; and, conversely, that the relation of DL to duration is level dependent.

Table 2, which may be accessed in the Psychonomic Society online archive, lists the F and p values for the one-way ANOVAs across subjects for analysis of trend. The one-way ANOVAs at each duration (for which each pedestal level contributed a single input) revealed significant linear trends in level for durations of $D = 0.627, 1.25, 2.51, 10.03$, and 20.06 msec, always representing a decline in DL with increasing level, and significant quadratic trends in level for durations of $D = 0.314, 0.627$, and 10.03 msec. (It is possible, in principle, simultaneously to have linear and quadratic trends; for example, a small but significant quadratic trend can be present as a bend at one end of a plot that shows an overall significant—i.e., nonzero—slope.) The one-way ANOVAs at each level revealed significant linear trends in duration for levels of 60–90 dB SPL, always representing a decline in DL with increasing duration but no significant quadratic trend in duration for any level.

ANOVAs Subject by Subject

Table 3 summarizes the results of the analyses of variance of the DLs, subject by subject. Level and duration were significant for each subject. Each subject showed a significant linear trend in level—that is, a general drop in the DL with increasing level for 2 or more durations, notably for $D \geq 10.03$ msec. Each subject also showed a significant quadratic trend in level—that is, a midlevel hump for two or more durations, notably $D \leq 2.51$ msec. All subjects showed a significant linear trend in duration—that is, a general drop in the DL with increasing duration for at least 2 levels. The subjects showed anywhere from no significant quadratic trend in duration for any analyzed level (Subject J.D.) to significant quadratic trends in duration—that is, midduration humps, for 5 levels (Subject T.C.). The significant quadratic duration trends for Subject S.S. at 50 dB SPL and Subject E.M. at 70 dB SPL actually represent valleys, not humps; this does not change the general conclusions.

EXPERIMENT 2

Method

Experiment 1 suggested a "midduration hump," peaking in the range of $D = 0.314$ –1.25 msec, for 6.5-kHz tones having levels of 50–60 dB SPL. To establish what D gives the peak, and the size of that peak, requires more durations near $D = 1$ msec.

Figure 1. DLs for the 6.5-kHz Gaussian-shaped tone pip (Experiment 1) as a function of equivalent rectangular duration D . Each row of panels represents an individual subject and each panel represents either two or three pedestal levels, with levels increasing from the left.

Experiment 2 emulated Experiment 1, except for the following: The subjects were 1 man, M.P. (age 20), and 3 women, E.F., E.G., and K.B. (average age 19.7 years). The durations used, in order, were $D = 2.0$, 0.1, 0.2, 1.0, and 8.78 msec. To train, the subjects did one block at each of 90, 60, and 40 dB SPL, in that order, for $D = 2.0$ msec. Subsequently, 90 dB SPL and 40 dB SPL were not used for DLs. For a given D , the subjects completed two blocks for quiet threshold, two blocks for 50 dB SPL, and two blocks for 60 dB SPL, in that order. This procedure was then repeated in reverse, and then again forward followed by reverse, for a total of eight blocks for each quiet threshold or pedestal level.

Results

Table 1 lists the quiet thresholds. Figure 3 shows the DLs. The detection thresholds for Subject M.P. were within 5 dB of 50 dB SPL at $D = 0.1$ msec and $D = 0.2$ msec; the respective increment thresholds were thus rejected. Being less extensive than those of the other subjects, the DLs of Subject M.P. were excluded from the two-way ANOVA across subjects. That ANOVA revealed no significant effects, and the one-way ANOVAs across

Figure 2. DLs for the 6.5-kHz Gaussian-shaped tone pip, averaged for the 5 subjects of Experiment 1. Not all subjects were able to provide DLs for all conditions (see Table 3), so some of the data points at lower levels are averages of fewer than 5 DLs. (Top panel) Abscissa in dB SPL. (Lower panel) Abscissa in an "average SL" scale. A unique SL was obtained for each duration and pedestal level by subtracting the across-subjects mean quiet threshold for that duration (Table 1) from that level.

subjects revealed no effect of duration for either 50 or 60 dB SPL. Table 4 (see the online archive) notes the results of the one-way ANOVAs, subject by subject. There were significant linear trends, the initial steep rise in the DL with increase in D , and significant quadratic trends (midduration humps).

Discussion

Recall that Gaussian shaping was used to minimize the product of the tone's duration and energy spectrum. Gaussian shaping also results in the energy spectrum's having a single lobe as a function of frequency. (See Gabor, 1946.) A well-focused spectrum explains why plotting DLs using an SL scale tends to bring the midlevel humps into alignment (Figure 2), as follows: Suppose the behavior of the DL is dominated by the rate of

energy passage through the neural channel centered on the characteristic frequency (CF) corresponding to the carrier frequency of the Gaussian-shaped tone pip. As the tone pip is shortened, its spectrum spreads out, reducing the energy passing through the neural channel and thus reducing the tone pip's effective level in that particular channel. The passing energy would be equivalent to that of a lower intensity, more gradual (and therefore more spectrally focused) Gaussian-shaped tone pip. Now, the midlevel hump is observed to shift toward lower pedestal levels as the tone is lengthened. For a given point on the DL curve of the shorter tone, the same energy through the neural channel would correspond to a congruent point on the DL plot for the longer tone. By equating energy flow, the DL curve for the longer tone could be constructed point by point from the DL curve for the shorter tone.

The shifting of the midlevel hump with duration is therefore consistent with the notion that the DL is determined by the energy passing through the CF channel. Gaussian shaping of the carrier tones must have kept the stimulus energy focused at the CF place, as desired. If so, the midlevel humps

Figure 3. DLs for the 6.5-kHz Gaussian-shaped tone pip (Experiment 2) as a function of equivalent rectangular duration D . Each panel represents an individual subject.

should not align in SL scales for a stimulus whose DL does not rely on any particular neural channel. In fact, the mid-level hump is found for very brief Gaussian-shaped packets of white noise (Nizami et al., 2001), but the midlevel humps align in SPL scales rather than in SL scales. Using SL scales actually throws the humps out of alignment.

CONCLUSIONS

The DL of a 6.5-kHz tone pip shows a midlevel rise called the “severe departure from Weber’s law.” The literature suggests that reducing the tone’s duration should accentuate the “severe departure” and that the increase should stop and reverse as durations fall, producing a “midduration hump” in the plot of DL versus duration. DLs were obtained for very brief Gaussian-shaped 6.5-kHz tone pips having equivalent rectangular durations D of 0.314–30 msec and levels of 30–90 dB SPL. A midlevel hump was found that grew as D fell to 0.627 msec, then shrank for $D = 0.314$ msec. Subsequent DLs were obtained for durations of $D = 0.1$ –8.78 msec and levels of 50 and 60 dB SPL. A hump was observed in the plot of DL versus duration for $1 < D < 2$ msec. Strong individual differences in the DLs precluded greater precision. The duration dependence of the midlevel rise in the DL suggests that there are two synergistic contributing processes, one that is duration dependent and another that is frequency dependent.

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NOTE

1. At first glance, the 2-kHz midlevel hump seems to be a form of the 6.5-kHz “severe departure.” The two are certainly comparable in size. For the 6.5-kHz Carlyon and Moore (1984) tones of 16 msec steady-state duration and 5-msec onset- and offset-ramps ($D \approx 21$ msec), the peak of the “severe departure” averaged 5.21 dB at 55 dB SPL, very similar to the peak value of 5.47 dB at 50 dB SPL for the Gaussian-shaped tone pip of $D = 2.51$ msec at 2 kHz (Nizami et al., 2001). However, the midlevel rise in the DL near 6 kHz can be much higher than either of these; it peaked at roughly 5 dB for a duration of $D \approx 26$ msec (Plack & Viemeister, 1992), whereas for $D \approx 3$ msec (2-msec plateau, 2-msec raised-cosine ramps), the rise grew to roughly 12 dB (Plack, 1998). Thus, the “severe departure” grows greatly as the tone is shortened to the kind of durations that evoked the 2-kHz midlevel hump. If the behavior holds, lengthening the tone should cause the “severe departure” to shrink, as it does, at least for 8-kHz tones. Carlyon and Moore (1984) found a largest DL of 4.47 dB at a level of 55 dB SPL and a duration of $D \approx 20$ msec, whereas Florentine et al. (1987) found a largest DL of 3.41 dB for tones having a level of 50 dB SPL and a duration of $D \approx 500$ msec.

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DESCRIPTION: The compressed archive file contains four files:

Nizami Table1.xls: Quiet thresholds for the tone pips used in Experiments 1 and 2.

Nizami Table1.pdf: Containing the above information in .pdf format.

Nizami Table2.xls: Results of one-way ANOVAs across subjects for Experiment 1.

Nizami Table2.pdf: Containing the above information in .pdf format.

Nizami Table3.xls: Results of the ANOVAs done subject by subject for Experiment 1.

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Nizami Table4.xls: Results of one-way ANOVAs done subject by subject for Experiment 2.

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