Level effects in psychophysical two-tone suppression

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Measurements of psychophysical two-tone suppression in a number of subjects are described. Levels of the stimulus components (suppressee, L_1, and suppressor, L_2) were the primary experimental variables. In all experiments the pulsation threshold was used with the probe frequency f_P fixed at the suppressee frequency f_1. In an initial experiment f_1 was fixed at 1 kHz. The suppressor frequency f_2 ranged from 0.2 to 1.4 kHz. At appropriate levels all subjects showed significant suppression. Suppression was found to decrease to zero as f_2 approached f_1. The amount of suppression depended on both L_1 and L_2 in a way not accounted for by any of the current theories of two-tone suppression. At higher overall levels suppression became increasingly prominent. The amount of two-tone suppression in a given stimulus condition depended strongly on the subject. The maximum amount of suppression measured was about 35 dB. In a second experiment it was verified that suppression follows the same pattern at other frequencies f_1 (0.5, 2, and 4 kHz). Data for equal f_2/f_1 ratios were quite similar. The two-tone suppression effect decreased in a noisy environment. Within a 20-dB range of signal-to-noise ratios the effect of noise changed from negligible to the virtually complete elimination of two-tone suppression.

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INTRODUCTION

For many practical purposes, auditory masking can be described adequately in terms of (quasi) linear processes (a recent example was reported by Patterson and Henning, 1977). Nevertheless, it has been obvious for more than 50 years that masking is a nonlinear phenomenon. Wegel and Lane (1924) quantified the nonlinear behavior in the so-called upward spread of masking. Another obvious violation of linearity is found in the cases where the additivity of masking does not apply. Most clearly that is the case in the suppression[1] effect, where addition of a second masker actually reduces the amount of masking produced by the first masker. Houtgast (1972, 1973, 1974a) first demonstrated the existence of significant psychoacoustical suppression effects, and noted the striking similarity between psychophysical and neurophysiological suppression data. His results initiated several other studies on the subject. The studies fall into two categories, viz. tone-on-tone (or two-tone) suppression (Houtgast, 1972, 1973, 1974a; Shannon, 1976; Duifhuis, 1977; Tyler and Small, 1977; Abbas, 1978; Tyler *et al.*, 1978) and noise-on-noise (band-widening) or noise-on-tone suppression (Houtgast, 1972, 1973, 1974a,b; Leshowitz and Lindstrom, 1977; Terry and Moore, 1977; Weber, 1978; O'Malley and Feth, 1978; Jesteadt and Javel, 1978; Weber and Green, 1978, 1979). Despite these combined efforts, our knowledge of the suppression patterns is still far from complete. In this paper we present and discuss additional material, restricting ourselves, however, to the category of two-tone suppression.

The experiments reported here had actually been set up to provide quantitative estimates of parameters of our specific theory on cochlear nonlinearity and the second filter (Duifhuis, 1976a). As a direct consequence of this aim, we studied two-tone suppression using the level (usually of the suppressor) as the primary independent variable. This contrasts with the data published so far (Houtgast, 1972, 1973, 1974a; Shannon 1976; Tyler and Small, 1977) where the suppressor frequency was the most extensively studied independent variable. Systematic studies of level effects are more to the point for a quantitative analysis of the auditory nonlinearity (see also Schöne, 1977). However, the results of our experiments turned out to be only approximately in agreement with our theoretical predictions, thus making estimates of model parameters unreliable. This does not mean that the results are valueless. They are relevant to the question of whether the amount of two-tone suppression depends on suppressor level only (Shannon, 1976; Sachs and Abbas, 1976; Javel *et al.*, 1978), or on the ratio of suppressor and suppressee amplitudes (Duifhuis, 1976a; Shannon, 1976; Hall, 1977). The primary aim of this paper has become to try and resolve this issue. The data will show that neither current interpretation is tenable. Besides stressing this point, the paper aims at extending the data base on two-tone suppression. This may help to provide a better background for future theorizing on auditory nonlinearity.

After some discussion on the general experimental paradigm to be used (Sec. I), we successively present our main results of two-tone suppression around 1 kHz (Sec. II), then the results at other frequencies (Sec. III), and finally the effect of a background of white noise on two-tone suppression (Sec. IV). A relatively large set of data is shown in these sections, in particular in Sec. II. This is considered essential for obtaining a proper overview of the effect and of how it depends on experimental conditions. The discussion of the data is postponed to Sec. V, where we compare our results with other psychophysical and neurophysiological data, and with current theoretical predictions.

[a)]Some preliminary results were presented at the 92nd (San Diego) meeting of the A. S. A. (Duifhuis, 1976b) and at the symposium on "Psychophysics and Physiology of Hearing" held at the University of Keele, April, 1977 (Duifhuis, 1977).

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I. METHOD

A. Introduction

Houtgast (e.g., 1974a, 1977) has shown experimentally that psychoacoustical suppression is demonstrable only if the probe signal is not presented simultaneously to the same ear to which suppressee and suppressor are presented. His interpretation, which is in line with our subsequent theoretical analysis (Duifhuis, 1976a), is as follows. The effect of a suppressor (masker 2) on the suppressed 1st masker (suppressee) is multiplicative and instantaneous. It occurs as long as suppressor and suppressee are presented together. If a small probe signal is presented simultaneously with the suppressee, then both will be suppressed by the suppressor. The ratio of probe and suppressee is thus left unaffected. Since the masked threshold of the probe happens to be determined largely by this ratio, the suppression effect does not show up. In the case of nonsimultaneous masking, only the suppressee undergoes suppression, and the probe is then unaffected. In this case the probe-to-suppressee ratio is changed, and suppression becomes apparent.

We decided to measure suppression monaurally. This limited the number of alternative techniques. The primary candidates were, in our opinion, the pulsation threshold technique, developed by Houtgast (1972, 1973, 1974a), and the forward masking method. Therefore, we decided to test the relative variabilities of the results of the two methods (Sec. IC).

B. General information

Stimuli were presented monaurally to the subject's better ear through KOSS PRO/600 AA (experiment 1) or Pioneer SE 700 (experiments 2 and 3) headphones. All levels are given in SPL (i.e., *re* 20 μPa, for continuous tones) based on the calibration on a B&K artificial ear type 4153 of the headphone used. All subjects had normal audiograms, deviations being less than 10 dB, except for HvC who had a 50-dB conductive loss in his contralateral ear. Subjects either came from our laboratory or were students from the Eindhoven University of Technology. Students participated in the program on the basis of a traineeship to be awarded with study credit points. They took part for a sufficiently long period (intensively for 3 to 6 months) to qualify as trained subjects. During the experiment, subjects were seated in a sound-treated booth.

Data have been collected over a 3-year period. During this period the experimental emphasis evolved, and minor changes occurred in the experimental setup. Only one observer (the author) was available for the entire period. Thus, unfortunately, the data do not form a complete closed set where all conditions are tested equally often for all subjects. Nevertheless, we believe that there is sufficient overlap between the conditions tested to allow for relevant comparisons across subjects and conditions, even though this requires some interpolation.

C. Pulsation threshold versus forward masking

Psychophysical study of auditory suppression aims at answering questions about cochlear nonlinearity. The adequate interpretation of psychophysical data requires the use of a theory which relates these data to cochlear responses. Unfortunately, at present this theory exists neither for the pulsation threshold, nor for forward masking data. Although it is plausible that both methods, when using a narrow-band probe signal, give information about the excitation level in the probe channel, the quantitative relations between thresholds and excitation levels are as yet undetermined. Thus, this fundamental consideration does not provide a basis for a choice between the two methods. Formally, it even prohibits a quantitative comparison of the results of the different methods. In view of this, our choice is based on the following, more pragmatic, consideration.

There is ample evidence in Houtgast's work (e.g., 1974a, his Fig. 5.1) that suppression effects are bigger in pulsation threshold than in forward masking. In this context it is useful to define sensitivity of the method as the ratio of the measured effect and its standard deviation. In order to evaluate this sensitivity, we determined the variability of the two methods. The conclusion (see Sec. IC4) is that the day-to-day variability in pulsation threshold is equal or less than forward masking. This makes pulsation threshold the more sensitive method, which is our main reason for using it.

In the following subsections we describe the stimuli, and present the data on day-to-day variability.

1. Pulsation threshold stimuli

We used a stimulus time pattern very similar to the one used by Houtgast (1972, 1973). The masker stimulus (suppressee + suppressor) and the probe are presented alternately with a repetition frequency of 4 Hz, or a cycle period T of 250 ms[2] (Fig. 1).

Ramps used in experiment 1 were cosine shaped and had durations of 20 ms. In experiments 2 and 3 the tone bursts were shaped with Grason–Stadler switches, which produced 25-ms linear ramps. Except perhaps at the very high levels ($\geq$80 dB) this difference was not perceptible. Ramps of masker bursts and probe bursts

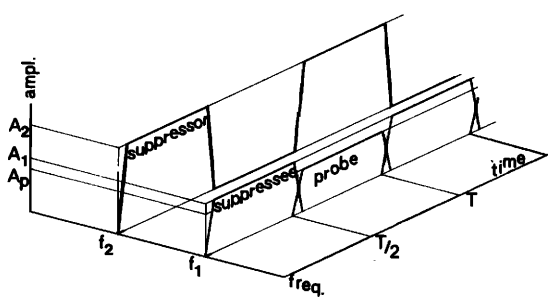

FIG. 1. Schematic time course of the stimulus used to measure two-tone suppression with the pulsation threshold. The masker (suppressee + suppressor) is interleaved with the scanning probe. Suppressee frequency f_1 equals probe frequency f_p. Suppressor frequency is a parameter. The cycle duration[2] T is approximately $\frac{1}{4}$ s, and the ramps of the tone bursts are 20 or 25 ms (see text).

overlapped. In particular the envelopes of suppressee and probe were matched carefully, so that no transients would be audible if the suppressor was absent and suppressee and probe had the same amplitude and frequency. To that end, care also had to be taken to ensure that the carriers of suppressee and probe were precisely in phase.

In our earlier experiments, subjects were presented with series of 10 cycles of the stimulus. The series could be started by the subject. This presentation mode will be referred to as mode A. In later experiments we employed a more comfortable listening situation, following a suggestion by Houtgast (personal communication). Here the pulsed masker (suppressee + suppressor) stimulus was repeated for an arbitrarily long period, started and stopped by the subject, but the probe was presented only during three consecutive cycles out of every eight (Fig. 2). In this way the subject was provided with a 1-s reference interval ($\theta/2$ to θ, where $\theta = 8T$) every 2 s. At pulsation threshold, the four reference masker bursts (interval $\theta/2, \theta$) are perceived separately, the four in the interval $(0, \theta/2)$ are connected by the continuously sounding probe. Thus, the listener roughly perceived $\frac{1}{2}\theta$ bursts of the probe. The repetition of the probe facilitates the focussing of the subject's attention on the probe tone. This setup is referenced as mode B.

In a typical experimental session, pulsation thresholds L_P were measured as a function of suppressor level L_2 with a fixed suppressee level L_1. In all experiments the probe frequency was equal to the suppressee frequency ($f_P = f_1$). The suppressor frequency f_2 was a parameter. In one session L_2 was gradually varied from low to high levels in order to minimize unwanted adaptation effects. Subjects adjusted the pulsation threshold by setting an attenuator which was wired in series with a second attenuator controlled by the experimenter. Between two adjustments the experimenter changed the setting of his attenuator quasirandomly. The experimenter controlled the independent variable L_2 and the other stimulus parameters.

2. Forward masking stimuli

For forward masking we used a two-interval, two-alternative, forced-choice paradigm. The two maskers, with durations of 400 ms, were separated by an 800-ms silent interval. Probe and masker had 20 ms cosine-shaped ramps. Probe duration was 20 ms at half amplitude, and probe onset started immediately at the end of the offset ramp of either the first or the second masker. The experimenter followed a sequential block up-and-down strategy for selecting probe levels. Typically 40 to 100 trials were required for each 75% threshold. Except for the temporal characteristics specified above, masker and probe were identical to those in the pulsation threshold stimuli.

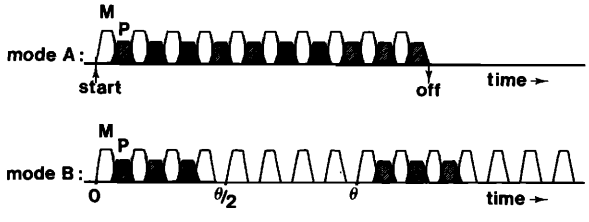

FIG. 2. Temporal organizations of presentation modes A and B. Mode A comprises ten full cycles of masker and probe. In mode B the masker bursts are presented for an arbitrarily long period but the probe bursts are presented during three out of every eight cycles. This defines a new cycle θ, with a duration of 2 s ($\theta = 8T$).

3. Variability

In the pilot experiment which was set up to evaluate variabilities in pulsation threshold and forward masking, stimulus parameters were fixed at $f_P = f_1 = 1$ kHz, $f_2 = 400$ Hz, and $L_1 = 45$ dB SPL. For one subject (JS) we measured the probe threshold L_P at six values of L_2. In one session the six forward masking thresholds were determined first, and immediately thereafter the six pulsation thresholds. The latter were always the average of three consecutive adjustments. The within-session standard deviation was estimated for each threshold (σ_i). Measurements were repeated in ten sessions, over a 5-week period. Table I gives the average thresholds, with the average within-session standard deviation σ_i, and the across-session standard deviation σ_a.

It is clear that in general the across-session standard deviation is quite high, and that it is significantly higher than the within-session value. Only for $L_2 \leq 70$ dB the pulsation threshold shows markedly less variability. This part of the results corresponds with branch (a) of the data to be discussed in Sec. II. It reflects the absence of an effect of L_2 so that the pulsation threshold is approximately set to $L_1 + \Delta L$ (ΔL is the just noticeable level difference). This interpretation is in line with the average level data as well as with their low variability. In the situation where both suppressor and suppressee are effective ($L_2 > 70$ dB), there is no significant difference in variability between the two methods. Because the across-session variability equals about three times the within-session variability, we consider the former to be the relevant. One common interpretation of large across-session variability is instability in the subjects' criterion, possibly due to insufficient training. We feel that the following alternative should be kept in mind, however. It is possible that the physiological state of the auditory system is

TABLE I. Forward masking and pulsation thresholds for one subject (JS) with estimates of within-series and across-series standard deviations. N is the number of replications for each parameter condition. Other parameter conditions are explained in the text.

	Forward masking				Pulsation threshold			
L_2	L_P	σ_i	σ_a	N	L_P	σ_i	σ_a	L_2
55	32.1	1.3	4.5	8	45.7	0.5	0.7	55
65	32.2	1.3	4.1	8	45.7	0.8	0.8	65
70	30.4	1.1	3.9	10	45.6	0.8	1.2	70
75	28.1	1.6	3.8	10	42.6	1.4	2.9	75
80	28.1	1.4	5.1	10	39.6	1.1	3.5	80
85	29.1	1.4	5.2	10	39.9	1.5	4.8	85

varying slowly, thereby changing its characteristics. Logically this is not necessarily a different interpretation, but in concurrent psychophysics it appears to be.

The variability was found to decrease for a masker frequency f_2 approaching the probe frequency. At $f_2 = 800$ Hz we found, averaged over three subjects (JS, HWZ, and HD) and over three masker levels ($L_2 = 75$, 85, and 90 dB; $L_1 = -\infty$), the following results for forward masking: $\sigma_i = 1.0$, $\sigma_a = 1.9$ dB, and for the pulsation threshold: $\sigma_i = 1.2$, and $\sigma_a = 2.2$ dB. Differences between the two methods are again small, and σ_a is again significantly greater than σ_i.

4. Conclusion

Since day-to-day variability is essentially equal for forward masking and pulsation threshold, and since the effects of suppression measured in terms of threshold differences are greater in pulsation threshold, we decided to use the pulsation threshold method for the experiments of this study.

II. RESULTS OF EXPERIMENT 1: TWO-TONE SUPPRESSION AT 1 kHz

The suppressee frequency f_1 was fixed at 1 kHz in the first series of experiments. A representative sample of the data is shown in Figs. 3–10, where the suppressor frequency f_2 is the parameter that changes from figure to figure. Panels within each figure show data for individual subjects. Qualitatively similar results were obtained from five other subjects from whom quantitative data were collected. Eight subjects ran an extensive set of stimulus conditions while three additional subjects were tested at only one condition.

Subjects HvC and DB used presentation mode A, the others used mode B, except HD who used both modes. Most data points are the average of results from at least three different sessions; per session the subject made three adjustments for each stimulus condition. The variability in L_P discussed in Sec. IC is quite representative of the data presented here.

We propose that the data for a fixed suppressee level L_1 can be characterized (Fig. 11) by a horizontal part (a), a descending middle part (b) with slope $-s_b$, and an ascending branch (c) with slope s_c. The smooth line fitting the data points is called the suppression curve. The breakpoint (1) at the transition of branches (a) and (b) is called the suppression threshold because it marks the point where an increase in L_2 causes a decrease in the curve. The depth D of the suppression notch (2) can be considered a quantitative measure of the suppression effect for the given parameter condition. Data from different subjects and conditions differ in size and location of the suppression notch. The above description uses four independent parameters, e.g., suppression threshold, suppression depth (D), and the slopes s_b and s_c. The dashed line (d) with slope s_d connects the suppression thresholds obtainable at different suppressee levels L_1. (Figure 11 shows a suppression curve for one L_1 only.) A necessary condition for suppression to depend on suppressor level only is that suppression

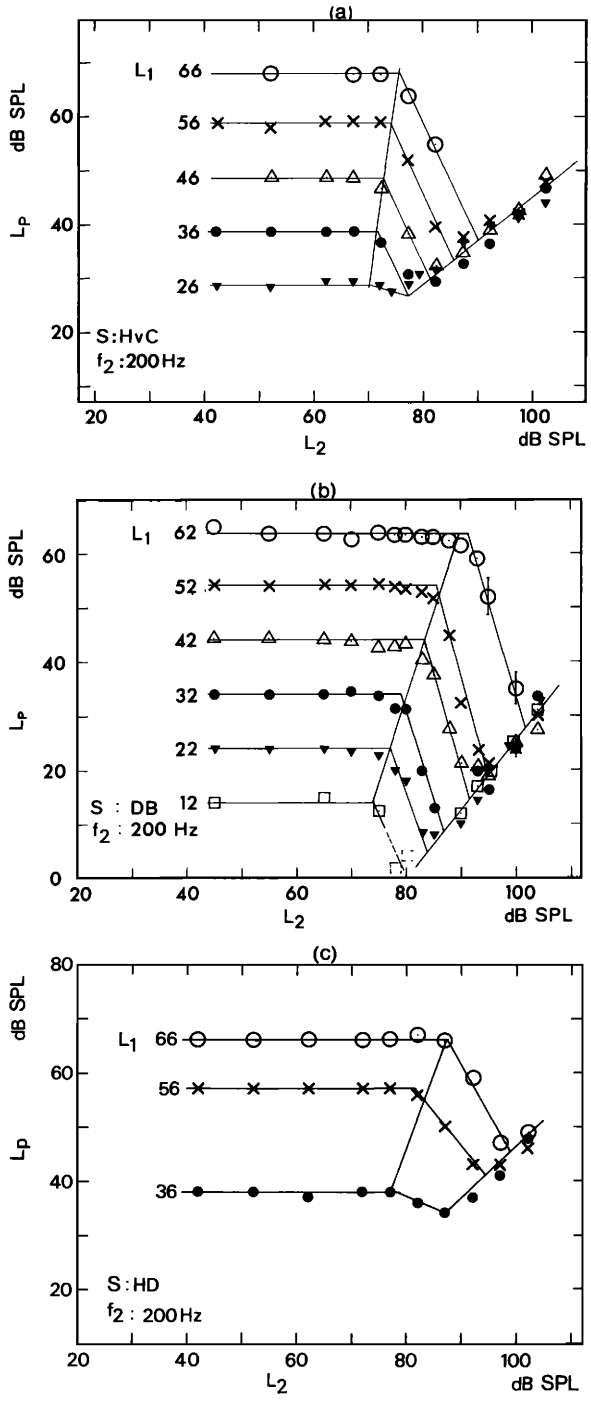

FIG. 3. Psychophysical two-tone suppression data obtained with the pulsation threshold for a 200-Hz suppressor. For the stimulus of Fig. 1 the measured probe threshold L_P is plotted as a function of suppressor level L_2 with suppressee level L_1 as parameter. Note the qualitative similarity and quantitative differences in the right-hand parts of the panels, which give separate displays for three subjects. Presentation mode used: A ($f_1 = 1$ kHz).

thresholds obtain at a fixed L_2, independent of L_1. In terms of Fig. 11 this implies $s_d = \infty$. The alternative interpretation, viz. that the suppression depends on the ratio of suppressor and suppressee amplitudes, or on $L_2 - L_1$, leads to the prediction $s_d = 1$. This results from the fact that the position of branch (a) at the L_P axis follows L_1 linearly (see below).

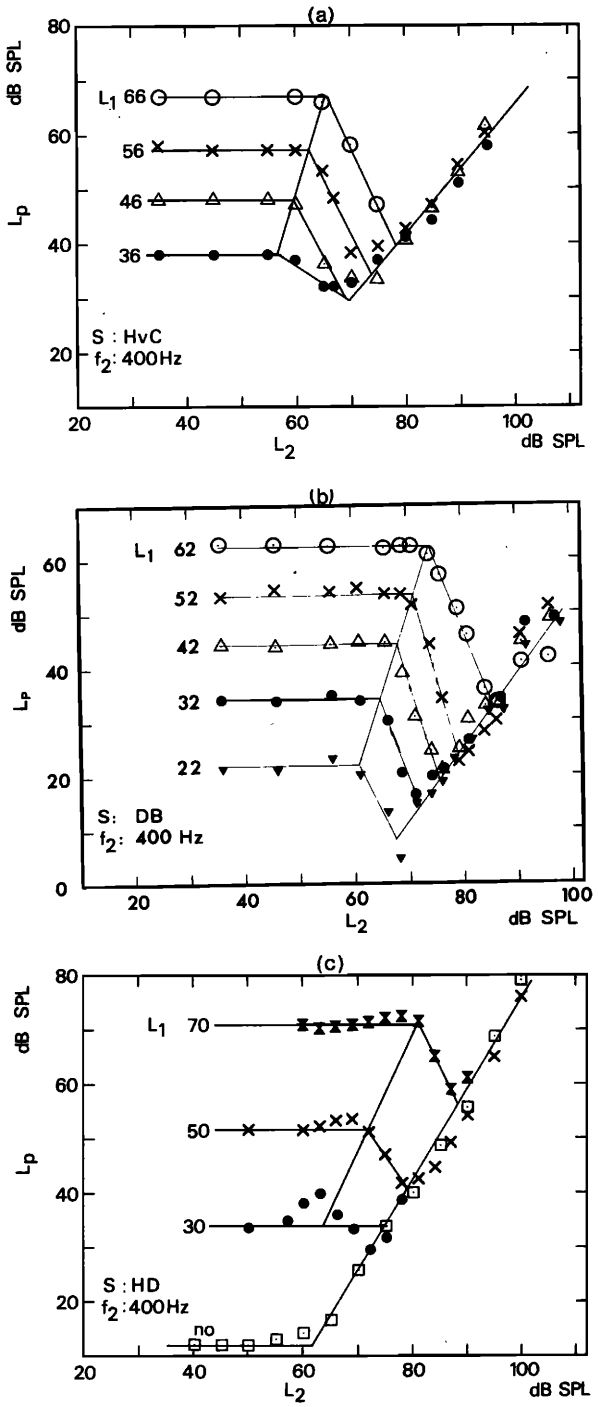

FIG. 4. As in Fig. 3, for a suppressor of 400 Hz. Presentation modes: A in panels (a) and (b), mode B in (c). The no-L_1 data points were obtained in absence of the suppressee.

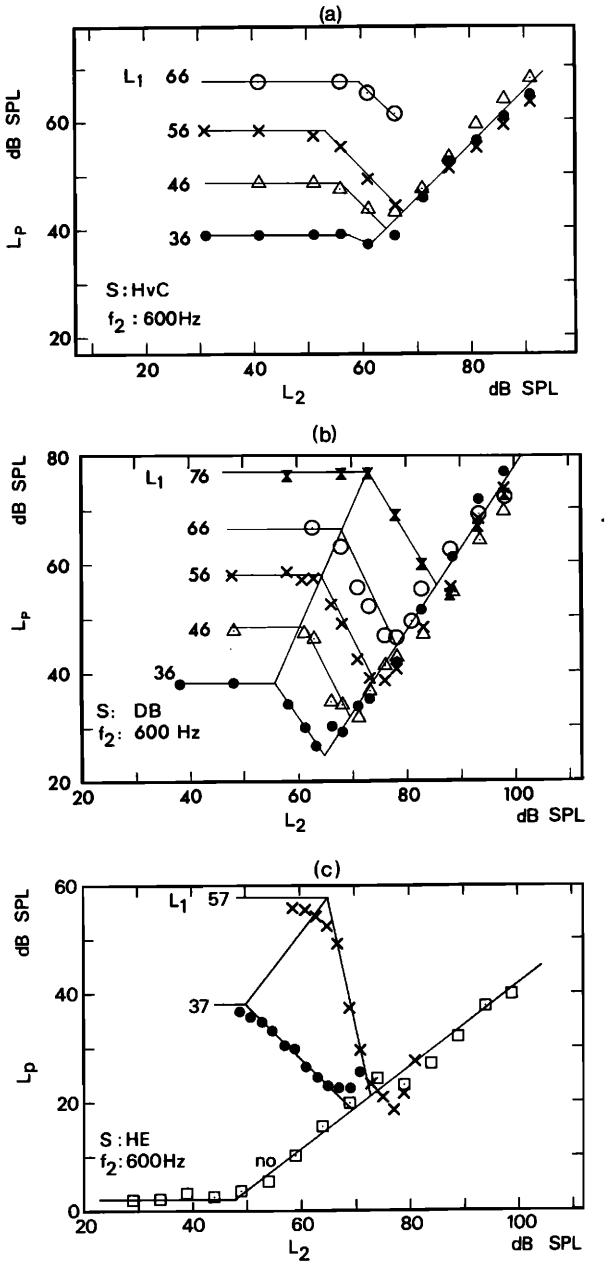

FIG. 5. As in Fig. 3, for a suppressor of 800 Hz. Presentation modes: A in (a) and (b), B in (c).

In view of the proposed characterization and the outcome of the data, it appears appropriate to distinguish the data for $f_2 < f_1$ (Figs. 3–6) from the data for $f_2 > f_1$ (Figs. 7–10). They are described separately in the next subsections.

A. Description of the results for $f_2 < f_1$

Consider the data points for $L_1 = 42$ dB (open triangles) in Fig. 3(b). For $L_2 < 80$ dB, the 200-Hz suppressor has no significant effect on L_p. In this range L_p is adjusted to $L_1 + \Delta L$, where ΔL is the subjects intensity difference limen[3]. Above 80 dB, however, the suppressor has a dramatic effect. A 10-dB increase of L_2 leads to a sharp drop in L_p, to a suppression depth of $D = 25$ dB. A further increase of L_2 beyond 90 dB produces the ascending branch (c). (Throughout the description of the data we use the terminology and notation defined in Fig. 11.)

Turning to other suppressee levels one notes the parallel branches (a) where L_p grows almost linearly with L_1, in line with the intensity difference limen criterion.

The suppression thresholds (1) change systematically with L_1. They fit reasonably well the straight line (d). The slope of this line, s_d, is much greater than 1, but it is also quite different from infinity. This means that neither of the original hypotheses is supported by the

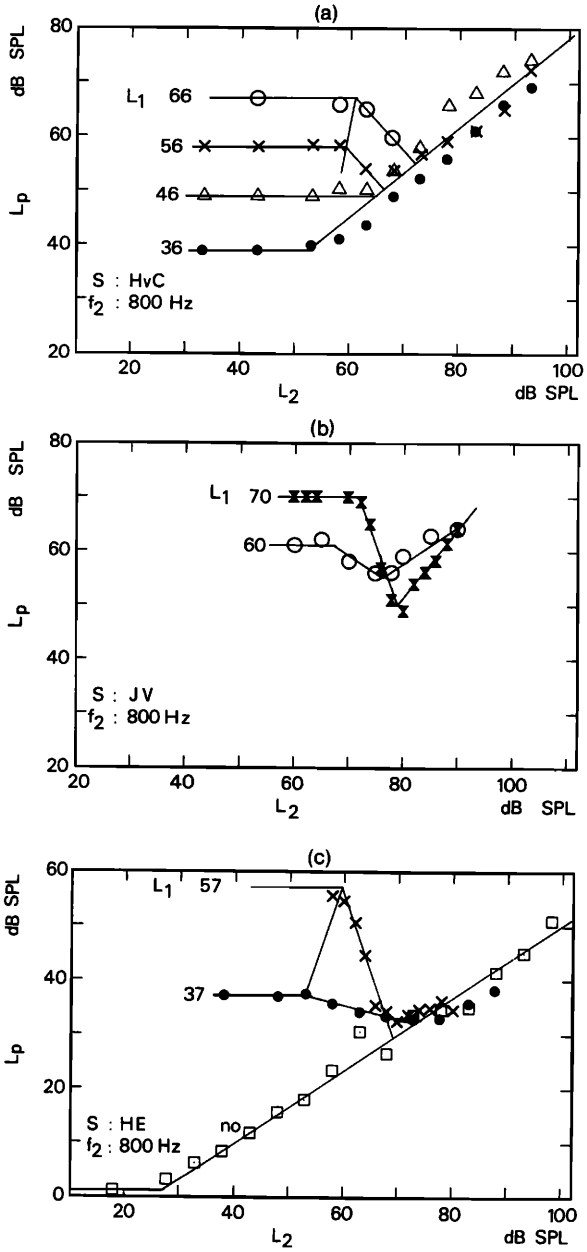

FIG. 6. As in Fig. 3, for a suppressor of 800 Hz. Presentation modes: A in (a), B in (b) and (c).

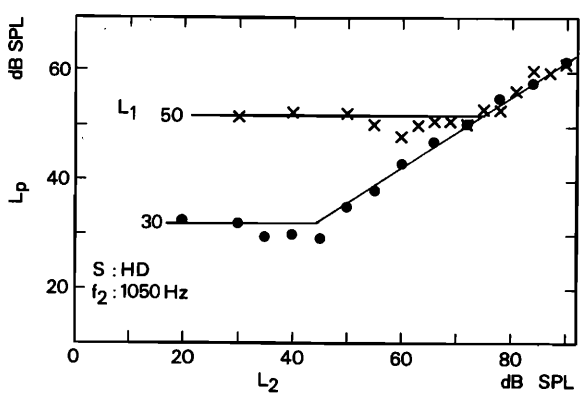

FIG. 7. As in Fig. 3, for a suppressor of 1.05 kHz. Presentation mode: B.

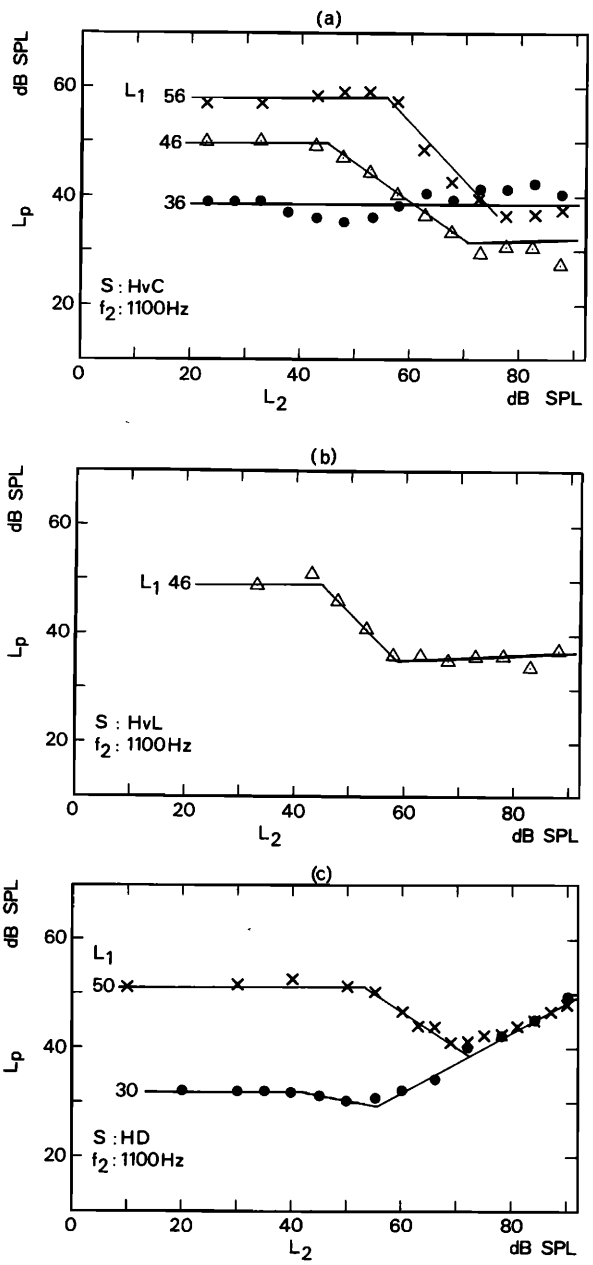

FIG. 8. As in Fig. 3, for a suppressor of 1.1 kHz. Presentation modes: A in (a) and (b), B in (c).

data. Instead, the amount of suppression produced by a fixed suppressor L_2, as well as the amount produced at a constant $L_2 - L_1$, still depends on L_1 and L_2, as can be verified directly from the data.

The slopes of the descending branches s_b in some cases show a tendency to increase with increasing suppressee level L_1 [e.g., Figs. 5(c), 6(c)]. This is most pronounced in the lower L_1 range. At higher L_1 ($\gtrsim$50 dB SPL) it is not possible to conclude on the basis of the present data that the descending parts are not parallel.

The suppression depth D increases monotonically with suppressee level L_1.

The ascending branches (c) are generally asymptotic with a single line when $L_2 \gg L_1$. This suggests that this part of the curve is determined by L_2. To check this,

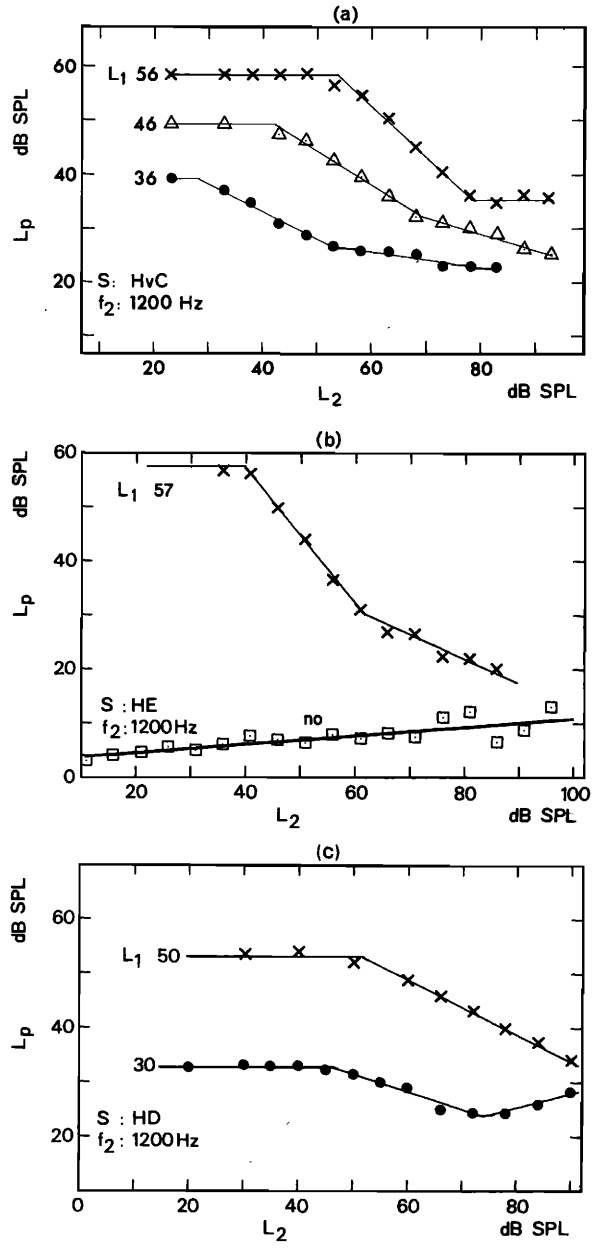

FIG. 9. As in Fig. 3, for a suppressor of 1.2 kHz. Presentation modes: A in (a), and B in (b) and (c). Note that the descending branch tends to fall off more steeply at the beginning than at the end.

several series were run without suppressee ($L_1 = -\infty$). Data are shown in Figs. 4(c), 5(c), 6(c), and 9(b). In some cases it was found that data curves at high suppressee levels crossed those at lower suppressee levels before converging to the asymptote [Figs. 6(b), (c)]. This could indicate that the suppressor itself is suppressed by the suppressee, thus requiring a higher suppressor level for the same pulsation threshold. In view of the error margin of the data (Sec. IC) it is uncertain whether the latter effect is significant. The assumption that L_2 governs the asymptotic behavior appears to be corroborated.

Comparisons among subjects [e.g., Figs. 5(a), (b), and (c)] show that, although the gross qualitative patterns are identical, marked quantitative differences

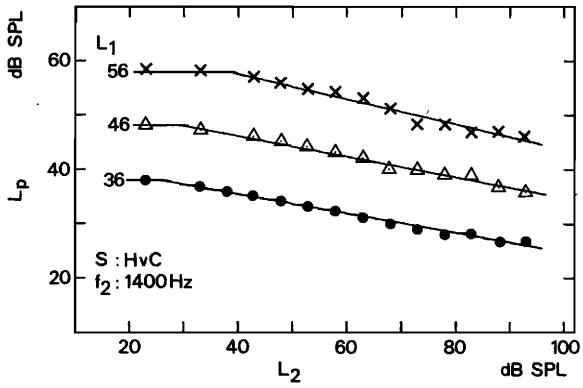

FIG. 10. As in Fig. 3, for a suppressor of 1.4 kHz. Presentation mode: A.

emerge. Slopes s_b, s_c, and s_d differ, and for a fixed L_1 the location of the suppression threshold as well as suppression depth are subject-dependent. For $L_1 \approx 55$ dB, the suppression threshold assumes values of 73 (HvC), 80 (HD), and 85 dB (DB). We observed that suppression thresholds can differ by as much as 20 dB between normal subjects! The suppression depth, too, is quite variable. For the conditions and subjects referred to above we find approximately $D = 22$ (HvC), $D = 14$ (HD), and $D = 33$ dB (DB).

Within subjects, the increase of suppressor frequency f_2 (see Figs. 4–6), has a slight effect on the slopes s_b, s_c, and s_d. The major effect is that the asymptote (c) and line (d) shift to lower L_2 values. Line (c) tends to shift more than (d) so that the amount of suppression decreases. These trends are apparent in all data, but again there are large quantitative differences. For $L_1 \approx 45$ dB the suppression threshold shifts by about 15 dB for HvC and about 30 dB for DB if f_2 changes from 200 to 600 Hz.

Summing up the primary results, we have found that strong suppression effects emerge for $f_2 < f_1$ amounting to suppression depths of as much as 30 dB. Intersubject variability is almost as marked as the suppression effect. Intrasubject variability, although quite large, is

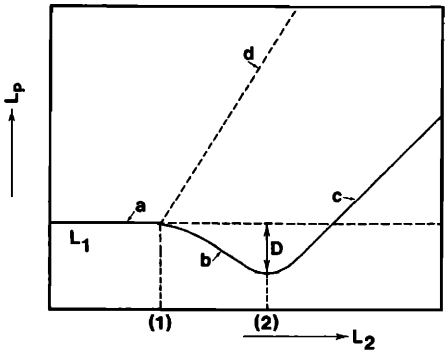

FIG. 11. Schematic characterization of the two-tone suppression data for a fixed L_1. The ordinate gives the pulsation threshold L_p as a function of suppressor level L_2. Breakpoint (1) is termed the suppression threshold. The deepest point of the suppression notch (2) defines the suppression depth D. The dashed line (d) connects suppression thresholds for different suppressee levels L_1 (not shown). Slopes of (b), (c), and (d) are denoted s_b, s_c, and s_d.

significantly smaller. The amount of suppression depends in a complex way on suppressor level as well as on suppressee level.

B. Description of the results for $f_2 > f_1$

The data in Figs. 7–10 show some features similar to those in Figs. 3–6. Again suppression effects of $D > 20$ dB emerge. But some marked differences can also be observed. The general fit to Fig. 11 is poorer. The ascending branch (c) requires too high suppressor levels if f_2 increases above 1.1 kHz. This is not surprising in view of the fact that the psychophysical tuning curve (e.g., Houtgast, 1973; Vogten, 1974, 1978; Zwicker, 1974; Moore, 1978) is very steep on the high-frequency side, so that these frequencies are virtually unable to elicit an actual response at f_1.

Another feature is that the slope of the descending branch s_b decreases significantly as f_2 increases. For a fixed f_2 the increase of this slope with L_1 seems to be somewhat more apparent than in the data for $f_2 < f_1$. In a number of cases the descending branch (b) shows a breakpoint without, or before, approaching the ascending asymptote [e.g., Figs. 9(a), (b)]. The slope s_d of the line connecting the suppression thresholds tends to be significantly smaller than for $f_2 < f_1$. Also, the suppression thresholds tend to occur at lower masker levels, especially as long as $L_1 \lesssim 60$ dB.

Subjectively, the experiments with $f_2 > f_1$ are more difficult than those with $f_2 < f_1$ because of the presence of combination tones. The existence region for odd-order combination tones shows a marked similarity with the high-frequency, two-tone suppression "region." Because the pulsation threshold method supposedly guides the listener's attention to the "probe channel" we suspect, however, that the combination tones have only a minor effect on the pulsation threshold. This point deserves direct experimental verification.

Before discussing the above results we first describe experiments 2 and 3, and present their results.

III. RESULTS OF EXPERIMENT 2: TWO-TONE SUPPRESSION AT OTHER FREQUENCIES

In order to check the generalizability of the 1-kHz data, additional data were collected at $f_1 = 0.5$, 2, and 4 kHz. Two subjects (JV and MS) participated in this experiment. Only two suppressee levels were presented in most cases. Results of one subject (JV) at one suppressee level, $L_1 = 60$ dB, are presented in Fig. 12. Panels (a) to (d) show results for f_2/f_1 ratios of 0.2, 0.4, 0.6, and 1.2, respectively. The parameter within each panel is f_1.

Since measurements were not extended beyond $L_2 = 90$ dB SPL, the ascending branches are missing in Figs. 12(a), 12(b) (except for $f_1 = 4$ kHz), and 12(d). In other respects the results are qualitatively similar to the data presented in Figs. 3–5, and 9.

For $f_2 < f_1$, quantitative differences emerge. At $f_2 = 0.2 f_1$ [Fig. 12(a)] we observed no suppression for $f_1 = 4$ kHz. $L_2 = 90$ dB produces significantly more suppression at $f_1 = 1$ than at $f_1 = 0.5$ kHz. This, however, may be due to different auditory sensitivity for the two corresponding maskers, which occur at 200 and 100 Hz, respectively. From Figs. 12(b) and 12(c) it is concluded

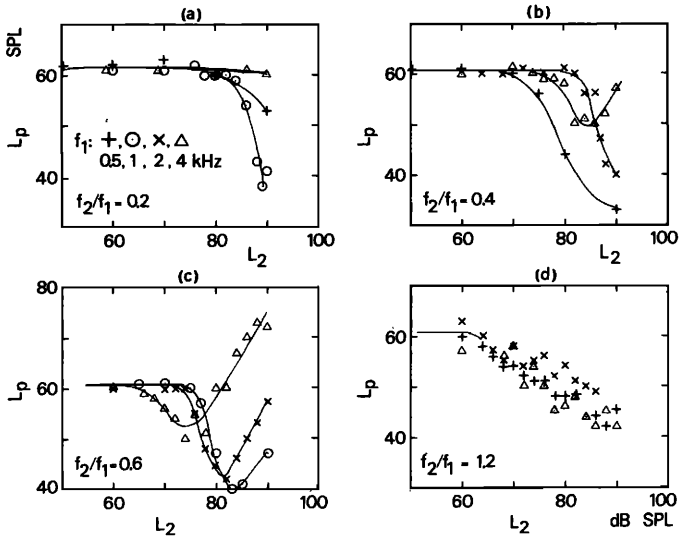

FIG. 12. A sample of two-tone suppression data at different suppressee frequencies f_1. Layout as before. $L_1 = 60$ dB. Each panel combines data with equal f_2/f_1 ratio. (In all cases only three of the four possible f_1 values are available.) Subject: JV; presentation mode: B.

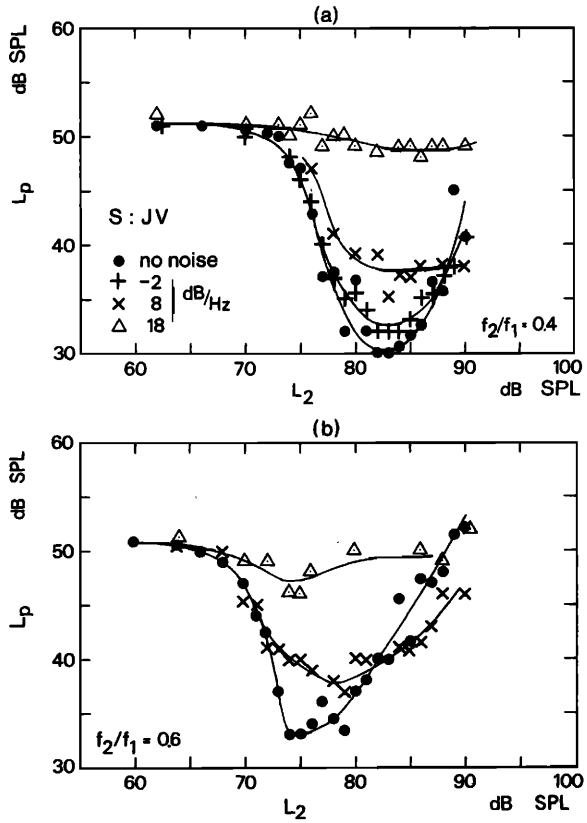

FIG. 13. Two-tone suppression data (layout as before) at $f_p = f_1 = 2$ kHz and $f_2 = 800$ Hz or 1.2 kHz [Panel (a) or (b)], for several continuous white-noise backgrounds. Parameter is the spectral density of the noise in dB/Hz. (Note that the scales have been expanded; divisions occur at every 5 dB instead of every 10 as before.)

that suppression depth D decreases with increasing f_1. The suppression threshold, however, shows a nonmonotonic behavior. It is relatively low at $f_1 = 0.5$ kHz, increases at $f_1 = 1$ or 2 kHz, and decreases again at 4 kHz.

The results for $f_2 = 1.2 f_2$ [Fig. 12(d)] are approximately independent of frequency. The minor systematic differences hardly exceed the expected range of variability.

Data for the other subject were similar in virtually all respects noted above. The results at other suppressee levels (compare the no-noise data in Fig. 13) tended to corroborate the findings of Sec. II. However, the tendency of suppression depth D to increase with increasing suppressee levels was no longer found at $f_1 = 4$ kHz.[4]

IV. RESULTS OF EXPERIMENT 3: TWO-TONE SUPPRESSION IN A BACKGROUND OF CONTINUOUS WHITE NOISE

The two subjects of experiment 2 participated in an experiment to determine the effect of a continuous white noise background on two-tone suppression. A number of experimental conditions in which a clear suppression effect had been measured were rerun with continuous white noise added to the stimulus. The noise was presented at the following spectral densities: $N_0 = -2$, 8, and 18 dB/Hz. Typical results are shown in Fig. 13.

The major effect of the noise is to "fill up" the suppression notch, or to decrease the suppression depth D. A 10- to 20-dB increase of noise level suffices to reduce D from near maximum to zero. The second observer fully corroborated these results. A second effect that was observed regularly was that the suppression notch extends towards the right at "moderate" noise levels. This is apparent, for example, in Fig. 15(b), where the curve for $N_0 = 8$ dB/Hz falls below the no-noise curve for $L_2 > 80$ dB. At the highest noise levels used, the present data provide no reliable information on the presence of an ascending asymptote.

V. DISCUSSION

A. Relation to other psychophysical two-tone suppression data

1. Pulsation threshold data

Houtgast (1972) first demonstrated the existence of psychophysical two-tone suppression using the pulsation threshold technique for the stimulus condition $L_2 = 60$ dB, $f_2 = 1$ kHz, $L_1 = 40$ dB, in the range $0.5 < f_1 < 0.95$ kHz. Maximum suppression, $D \approx 8$ dB, occurred at about $f_1 = 0.9$ kHz. Suppression decreased gradually as f_1 decreased, and it decreased sharply with increase of f_1 above 0.9 kHz. No suppression was apparent for $f_2 < f_1$. The results are confirmed and extended in Houtgast's (1973) study. At a higher suppressor level ($L_2 = 80$ dB) suppression was found on both sides of f_2. For a 300-Hz suppressor at approximately 72 dB, however, no suppression was found for $f_2 < f_1$. In later experiments f_1 was fixed at 1 kHz, L_1 at 40 dB, and suppression was measured as a function of f_2 and L_2. Data are reduced to suppression contours in an L_2 vs f_2 plot. This facilitates the comparison with neural data. A similar plot of our two-tone suppression data for HvC is given in Fig. 14. The figure gives 3 dB suppression contours for a fixed probe frequency of 1 kHz at three different levels of L_1 (within the V-shaped contours, suppression is more than 3 dB). Our results at the lowest suppressee level, $L_1 = 36$ dB, are very similar to Houtgast's data at 40 dB. It is clear from Fig. 14, as it was already from Figs. 3–6, that for $f_2 < 1$ kHz the suppression area grows significantly with increasing L_1. An analysis of the data of Houtgast (1974a, Fig. 5.3) confirms the finding that the slope s_b of the descending branch (see Fig. 11) of the suppression curve is quite steep for $f_2 < f_1$ and gradually decreases as f_2 increases above f_1. The novel aspect in our data, then, is that we have systematically studied level effects in order to find the slopes s_b, s_c, and s_d (Fig. 11). This led us to discover that suppression is not merely an effect of suppressor–suppressee amplitude ratio but that it also increases as the overall level increases. This does not seem very surprising in the context of the idea that the higher the levels, the more pronounced the effects of the nonlinearity will be. This point will be returned to in Sec. VC.

2. Forward masking data

Shannon (1976) measured two-tone suppression using forward masking. (Because the forward masking data differ quantitatively from the pulsation threshold data, see also Sec. IC, Shannon used the term unmasking instead of suppression.) He too used a limited set of level parameters. Most of his data are for $L_1 = 40$ dB and $f_1 = 1$ kHz, with f_2 as the independent variable. He never found more than 10 dB suppression for $f_2 > f_1$, and only once more than 5 dB for $f_2 < f_1$. This underscores Houtgast's (1973) conclusion that the pulsation threshold reveals greater effects (cf. Sec. IC). In so far as Shannon's data exhibit sufficiently large suppression to show significant differences in the suppression effect, the following trends appear. Suppression in-

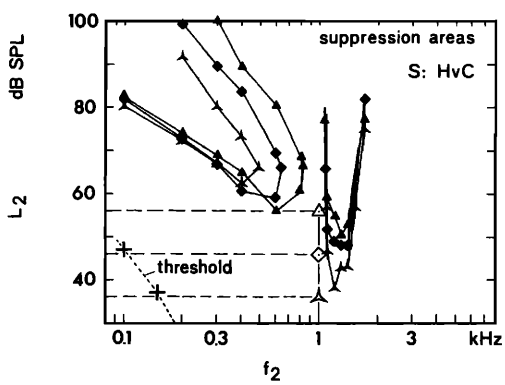

FIG. 14. Two-tone suppression areas on both sides of a fixed tone at 1 kHz for three levels of the fixed tone (suppressee) L_1. The open symbols at 1 kHz indicate the L_1 values for the data points with the corresponding filled symbols. The data points result partly from Figs. 3–10. The points mark the L_2 interval with more than 3-dB suppression.

creases as L_1 increases (his Fig. 7). For $f_2 < f_1$ suppression increases as the overall level increases ($L_2 = L_1 + 20$ dB); for $f_2 > f_1$ the differences are judged to be insignificant (his Sec. III B). Shannon also found that suppression results for equal f_2/f_1 ratio were similar. One out of his five subjects, however, did not show suppression at 1 or 2 kHz, but observed it at 4 and 6 kHz. Two of Shannon's summarizing conclusions refer directly to level effects. One states that for $f_2 < f_1$ suppression depends only on L_2. The other concludes that for $f_2 > f_1$ suppression depends on $L_2 - L_1$. If we confront these conclusions with our data, then the first conclusion, which implies that $s_d = \infty$ for $f_2 < f_1$, could apply only to HvC's 600- and 800-Hz data. For all other subjects, s_d is significantly smaller. Moreover, L_1 determines the location of breakpoint (2), which is the point where maximum suppression occurs. Shannon's first conclusion, therefore, is not generally valid. His second conclusion implies that for $f_2 > f_1$ the slope $s_d = 1$ and that the descending branches (b) are parallel. Our data on this point are less clearcut, but again Shannon's characterization appears to oversimplify the data somewhat. At 1.1 and 1.2 kHz, for instance, HvC's data [Figs. 8(a) and 9(a)] give the impression that the descending branches are not precisely parallel. Therefore, we consider Shannon's statements as a first-order description of the data, which, upon closer inspection, needs significant refinements.

3. Backward masking data

Tyler and Small (1977) demonstrated two-tone suppression in backward masking. They used the stimulus parameters $f_1 = 1$ kHz, $L_1 = 40$ dB, and $L_2 = 70$ dB, with f_2 as an independent variable. All subjects showed suppression for $f_2 > f_1$, and two out of five found suppression for $f_2 < f_1$. Suppression was never more than 10 dB. For $f_2 > f_1$ maximum suppression occurs on the average at 1.5 kHz. This is high compared with the high-frequency suppression areas in pulsation threshold and forward masking, where maximum suppression occurs at about 1.2 kHz (Houtgast, 1973, 1974a; Shannon, 1976; this study, Fig. 14). The result that only two subjects showed suppression for $f_2 < f_1$ could be caused by the choice of level parameters. At the levels used by Tyler and Small, for instance, not all of our subjects showed suppression for $f_2 < f_1$, whereas they did at appropriately higher levels.

There are some interesting problems with the possible interpretation of suppression in backward making. Duifhuis (1973) suggested that backward detection masking is caused by transients in the responses of the peripheral ear. This classifies it as a sort of internal simultaneous masking, so that in line with the reasoning in Sec. IA, no suppression would be expected. Weber and Green (1978, 1979) reported that suppression was much more pronounced in backward masking than in forward masking. This seems to contradict our ideas. However, they also report that the suppression in backward masking is almost negligible if the suppressor is a tone rather than a noise band. They conclude, also on the basis of other experimental data, that the suppression which they measured is a central rather than a peripheral process. More recently, Nackmias and Green (personal communication) have found that the backward masking data reported were not the detection thresholds, but apparently some other. Detection thresholds for a noise band suppressor also showed little or no suppression. Although this is consistent with our interpretation, it leaves the question what thresholds were measured in Weber and Green's studies, and how these and Tyler and Small's data are to be interpreted.

4. Weber function

Another point of interest, which will be addressed only briefly here, is the behavior of the asymptotic slopes s_c as a function of $f_2/f_1 (f_1 = f_P)$. Inspection of the data in Figs. 3–10 shows a systematic trend which is somewhat oversimplified by stating that, for $f_2 < f_1$, s_c is most often steeper than 1, and for $f_2 > f_1$ it becomes significantly smaller than 1. This effect was earlier reported in simultaneous masking by Wegel and Lane (1924). Weber's law (except for the "near miss") appears to hold only if $f_2 = f_1$. Recent data on the issue confirm this result both in simultaneous masking (Schöne, 1977; Vogten, 1978) and in pulsation threshold (Verschuure, 1978). These data are relevant to the theory of auditory nonlinearity. The asymmetries around $f_1 = f_2$, both in s_c and in suppression, suggest a common underlying mechanism.

5. Suppression by noise

The results of experiment 3 are related to data where wide-band noise acts as a suppressor (Houtgast, 1972, 1974a; Leshowitz and Lindstrom, 1977; Terry and Moore, 1977; Weber, 1978; Jesteadt and Javel, 1978) Houtgast showed that wide-band noise is able to suppress the response to a tone added to the noise, the other data suggest that in a wide noise band the center part of the band (around the probe tone frequency) is suppressed by the lateral parts. Considering Fig. 14, it is plausible that this is due to the parts of the noise band just above and below the test tone frequency that fall in the suppression areas (cf. Houtgast, 1974a, and Weber, 1978). In our case the background noise is thus able to suppress the suppressee. If suppression obtained in this way is significant, then addition of the tonal suppressor does not necessarily amplify the suppression effect. Suppression is a nonlinear phenomenon, so that one should not expect the effects of two added suppressors to add up. It is more likely that the more effective suppressor will dominate the suppression effect. In other words, the suppression effect appears to be "used up" by the dominant suppressor, and the second suppressor is ineffective. The continuous background noise affects both probe and suppressee. Therefore, suppression is not apparent in a downward shift of the horizontal branch (a) of the suppression curve, which supposedly reflects equality of the responses to probe and suppressee.

6. Variability

Day-to-day variability in the pulsation thresholds reported here is characterized reasonably well by the data in Table I. Although we consider it quite high, it does

seem to be exceptional in comparison with other data. Verschuure (1978) indicates values of σ_a from 1 to 4 dB in his Figs. 13–15, measured with a single masker. Most other experimenters give less explicit data on variability within subjects. There are, however, several reports on variability amongst subjects. Fastl (1975) reports interquartile ranges of over 15 dB in pulsation thresholds measured in eight subjects. Houtgast (1974a) gives 2σ confidence intervals in the frequency domain, which would correspond to level ranges similar to the above values. Thus, it is a consistent finding that there are marked quantitative differences in the subjects' responses in these tasks.

B. Relation to neurophysiological two-tone suppression data

Houtgast (1972, 1973, 1974a) has pointed out the marked similarities between psychophysical and neural (auditory nerve) data (Nomoto *et al.*, 1964; Sachs and Kiang, 1968; Arthur *et al.*, 1971) on two-tone supression. Starting from his observation, we will in this paper examine the similarity in the details of level effects. Two studies in particular contain data that are suitable for a comparison: those of Abbas and Sachs (1976) and Javel *et al.* (1978). Furthermore, Abbas' recent paper (1978) gives a direct comparison of physiological and psychophysical data on the effect of suppressee frequency in two-tone suppression. In both cases suppression was most prominent with the suppressor at the characteristic frequency or at f_P.

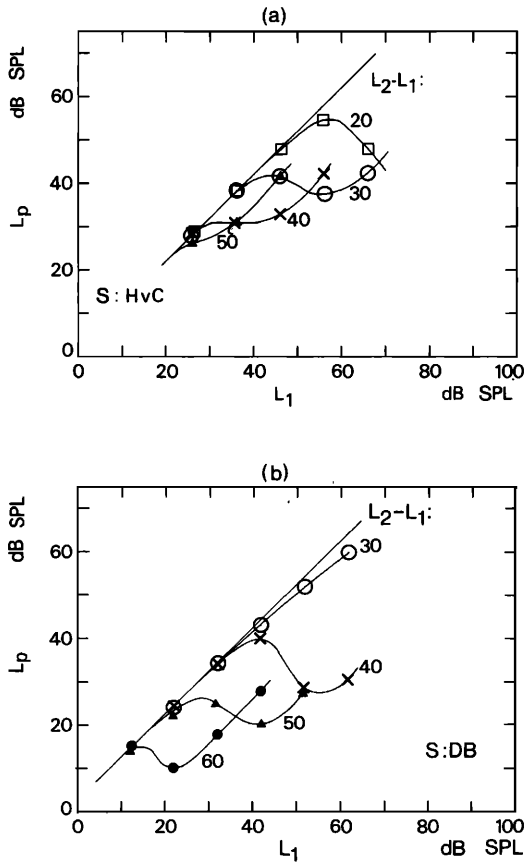

FIG. 15. Two-tone suppression as a function of overall masker level with suppressor/suppressee ratio (L_2-L_1) as a parameter. Data in panels (a) and (b) for two different subjects are derived from Figs. 3(a) and (b), so that $f_1=1$ kHz and $f_2=1200$ Hz.

Besides the all too obvious caution that should be exercised when comparing neural data (different species, anaesthetic) with psychophysical data, one point is very obvious when we are dealing with level effects. Responses in auditory-nerve fibers have a very limited dynamic range, at the upper end of which saturation occurs. In psychophysical data no clearcut evidence of saturation is at present available. On the one hand, this is a complicating factor, but on the other hand, it may be illuminating in suggesting that phenomena that are apparent in both psychophysical and neural data are not attributable to the saturation mechanism.

Abbas and Sachs (1976) observed that for $f_2<f_1$ the suppression threshold increases somewhat as the suppressee level L_1 increases ($s_d<\infty$), but not as fast as L_1 ($s_d>1$). The slope of the decreasing branch s_b^* in log normalized fractional response per dB is independent of L_1(their Figs. 3 and 4). If the overall level is increased, the response tends to be nonmonotonic, showing a local maximum near the point where the response déviates from the suppressee-alone response and a local minimum where the suppressor-alone response is approximated. All these descriptions also apply to our data, with some reservation about the second point. This is illustrated in Fig. 15 with a replot of data from Figs. 3(a), and 3(b), where L_2-L_1 is the parameter and L_1 (or L_2) the independent variable. Panels (a) and (b) for HvC and DB, respectively, indicate again large quantitative intersubject differences.

For $f_2>f_1$ Abbas and Sachs' data exhibit a suppression threshold which, to a first approximation, depends on L_2-L_1 only (their Fig. 1). However, for a unit driven into saturation, the suppression threshold tends to shift more than proportionally with level. This means that at the lower levels $s_d\approx 1$, and at higher levels $s_d<1$. Also a slight tendency for s_b to decrease with increasing L_1 emerges. This latter effect is not observed in the psychophysical data. A very marked effect, again in agreement with our data, is that the slope s_b decreases markedly with increasing f_2. Finally, for $f_2>f_1$ the responses increase monotonically with increasing overall level.

Javel *et al.* (1978) show data for $f_2>f_1$. The data can be summarized as follows: The amount of suppression depends only on suppressor level. Suppression increases as L_2 increases, and it decreases, for a fixed L_2, as f_2 increases (beyond $1.2f_1$). Their first conclusion is clearly at variance with psychophysical data, but at first glance it does not seem to describe Abbas and Sachs' data either. Nevertheless, Sachs and Abbas (1976) were able to interpret their data in much the same way as Javel *et al.* We return to this point in Sec. VC. Another interesting observation made by Javel *et al.* (1978) is that the amount of suppression depends on the separation between displacement peaks established by f_2 and f_1 on the basilar membrane. This conclusion could be a more precise statement of our subsequent conclusion that suppression depends to a first

approximation on the ratio of f_2/f_1 and not on their respective values.

C. Theoretical implications

In this subsection we evaluate predictions of current two-tone suppression theories against data on level effects in suppression.

Duifhuis' (1976a) model can be regarded as an elaboration of the BPNL model proposed by Pfeiffer (1970), who was in turn inspired by Engebretson and Eldredge (1968). Duifhuis assumed that the tuning frequency of the first filter was about 1.2 times that of the second, and the compressive nonlinearity was approximated by a power-law relation. Predictions of the model and the deviations and similarities with data as presented in this paper are discussed in Duifhuis (1977). The conclusion is that for a BPNL model with an essential power-law nonlinearity, two-tone suppression depends on $L_2 - L_1$ and not on the respective levels. The dependence on the ratio f_2/f_1 is governed by the filter transfer functions. Specific predictions are the general shape of Fig. 11, with the parameter values $s_a = 0$, $s_b = 1/\nu - 1$, $s_c = s_d = 1$ (ν the power of the nonlinearity). The most distinct deviation of data from the model is that the data show $s_d > s_c \geq 1$. This causes the suppression depth D to vanish at low levels. The data suggest that at low levels the system behaves more or less linearly.

Hall (1977) assumes that the neural response is related directly to the first or second spatial derivative of the traveling wave along the basilar membrane. Further he assumes that basilar membrane damping grows (quadratically) with membrane velocity. At high levels this nonlinearity gives approximately a cubic-root relation between velocity and pressure. At low levels, however, the relation is linear. As in Duifhuis' model, the power-law relation predicts that suppression depends on the ratio of suppressor and suppressee amplitudes, or on $L_2 - L_1$.

Zwislocki and Sokolich (1974) presented a model for auditory nerve responses, based on an antagonistic interaction between activities from inner and outer hair cells that produces two-tone suppression. However, the model is not sufficiently quantitative to allow a comparison with data on level effects in two-tone suppression. Moreover, recent data on tuning of hair cells (Russell and Sellick, 1977) led to the proposal of an alternative sharpening mechanism in the organ of Corti (Zwislocki and Kletsky, 1978, 1979). As the Duifhuis (1976a) model, this model focuses attention on the radial driving component of the hair cells. At this point it is not clear what implications the new model has as regards two-tone suppression. The finding of two-tone suppression in cochlear microphonics (Legouix *et al.*, 1977) lends support to the notion that the nonlinearity producing two-tone suppression (and at the same time sharpening and combination tone generation, see Duifhuis, 1976a) should be located at or before the hair cell level. The data mentioned above, therefore, appear to contradict Manley's (1977) model of sharpening, which also claims an as yet unquantified effect of two-tone suppression.

Sachs and Abbas (1976) presented a phenomenological model for two-tone suppression. Basically it consists of a nonlinear gain factor, governed by the suppressor only, followed by a saturation. The model quantifies their claim, supported by Javel *et al.* (1978), that two-tone suppression depends on suppressor level. Figure 16(a) schematically depicts the consequences of this assumption. In the unsaturated response the suppression threshold is independent of the suppressee level L_1 (the threshold is at the vertical dashed line). The experimental finding that the suppression threshold increases with suppressee level L_1 may at first glance appear to contradict the model's prediction. However, in Sachs and Abbas' model, this behavior follows from the subsequent saturation. The higher the value of L_1 the more suppression is needed to arrive at an unsaturated response. Thus, the suppression threshold is

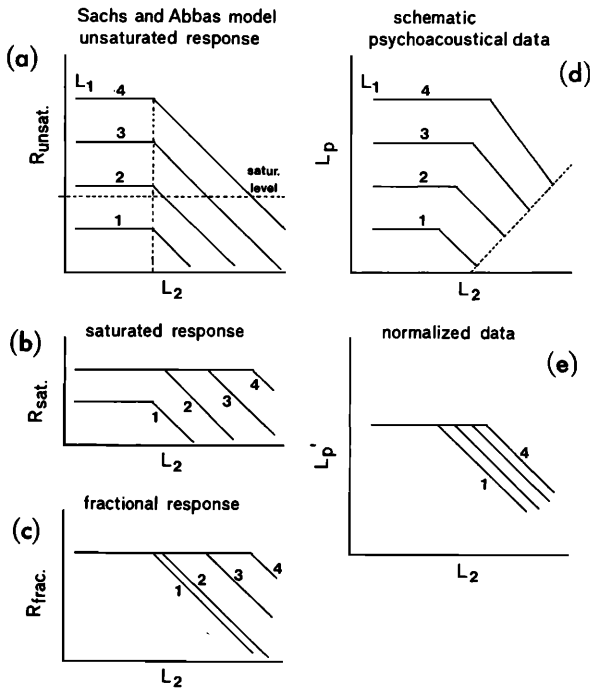

FIG. 16. Illustration of the dependence of the two-tone suppression threshold on suppressee level L_1 in the Sachs and Abbas model (left-hand panels) and in psychophysical data (right-hand panels). Arbitrary logarithmic scales are used. Suppressee level increases from curves 1–4. The top-left panel shows the assumed effect of a multiplicative suppression which depends on L_2 only, before saturation takes place. Here the suppression threshold is independent of L_1. The saturation level of the following saturation is indicated by the horizontal dashed line. The middle left panel presents the effect of a very schematic hard-limiting saturation. Now a shift of suppression threshold with L_1 is apparent. Normalization of the data to fractional response in the lower left panel gives essentially the same pattern, but it is noted that for all levels that do not drive the system into saturation, like curve 1, the fractional response curves will merge to a single line. This means that for low levels the suppression threshold is not expected to shift with L_1. The top-right panel gives schematic data of experiment 1. The suppression threshold changes with L_1 although no signs of saturation are apparent. When normalized (bottom right) the result is similar to panel (c) (bottom left).

predicted to shift with L_1, as indicated in Fig. 16(b). (In this schematic plot we assumed a hard-limiting saturation.) As long as saturation plays a role, the step of normalizing the saturated response to "fractional response" (Abbas and Sachs, 1976) does not markedly affect the picture [Fig. 16(b), (c)]. It is noted that the amount of shift of the suppression threshold depends on the slope of the decending branch s_b. Except for a minor point, viz. that the model does not specify where and how the suppressor can become excitatory [branch (c) in Fig. 11], all neural data can be fitted by parameter adjustment. This requires the proper choice of three free parameters; a fourth parameter is based on single-tone intensity response curves. Four parameters also describe our data (see Sec. II). A more serious problem with the model is that it requires saturation for the suppression threshold to depend on L_1. This makes it invalid for psychophysical data [Fig. 16(d)] where we are dealing with Weber's law (applicable for the present purpose) rather than with hard-limiting saturation. However, when normalized similarly to the neural data psychophysical and neural behavior of the suppression threshold as a function of L_1 are very similar (Fig. 16(c), 16(e)]. Therefore, we suspect that the conclusion reached by Sachs and Abbas, and by Javel *et al.*, viz. that the amount of suppression depends on L_2 only, is an artefact of normalization and saturation. It does not characterize the suppression mechanism.

Thus, the present models of two-tone suppression do account for several aspect of the data, but no model appears to be complete. This paper has presented additional data to impose new limits on further theorizing.

VI. CONCLUSIONS

Psychophysical two-tone suppression was observed for each of 11 listeners. Data are presented for six of them. Listeners used the pulsation threshold to measure the effect.

At the appropriate levels and frequencies, suppression effects of several tens of decibels were found both for $f_2 > f_1$ and for $f_2 < f_1$.

The effect of level on suppression is "nonlinear," i.e., suppression is more prominent at higher levels than at lower levels.

Suppression is very dependent on the subject; therefore our data are not averaged across subjects. Only the general shape of the suppression data is constant. The absolute amount of suppression, as well as the dependence on level, are highly variable.

The amount of suppression depends not only on suppressor and suppressee frequencies (f_2, f_1) but also on suppressor level and suppressee level (as well as on the subject). This contradicts claims in the literature that it is determined solely by the suppressor level.

The amount of suppression can be reduced by the addition of a background of continuous white noise.

Current theories are unable to predict precisely the level effects which emerge from the data.

ACKNOWLEDGMENTS

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[1]The use of the term suppression was first advocated by Hind *et al.* (1970) for the phenomenon that the addition of a second tone could reduce the response to a tone at the characteristic frequency of an auditory-nerve fiber. Hitherto the phenomenon had been termed two-tone inhibition. Since it was doubtful whether true neural inhibition was involved at auditory-nerve fiber level, it appeared desirable to use the more neutral term suppression. The psychophysical phenomena studied by Houtgast were considered to be so similar to the neural phenomena that it was deemed appropriate to use the same term in psychoacoustics, thereby suggesting that the two phenomena reflect a single mechanism in auditory processing. We support this hypothesis and therefore prefer the use of the term "suppression" to the use of "unmasking," an admittedly less pretentious term.

[2]In some of the experiments T was 240 ms, in others it was 250 ms. The difference was imposed by limitations of the timing and gating apparatus available at the time. Since the extremum in the modulation transfer function is relatively broad, we assume that this difference has no effect on pulsation threshold data. Houtgast too (1973, p. 170) remarks that "Neither the exact way of smoothing, nor the exact alternation rate of 4 Hz, were found to be very critical."

[3]The pulsation threshold criterion is "one sided," hence the plus sign. At pulsation threshold the probe sounds continuously, above pulsation threshold the probe is pulsing, but below pulsation threshold the sensation evoked by the probe depends on stimulus parameters (cf. Houtgast, 1972, his Sec. II).

[4]Readers interested in these data can request a copy of IPO report 315 (in Dutch).

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