

This article was published in an Elsevier journal. The attached copy is furnished to the author for non-commercial research and education use, including for instruction at the author's institution, sharing with colleagues and providing to institution administration.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



## Research paper

# Response growth using a low-frequency suppressor

Jeffrey J. DiGiovanni <sup>\*</sup>, Padmaja Nair

*Auditory Psychophysics and Signal Processing Laboratory, School of Hearing, Speech and Language Sciences, W151a Grover Center, Ohio University, Athens, OH 45701, USA*

Received 26 January 2007; received in revised form 24 August 2007; accepted 31 August 2007

Available online 6 September 2007

---

**Abstract**

Numerous psychophysical studies on two-tone suppression have been carried out. More recently, researchers have attempted to relate the magnitude of suppression to the level of suppressor. [Wojtczak, M., Viemeister, N.F., 2005. Psychophysical response growth under suppression. In: Pressnitzer, D., de Cheveigne, A., McAdams, S., Collet, L. (Eds.), *Auditory Signal Processing: Physiology, Psychoacoustics, and Models*. Springer, New York, pp. 67–74] demonstrated that the magnitude of suppression for a higher-frequency, fixed-level suppressor decreases with increasing level of the suppressor. This suggests a linearization of the basilar membrane response in presence of a high-frequency suppressor. The present study expands these results to a low-frequency suppressor of varying intensity levels. Detection of a 10-ms, 4.0-kHz probe was measured under different forward-masking conditions: one with a 200-ms, 4.0-kHz masker (suppressor) presented with no suppressor and another with the same masker paired with a 2.2-kHz, 200-ms suppressor. The 4.0-kHz masker level was varied adaptively and a range of probe levels was used to measure the growth of suppression. Results indicate that (1) the magnitude of suppression increases with increasing suppressor level and (2) generally, the probe level was not related to the magnitude of suppression.

© 2007 Elsevier B.V. All rights reserved.

**Keywords:** Suppression; Psychoacoustics; Psychophysics; Basilar membrane; Forward masking; Masking

---

**1. Introduction**

Two-tone suppression refers to the phenomenon of the reduction of a response to a tone in the presence of another tone. Although this occurrence has been demonstrated at various levels of the auditory system, it has been attributed to the interaction between the outer hair cells and the basilar membrane within the cochlea (Ruggero et al., 1992). Stoop and Kern (2004) used cochlear biophysics to provide qualitative and quantitative evidence for two-tone suppression, thereby demonstrating that the active elements of the cochlea are responsible. Since two-tone suppression results from the nonlinear processing of the basilar membrane,

level effects on the magnitude of suppression have generated a great deal of interest among researchers. Numerous studies examining the relation between amount of suppression and level of suppressor and/or suppressor have been conducted (Duifhuis, 1980; Javel et al., 1978; Ruggero et al., 1992; Shannon, 1976; Wojtczak and Viemeister, 2005).

Physiologic studies have succeeded in relating the magnitude of suppression to suppressor and/or suppressor levels. (Javel et al., 1978) measured auditory-nerve data in cats in the presence of a suppressor higher than the characteristic frequency (CF). The suppressor was fixed in intensity while a second excitatory tone of variable intensity was introduced. Suppression was observed in the form of reduced response to the excitatory tone by a fixed amount irrespective of the intensity of the excitatory tone. Rate-intensity functions were obtained for excitatory tones of different frequencies with and without the suppressor. Results indicated

---

*Abbreviations:* CF, characteristic frequency; ERB, equivalent rectangular bandwidth; GMB, growth-of-maskability

<sup>\*</sup> Corresponding author. Tel.: +1 740 597 1260.

*E-mail address:* [digiovan@ohio.edu](mailto:digiovan@ohio.edu) (J.J. DiGiovanni).

that the amount of suppression of the response to an excitatory tone caused by a suppressor is dependent on the intensity of the suppressor. Additionally, increased frequency separation between the suppressor and the excitatory tone produced a reduction in the amount of suppression. Their findings should be interpreted with caution, however, as they only used high-spontaneous rate fibers. These fibers have a low threshold and a small dynamic range which is generally limited to the linear response portion of the basilar membrane.

Ruggero et al., (1992) conducted a physiologic study and demonstrated two-tone suppression for the CF probe tones using suppressors with frequencies both higher and lower than the CF (herein: high-frequency suppressor and low-frequency suppressor, respectively). They found that suppression magnitude for a fixed level suppressor decreases as a function of increasing probe intensity. Also, the rate of growth of suppression magnitude with suppressor intensity was higher for low-frequency suppressors than for high-frequency suppressors.

Although physiologic studies have provided ample data relating the magnitude of suppression to suppressee levels (Javel et al., 1978; Ruggero et al., 1992), psychophysical studies have not. Historically, psychophysical studies have either examined suppression by using a constant suppressee and varying suppressor levels or by varying both levels while keeping the difference between them constant (Duijhuis, 1980; Shannon, 1976).

Shannon (1976) studied two-tone suppression using forward masking where the probe consisted of a single sinusoid and the suppressor was gated with a masker of the same frequency as the probe. The amount of suppression, or 'unmasking' as Shannon referred to it, is the difference between the masked threshold of the probe with and without the suppressor. The probe was a 1.0-kHz tone while the suppressors ranged in frequency from 0.3 to 4.5 kHz. Intensity levels of the suppressor and the suppressee were varied with the difference between them fixed at 20 dB. Results suggested that for low-frequency suppressors the magnitude of suppression was dependent only on the level of the suppressor. However, for high-frequency suppressors, suppression was dependent on the difference between the suppressor and the suppressee levels.

In contrast, Duijhuis (1980) measured level effects in psychophysical suppression using the pulsation threshold for a probe of 1.0 kHz and suppressors ranging in frequencies from 0.2 to 1.4 kHz. Suppression was observed for both low-frequency and high-frequency suppressors with the magnitude of suppression being dependent on both the level of both the suppressor and the suppressee. Therefore, when the overall level was higher, more suppression was observed. In contrast to Shannon (1976), Duijhuis found that magnitude of suppression was neither exclusively dependent on level of the suppressor nor was it consistent for a constant suppressor/suppressee amplitude ratio. Duijhuis postulated that Shannon's conclusions were too simplistic in nature and needed significant modifications.

In an attempt to relate the magnitude of suppression to suppressee levels, Wojtczak and Viemeister (2005) conducted a psychophysical study using a fixed-level suppressor. They tested the hypothesis that the response to a CF is less compressive in the presence of a fixed-level suppressor than it is in quiet. They obtained growth-of-maskability (GMB) functions for five different suppressor levels across several probe levels with a high-frequency suppressor. The results suggested that the magnitude of suppression for a fixed-level suppressor decreases with increasing suppressee levels as found by Ruggero et al. (1992), i.e. the response to a tone becomes less compressive in the presence of a higher frequency suppressor. No inference could be drawn regarding low-frequency suppressors.

The purpose of the present study is to expand the findings of Wojtczak and Viemeister (2005) for a low-frequency suppressor. For a high-frequency suppressor, it is the non-linear growth of the high-frequency side of the suppressee excitation pattern that interacts with the suppressor. For a low-frequency suppressor, it is the linear growth of the low-frequency side of the suppressee tone excitation pattern that interacts with the suppressor. Given this fundamental difference in suppressor/suppressee interaction for low- and high-frequency suppressors, an investigation of a low-frequency suppressor is warranted. There are two hypotheses: (1) the amount of suppression will increase with suppressor level and (2) the low-frequency suppressor will manifest differently than a high-frequency suppressor in that suppression will be observed with increasing probe levels. This experiment studies two-tone suppression using forward masking to investigate whether the linearization of the basilar membrane at CF measured in the presence of a fixed-level suppressor is also observed for low-frequency suppressors.

## 2. Materials and methods

### 2.1. Participants

Three normal-hearing listeners were recruited as participants. The ages of participants were 25, 25, and 22 years, respectively. Informed consent was obtained from all participants and they were paid for participation. All participants had audiometric thresholds of 15 dB HL or better from 0.25 to 8.0 kHz and a negative report of auditory pathology.

### 2.2. Stimuli

The stimuli were generated digitally at a sampling rate of 24.414 kHz using a computer (Dell Dimension, DIM 4550). The computer controlled a signal processor (Tucker-Davis Technologies, RP2.1) with a 24-bit digital to analog converter. After filtering and attenuation (Tucker-Davis Technologies, PA-5), sounds were presented to the listener through insert earphones (Etymotic Research Labs, ER-2). Stimuli were generated using the

aforementioned hardware and consisted of the following: a 10-ms, 4.0-kHz probe tone, a 200-ms, 4.0-kHz pure-tone masker (suppressee), a 200-ms, 2.2-kHz pure-tone suppressor and a 200-ms notched-noise masker all presented to the test ear. A 200-ms, 1-ERB wide noise centered at 4.0 kHz was presented to the contralateral ear. All stimuli had 10-ms raised cosine ramps, except for the probe which had 5-ms raised cosine ramps.

Pilot data was used to determine the frequency of the suppressor. The closest frequency to the 4.0-kHz probe tone at which a measurable amount of suppression could be recorded while keeping the intensity at a comfortable level was a suppressor of 2.2 kHz. A notched-noise centered at 4.0 kHz with a 1.0-kHz bandwidth was gated simultaneously with the 4.0-kHz probe to prevent off-frequency listening. For each participant, the level of notched-noise required to just mask the different probe levels was determined and this notched-noise was then fixed to 15 dB below this level. Finally, the 50 dB SPL, 1-ERB wide, cue was presented to the contralateral ear for the duration of the masker to reduce confusion between the 4.0-kHz masker and probe for the forward-masking paradigm to be described.

### 2.3. Procedure

All testing was completed with an adaptive three-interval forced choice procedure with a two-up, one-down decision rule to track 70.7% on the psychometric function (Levitt, 1971). This method was used to measure detection of a 10-ms, 4.0-kHz probe tone in a forward masking paradigm with a 200-ms, 4.0-kHz masker. These thresholds were measured with and without a 200-ms, 2.2-kHz suppressor gated simultaneously with the masker. Each block consisted of 10 turnarounds, of which threshold was calculated from the final 8. Correct answer feedback was provided following each response for a given trial. A minimum of two hours of practice was given to each participant before data collection began. Fixed probe levels of 40, 45, 50, 60, 70 and 80 dB SPL were used while the masker varied adaptively in level. The probe and the masker were temporally separated by a 2-ms gap to ensure that the masker would remain at a comfortable level.

Each participant was tested with five different suppressor levels over a 20-dB range. To ensure the suppressor level was within an appropriate range, two adaptive, three-interval forced choice procedures were performed. These procedures, as well as the one for the main experiment, used the same decision rule and threshold calculations discussed above. Before the first procedure was run, the absolute threshold of a 4.0-kHz, 200-ms probe tone was determined using a quick and efficient technique, namely a computer-implemented version of Békésy audiometry. Participants pressed a button on a computer keyboard to signal “louder” or “softer” which raised or lowered the signal level in 1.5-dB steps.

After absolute threshold was determined, the first forced-choice procedure was run to determine the lowest suppressor level for each participant. The lowest suppressor level was defined as the level of a 2.2-kHz, 200-ms tone required to just mask a 4.0-kHz, 200-ms tone (later used as forward masker) presented 15-dB above its absolute threshold. The level that is measured reveals the lowest level that the high-frequency tail of the 2.2-kHz excitation pattern extends to the 4.0-kHz place. At this level, and above, a 2.2-kHz pure tone would be expected to have a suppressive effect on the 4.0-kHz probe. However, if the level of the suppressor is too high, then excitatory masking of the 4-kHz probe would occur during the main experiment. To mitigate this, a second procedure was run to find the highest allowable suppressor level.

The highest allowable suppressor level was determined by measuring the level of the 200-ms, 2.2-kHz tone that just raised the detection threshold of the 10-ms, 4.0-kHz probe tone in forward masking. Each participant was tested with five suppressor levels, 5-dB apart over a 20-dB range. Even though the five levels were different for each participant, they had three commonalities: (1) the five suppressor levels spanned the same range for all participants, (2) they were equally spaced in dB, and (3) the lowest suppressor level was based on the first procedure described above. Therefore, the five suppressor levels can be collapsed across participants for analysis purposes.

Three blocks were collected for each condition, i.e. a given probe level with a given suppressor condition. For the main experiment, the presentation order was randomized. All procedures in this experiment were approved by Ohio University's Institutional Review Board.

### 3. Results

Fig. 1 shows growth-of-maskability (GMB) functions for different suppressor conditions. Each panel represents the data for a single participant. Masker levels at threshold are plotted as a function of probe level for each suppressor condition. The closed symbols represent masker levels needed for the no-suppressor condition while the open symbols represent masker levels needed for masker-with-suppressor condition. For all three participants, the masker levels needed to mask the probe increased with increasing probe levels and the slope of the GMB function is similar for both the masker-with-suppressor and no-suppressor conditions.

Fig. 2 depicts the magnitude of suppression across different probe levels for each suppressor condition. Each panel represents the data for a single participant. The difference between the masker levels required to just mask the probe with and without the suppressor determined the amount of suppression. Different symbols are used to represent different suppressor conditions.

To formalize the findings, a two-way, repeated measures analysis of variance (ANOVA) was performed on these data with masker level as the dependent variable and condition

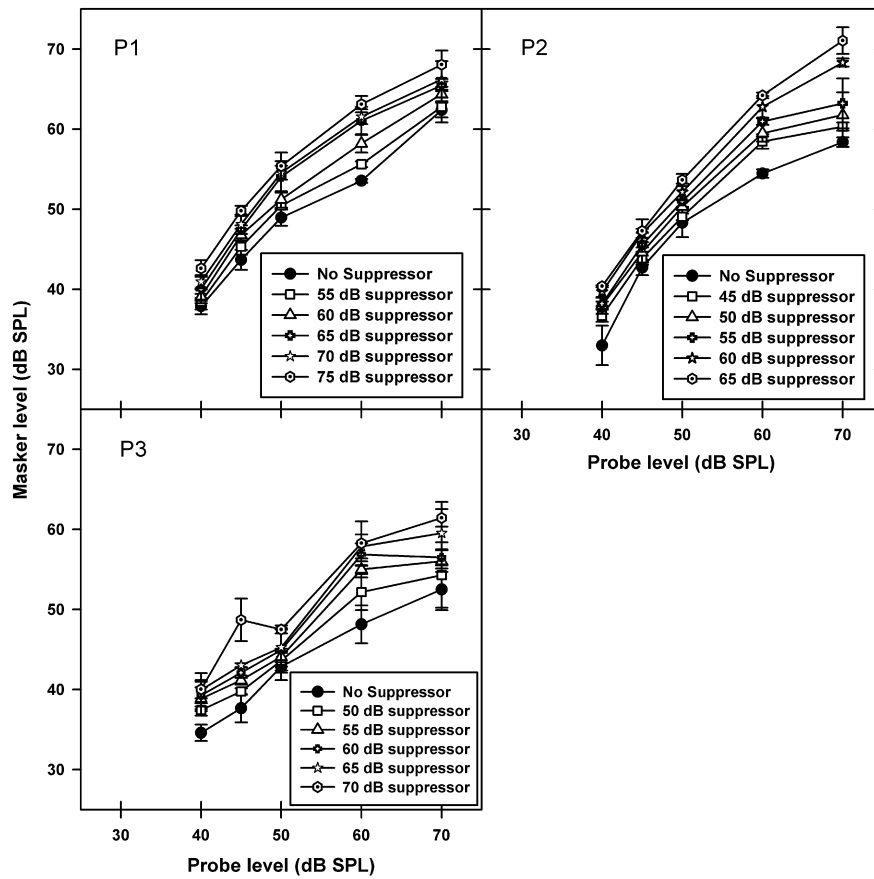


Fig. 1. Growth-of-maskability (GMB) functions. Masker levels required to mask probe with (open symbols) and without (filled symbols) a suppressor. Each function is a separate suppressor level (dB SPL). The error bars represent one standard deviation above and below the average masker level for that participant and condition.

(suppressor level) and probe level as independent variables. Six conditions were considered: no suppressor and five suppressor levels. The five suppressor conditions were the five suppressor levels for the participants, from lowest to highest. For example, the lowest suppressor level data for each participant is 55, 45, and 50 dB SPL for P1, P2 and P3, respectively. To increase the applicability of the ANOVA, all six conditions were normalized against the no-suppressor condition. There was a significant effect of condition ( $F(5,89) = 144.3, p < 0.05$ ) but not on probe level ( $F(4,89) = 3.6, p = 0.058$ ) with a significant condition by probe-level interaction ( $F(20,89) = 2.4, p < 0.05$ ).

To better understand the significance of changing the suppressor level, post-hoc pairwise comparisons were made for the suppressor level. Without exception, any given condition (suppressor level) is significantly different than all the other conditions ( $p < 0.05$ ). Also, to investigate the amount of suppression with increasing probe level, a Tukey–Kramer Multiple-Comparison Test was performed on probe level. The amount of suppression in the probe level comparisons was not significant except that the 60-dB SPL probe level revealed significantly more suppression than the 50-dB SPL probe level across suppressor levels ( $p < 0.05$ ).

#### 4. Discussion

Results indicate that the masker levels at threshold increased in the presence of a 2.2-kHz suppressor, which is likely a result of a reduced response to the 4.0-kHz masker under suppression. In that regard, suppression was demonstrated across all probe levels and for each suppressor condition across all participants. Greater suppressor levels led to significantly greater suppression. These findings support the hypotheses under test.

The slope of the GMB function, however, remained similar both in the presence and absence of the suppressor. This is supported by the fact that there was no significant change in the amount of suppression for the various probe levels outside the 50 vs. 60-dB SPL probe levels. The internal response produced by a masker for a given probe condition also remained the same in the presence and absence of a suppressor. Since the slope of the GMB function is similar for both the suppressor and no-suppressor conditions, we can conclude that there is no linearization of the internal response to the masker in the presence of the low-frequency suppressor for the conditions tested. Referring to Fig. 2, though not statistically significant, there is a subtle trend to have less suppression at the highest probe

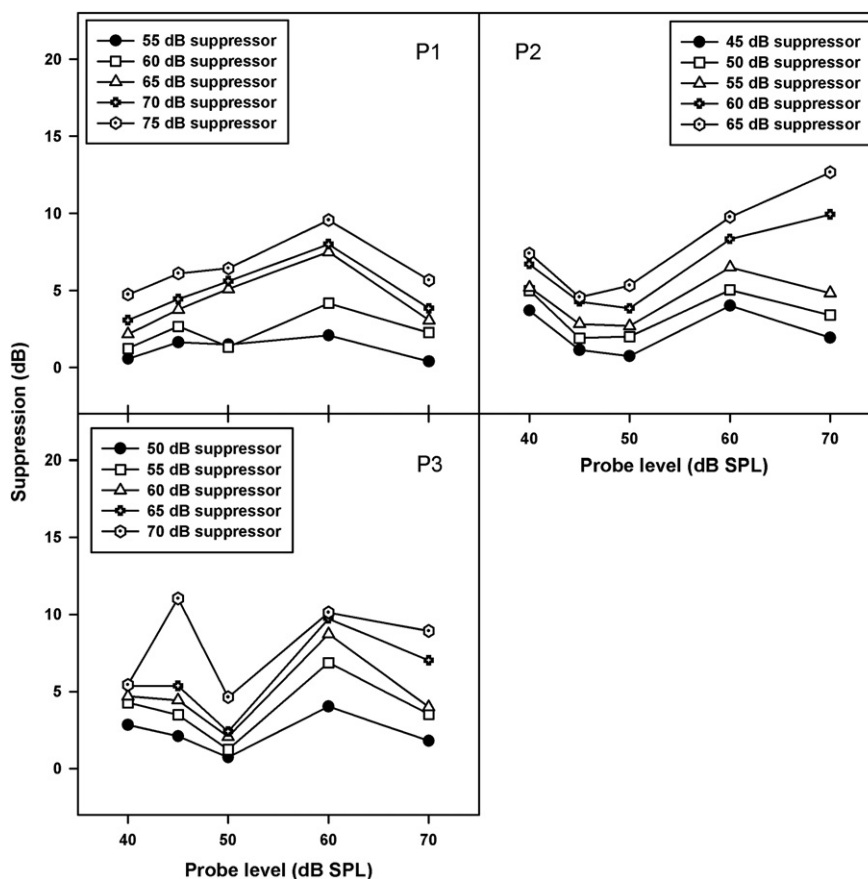


Fig. 2. Magnitude of suppression. These curves were derived by subtracting the 'no suppressor' function from each of the 'with suppressor' conditions.

level. Another experiment using higher probe levels could address this, though this may be difficult without presenting excessively high signal levels.

The current findings differ from the findings of Wojtczak and Viemeister (2005) who reported shallower GMB functions in the presence of a suppressor. This could be attributed to the fact that they used a high-frequency suppressor as opposed to a low-frequency suppressor as used in the current study. Basilar membrane mechanics reveal that excitation patterns vary for high-frequency and low-frequency tones. Shannon (1980) reported that different mechanisms are involved for suppression using low-frequency versus high-frequency suppressors. He postulated that whereas high-frequency suppressors depend on the total excitation pattern of the basilar membrane, low-frequency suppressors only depend on the active mechanism, specifically they interfere with the outer hair cell function to cause suppression. This possibly explains the difference between the current findings and those reported by Wojtczak and Viemeister (2005).

Wojtczak and Viemeister (2005) also found that the magnitude of suppression decreases with increasing level of the suppressee as reported by Ruggero et al. (1992). They attributed the level effects they observed were a result of a reduction in gain at the probe frequency. The reduction, they argued, was related to unsuppressed gain of

the probe tone. In the current study, magnitude of suppression was found to increase with an increasing suppressor level. Suppression, however, was not heavily dependent upon probe level. Suppression, therefore, manifests as a reduction of cochlear gain at all probe levels tested. This would imply that the low-frequency suppressor interferes with basilar membrane mechanics possibly by affecting the action of outer hair cells, which is consistent with the findings of Shannon (1980).

## 5. Summary and Conclusions

The data in this study support the notion that response growth patterns for low-frequency suppressors vary considerably from those for high-frequency suppressors. No linearization of basilar membrane response to a masker was seen at the probe levels tested in the presence of a low-frequency suppressor. With one exception, the magnitude of suppression did not vary significantly regardless of probe level, despite some inter-participant variability. This is inconsistent with the findings of Wojtczak and Viemeister (2005) who conducted a similar study using a high-frequency suppressor. The difference in the findings is attributable to basilar membrane mechanics and different causative mechanisms for suppression involving low-frequency and high-frequency suppressors.

**References**

- Duifhuis, H., 1980. Level effects in psychophysical two-tone suppression. *J. Acoust. Soc. Am.* 67 (3), 914–927.
- Javel, E., Daniel Geisler, C., Ravindran, A., 1978. Two-tone suppression in auditory nerve of the cat: rate-intensity and temporal analyses. *J. Acoust. Soc. Am.* 63 (4), 1093–1104.
- Levitt, H., 1971. Transformed up-down methods in psychoacoustics. *J. Acoust. Soc. Am.* 49, 467–477.
- Ruggero, M.A., Robles, L., Rich, N.C., 1992. Two-tone suppression in the basilar membrane of the cochlea: mechanical basis of auditory-nerve rate suppression. *J. Neurophysiol.* 68 (4), 1087–1099.
- Shannon, R.V., 1976. Two-tone unmasking and suppression in a forward-masking situation. *J. Acoust. Soc. Am.* 59 (6), 1460–1470.
- Shannon, R.V., 1980. A two-process model of suppression. *J. Acoust. Soc. Am.* 68 (S1), S37.
- Stoop, R., Kern, A., 2004. Essential auditory contrast-sharpening is preneuronal. *Proceedings of the National Academy of Sciences of the United States of America* 101, 9179–9181.
- Wojtczak, M., Viemeister, N.F., 2005. Psychophysical response growth under suppression. In: Pressnitzer, D., de Cheveigne, A., McAdams, S., Collet, L. (Eds.), *Auditory Signal Processing: Physiology, Psychoacoustics, and Models*. Springer-Verlag, New York, pp. 67–74.