Loudness growth in forward masking: Relation to intensity discrimination

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The growth of loudness of a tone burst following an intense forward masker was measured as a function of the tone level. The level of the forward-masked tone was adjusted to balance the loudness of a standard tone presented without a forward masker, using a 2AFC, double-staircase, tracking procedure. The forward masker was a 90-dB SPL, 100-ms, 1000-Hz pure tone. The standard tone and the masked tone were both 25-ms, 1000-Hz pure tones. The forward masker and the masked tone were always presented in the first interval. With a 100-ms delay between them, there was little or no threshold elevation for the masked tone. However, the masker caused the masked tone to sound louder than it would if it had not been masked, a phenomenon termed "loudness enhancement" [Irwin and Zwislocki, Percept. Psychophys. **10**, 189–192 (1971); Galambos *et al.*, J. Acoust. Soc. Am. **52**, 1127–1130 (1972)]. In addition, the present results show a nonmonotonic enhancement function that the forward masker introduced a 10–16-dB enhancement effect for tones of 40–65 dB SPL and no significant effect for the 30 and 90 dB SPL tones. The loudness variability in forward masking was estimated from the upper and lower sequences tracking the 21% and the 79% louder response levels on the psychometric function, respectively. The variability demonstrated a similar nonmonotonic function. In forward masking loudness grows more steeply at low-medium sensation levels, and merges with normal growth at high levels. The relationship between loudness growth and intensity discrimination is also examined. The present study argues that loudness enhancement does not directly contribute to the midlevel hump on the forward-masked intensity discrimination function, but rather that the increase in loudness variability caused by forward masking is responsible for the midlevel hump.

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INTRODUCTION

Loudness is usually measured for a simple stimulus presented in isolation. However, in realistic auditory experiences, sound occurs rarely in isolation but mostly in a complex temporal stream of sounds. Loudness may be different for a sound presented before or after another sound, as evidenced by the loudness enhancement effect found 20 years ago (Irwin and Zwislocki, 1971; Galambos *et al.*, 1972).

Irwin and Zwislocki (1971) studied loudness enhancement effect using a pair of tone bursts with the same level, duration, and frequency. They found that the second burst in the pair sounds louder than it would if it had been presented alone, even in long interburst intervals where two bursts are clearly heard separately. Since this was different from the traditional loudness summation (see a later study by Zwislocki *et al.*, 1974), Irwin and Zwislocki termed this effect "loudness enhancement." However, under the conditions of Irwin and Zwislocki, the loudness enhancement effect was rather small, with a maximum of about 6 dB at short interburst intervals.

Independently, Galambos *et al.* (1972) also found that the loudness of the second burst following contralateral stimulation can be enhanced by as much as 15 dB in conditions where the duration and the level of the first tone burst were 250 ms and 95 dB SPL, and the duration and the level of the second tone burst were 2 ms and 73 dB SPL. Loudness enhancement was also shown to be frequency- and level-dependent. The maximal effect occurs when the tone pair has similar frequency (Galambos *et al.*, 1972; Zwislocki and Sokolich, 1974) and when the level of the first tone burst is 20 to 40 dB greater than that of the second tone (Zwislocki and Sokolich, 1974; Elmasian *et al.*, 1980).

Additionally, later studies on the loudness change in different paradigms found that (1) loudness enhancement following ipsilateral stimulation is greater than that following contralateral stimulation (Elmasian and Galambos, 1975), (2) backward masking also produces loudness enhancement but less than the equivalent forward masking conditions, (3) loudness may be reduced when the first tone burst is less intense than the second one (Elmasian *et al.*, 1980), and (4) loudness may be enhanced for pure tones in simultaneous masking by a broadband noise in the contralateral ear (Rowley and Studebaker, 1971). There was also a body of literature on loudness change in simultaneous masking, termed partial masking, where loudness of the signal is usually decreased rather than enhanced by the masker (Scharf, 1964; Smits and Duifhuis, 1982).

Because the first tone burst could be viewed as a forward masker, early studies favored poststimulatory inhibition at the peripheral or brain-stem level to explain the loudness enhancement effect. Irwin and Zwislocki (1971) suggested that an interaction of temporal summation with slow poststimulatory inhibition in brain stem and with fast poststimu-

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latory inhibition in the eighth nerve can account for the different decays of loudness enhancement observed in contralateral and ipsilateral forward masking. Galambos *et al.* (1972) also hypothesized a brain-stem site for loudness enhancement. Later studies, however, resorted to central mechanisms such as "principle of maximum similarity" (Zwislocki and Sokolich, 1974) and "mergence and difficulty in processing" (Elmasian *et al.*, 1980). However, in the 1980's, loudness enhancement received little attention and its underlying physiological mechanisms remained unclear.

Another important implication of loudness enhancement is that the effect of forward masking is not limited to threshold elevation. The threshold of detection with forward masking declines to the unmasked value in approximately 100–200 ms, whereas the loudness enhancement effect can last as long as 500 ms (Galambos *et al.*, 1972; Zwislocki and Sokolich, 1974; Elmasian *et al.*, 1980). Recently, Zeng *et al.* (1991) and Zeng and Turner (1992) found that another suprathreshold measure, intensity discrimination, was also poor for forward masking conditions which produced no threshold shift. They reported a nonmonotonic intensity jnd function in which jnd's were largest for the masked tones of medium levels. This "midlevel hump" was subsequently verified by reports from other laboratories (Plack and Viemeister, 1992a, b; Carlyon and Beveridge, 1993). Based on a physiological study showing that low-SR neurons recover slower than high-SR neurons from forward masking (Relkin and Doucet, 1991), the midlevel hump has been hypothesized to reflect the restricted contribution of low-spontaneous rate (SR) neurons to intensity discrimination in forward masking (Zeng *et al.*, 1991). However, there have been other data suggesting that the hump may be related to other phenomena such as off-frequency listening (Plack and Viemeister, 1992a), backward masking (Plack and Viemeister, 1992b), phase-locking and loudness enhancement (Carlyon and Beveridge, 1993).

The specific question addressed in this paper is: Does loudness enhancement cause the midlevel hump in forward-masked intensity discrimination? To answer this question, one needs to compare these two effects under similar conditions, using similar methods, and using the same subjects. However, a literature review failed to find data in which loudness growth is systematically measured in a manner similar to that of Zeng *et al.* (1991) in measuring intensity discrimination. Additionally, all previous studies on loudness enhancement used the method of adjustment, which would confound the comparison between loudness growth and intensity discrimination in forward masking even if such data were available. Therefore, the first goal of this paper is to measure loudness growth of a pure-tone following another sound (forward masker), and the second goal is to investigate the relation between the midlevel jnd hump and loudness in forward masking.

A. Methods

1. Subjects

Three experienced listeners, one female and two males, including the author, participated in the present study. They were between 28 and 35 years old at the time of experiment. All had normal hearing as measured by conventional audiometry (less than 10 dB HL for frequencies between 125 and 5000 Hz). The jnd data come from the study of Zeng and Shannon (1994) in which the same three listeners also served as the subjects.

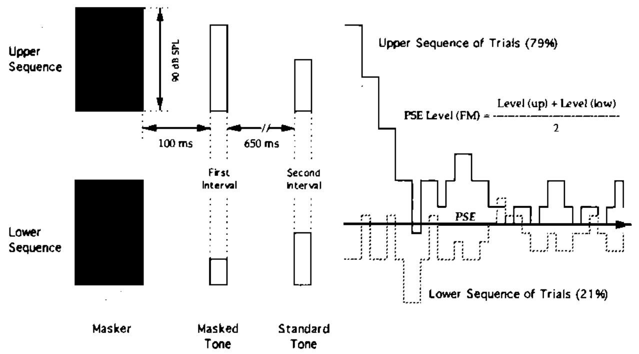

FIG. 1. Schematic demonstration of the measurement of loudness growth in forward masking using a randomly interleaved, double-staircase, adaptive procedure. For each level of the standard tone, there were two sequences of trials for the masked tone. The upper sequence tracked the level at which the masked tone was judged louder than the standard tone 79% of the time, and the lower sequence tracked the level at which the masked tone was judged louder 21% of the time. The balanced loudness, or the point of subjective equality (PSE), in forward masking was the average of the levels from these two sequences.

2. Stimuli

All stimuli were 1000-Hz pure tones. Figure 1 (left) shows the temporal paradigm of all stimuli. The forward masker was of 100-ms duration and was always presented first. The duration for the masked tone was 25 ms. The delay between the offset of the masker and the onset of the masked tone was 100 ms, at which the average threshold shift was 2 dB. The standard tone had a duration of 25 ms. All stimuli were turned on and off with 2.5-ms cosine-squared ramps. The interval between the offset of the masked tone and the onset of the standard tone was much larger, 650 ms. The silent interval from trial to trial was at least 2 s plus the subject's response time. The levels of the standard tone varied parametrically from 30 to 90 dB SPL in steps of 10 dB.

All stimuli were digitally generated by an IBM-PC computer and output through a 16-bit D/A converter at a sampling rate of 20 kHz (TDT model QDA2, Tucker–Davis Technologies). The stimuli were smoothed by an antialiasing filter (TDT model FLT3) with a cutoff frequency of 8 kHz. The levels for the standard tone and the masked tone were separately controlled by two programmable attenuators (TDT model PA3). The maximum level was limited to 100 dB SPL when the attenuator value was set to 0 dB. The level of the forward masker was always 90 dB SPL. Stimulus levels were calibrated with TDH-49 headphones mounted in an MX41/AR cushion in a NBS-9A coupler. Monaural stimulation was used and the right ear was chosen for all subjects. For all measurements, the subjects were seated in a double-walled, sound-treated booth and tested individually.

3. Procedure

Loudness balance was measured using a double-staircase, two-interval, forced-choice, adaptive procedure.

This procedure was originally developed by Jesteadt (1980) as an objective way to measure subjective judgments such as loudness and later modified in a minor way by Zeng and Turner (1991). Figure 1 (right) also shows the level change of the masked tones in the two sequences of trials. For each level of the standard tone, there were two sequences of trials for the masked tone. The upper sequence started at a level that was clearly louder than the standard, and the lower sequence started softer. The decision rule for the upper sequence was that the level of the masked tone decreased after three consecutive louder responses were recorded for the masked tone, and increased after one louder response was recorded for the standard. The upper sequence converges on a level at which the masked tone was judged louder than the standard tone 79% of the time (Levitt, 1971). The lower sequence had the opposite decision rule, in which the level of the masked tone decreased after one louder response to the masked tone, and increased after three consecutive louder responses to the standard. The lower sequence converges on a level at which the masked tone was judged louder 21% of the time. The point of subjective equality (PSE) is defined as the average of the levels of the two masked tones from the upper sequence and the lower sequence. The obtained PSE is approximately equal to the 50% point on the psychometric function, assuming a linear psychometric function between 21% and 79% points.

The starting level for the masked tone in the upper sequence was always 15 dB higher than the standard level, except for the 90-dB SPL standard tone, in which a 95-dB SPL starting level was used due to the maximum output limit of our equipment. The starting level for the masked tone in the lower sequence was always 25 dB lower than the standard level. These two sequences were randomly interleaved during the run. There were 12 reversals for each sequence in a run. The step size for the first four reversals was 5 dB, and 2 dB thereafter. The result was the mean of the last eight reversals for each run. Three runs were conducted for each data point, and 1 or 2 runs were added if the standard deviation across these three runs was greater than 5 dB. Subjects were instructed to listen to the loudness of the second (the masked tone) and the third tone (the standard tone) in each trial. If the masked tone was louder than the standard, they were to push the left button of a mouse; if the standard tone was louder, then push the right button. Subjects were not told which tone was the standard, nor were they given any feedback regarding the correct response.

Not only does the present adaptive procedure give an objective measure of loudness balance, it also provides an estimate of the variance of the judged loudness. As discussed by Schlauch and Wier (1987), the dB values estimating the 79% and the 21% "louder" response points on the psychometric function are essentially the just-noticeable increment and decrement, respectively. Assuming that the underlying psychometric function is linear between the 21% and 79% points, we can then use the level difference between the 50% and 79% points as an estimate of the jnd in forward masking. In a 2AFC task, the level difference (ΔI) between the 50% and 76% points represents the size of one standard deviation [$d' = \Delta I/\text{s.d.} = 1$, see Green and Swets (1966) for details].

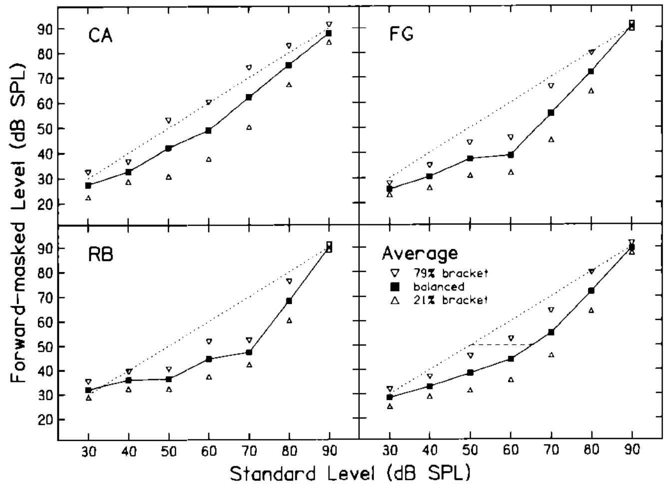

FIG. 2. Individual and average loudness balance functions in forward masking. The open triangles, inverted and regular, represent the 79% and the 21% points from the upper and the lower sequences, respectively. The filled squares represent the point of balanced loudness for the forward-masked tone, which is the level average of the two sequences. The dotted line represents a perfect loudness balance function in which the forward masker has no effect.

Thus we can use half of the bracket (50%–79%) as a close estimate of the standard deviation (50%–76%) of the judged loudness in forward masking, and will refer to this value as representing the "variability."

B. Results

Figure 2 shows data from the three individuals and the average data of the loudness balance function between the forward-masked tone and the standard tone. Although there are individual differences across subjects, they all demonstrate the same general trend. Therefore, only the average data (right-lower panel) will be discussed. The dotted line represents a loudness balance function in which the forward masker has no effect on the masked tone. The filled squares connected by a solid line represent the point of subjective equality for the forward-masked tone, which is the mean of the two sequences, and approximates the 50% point on the psychometric function. The open-inverted and open-regular triangles represent the 79% and the 21% points on the psychometric function, respectively.

Note two interesting results regarding the loudness balance function in forward masking. The horizontal dB difference between the dotted line and the solid line defines the magnitude of the loudness enhancement effect. For example (the horizontal dashed line), the 50-dB SPL forward-masked tone required a 65-dB SPL standard tone to balance its loudness, indicating a 15 dB enhancement effect. For the 30- and 90-dB SPL forward-masked tones (at the endpoints), the enhancement was nearly zero. Second, the bracket that defines the 21% to 79% range on the psychometric function is largest at midlevels and smaller at the two extremes.

Figure 3 plots the same results in a different form to highlight the above-noted two effects. The loudness enhancement magnitude and variability (stimulus values defining the 50%–79% range on the psychometric function) in dB are

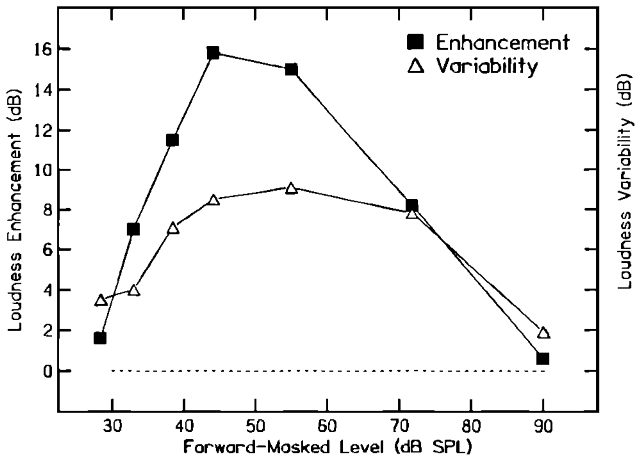

FIG. 3. Loudness enhancement and variability in forward masking. The filled squares represent the magnitude of loudness enhancement in dB (left Y axis) and the open triangles represents the size of loudness variability in dB (right Y axis). Both are computed from Fig. 2.

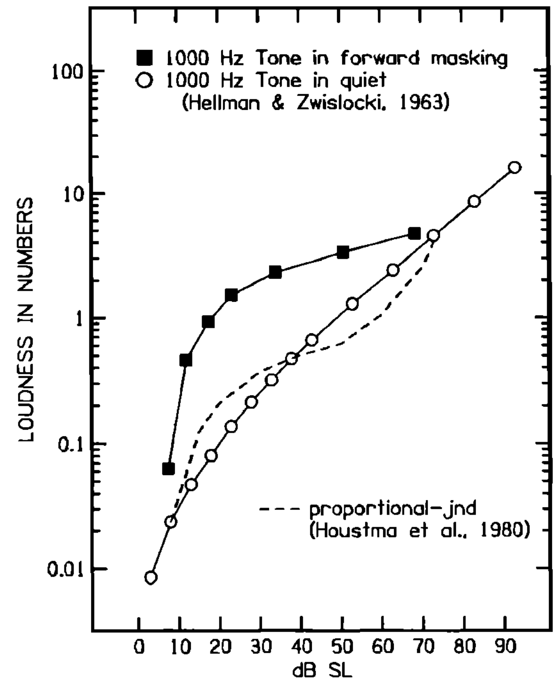

FIG. 4. Loudness growth functions in quiet (open circles) and in forward masking (filled squares). Dotted line represent the loudness function derived from the "proportional-jnd" hypothesis.

plotted as a function of the level of the forward-masked tone. Both functions are clearly nonmonotonic. The filled squares show the loudness enhancement effect. For the midlevel tones (40–65 dB SPL) under the present forward masking condition, there was a 10–16 dB loudness enhancement effect. The enhancement effect decreases for tones of lower and higher levels, and becomes insignificant for the 30- and 90-dB SPL tones. Open triangles show the variability of the loudness judgments in forward masking, which has a midlevel hump that is similar in form to the loudness enhancement effect and similar in magnitude to previous forward-masked intensity jnd function (Zeng *et al.*, 1991).

C. Discussion

This paper used a 2IFC, adaptive procedure to measure loudness in forward masking. Consistent with previous studies using the method of adjustment, this study showed that a forward masker enhances the loudness of the following tone. In addition, this study observed two new properties of the loudness enhancement effect under the present conditions. First, loudness enhancement is a nonmonotonic function with the largest effect at midlevels, and no significant effect at low and high levels. Second, the variability of the loudness judgments in forward masking demonstrates a similar nonmonotonic function.

1. Loudness growth in forward masking

A numerical loudness growth function in forward masking can be derived by combining (1) the present loudness balance function between the forward-masked tone and the unmasked tone, and (2) the established loudness growth data in the absence of masking for a 1000-Hz tone (Hellman and Zwislocki, 1963). Since the duration of the tones in present study is much shorter than that used by Hellman and Zwislocki, all derivations use sensation levels. First, compute the equivalent standard level for each level of the forward-masked tone from the loudness balance function between the forward-masked tone and the unmasked tone. Then substitute the equivalent unmasked value in a regression equation approximating the data of Hellman and Zwislocki, and obtain the numerical value for the forward-masked level. Figure 4 shows the derived loudness growth function in forward masking, in which loudness grows more steeply at low-medium sensation levels from 10 to 30 dB, becomes shallower than the standard at midlevels, and finally merges with the standard at 70 dB SL.

2. Relation of loudness to intensity discrimination

Attempts to relate intensity discrimination to loudness sensation can be traced back more than a hundred years to Fechner's proposal that a jnd in intensity produces a constant increment in loudness. Although Fechner's proposal and his logarithmic loudness function were rejected (Newman, 1933; Stevens, 1956), the discussion linking jnd to loudness continues to the present where, there seems to be three schools of thought on this question. First, modifying the proposals of Fechner and Riesz (1933), Braida and Durlach (1988), and Houtsma *et al.* (1980) suggested that loudness is determined by the jnd count after a normalization relative to the total number of jnd's. The experimental support for this "proportional-jnd" hypothesis came from loudness matching and intensity discrimination experiments in different types of sounds in normal-hearing listeners (Lim *et al.*, 1977; Houtsma *et al.*, 1980; Rankovic *et al.*, 1988). This hypothesis also implies that the size of the jnd is inversely proportional to the slope of loudness function. Contrary to this hypothesis, Zwislocki and Jordon (1986) compared the jnd's of normal hearing to that of cochlear-impaired listeners and found that the jnd's of both types of listeners are equal when the loudness are equal, even though the recruitment in cochlear-impaired listeners increases the slope of the loudness function. Independent experimental data lend additional

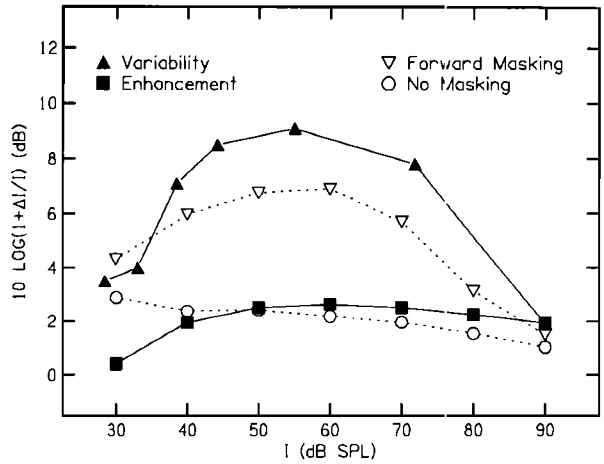

FIG. 5. Intensity discrimination functions in quiet and in forward masking. The open circles represent jnd's measured in quiet, and the open, inverted triangles represent the jnd's in forward masking. The filled squares represent the derived jnd's considering the loudness enhancement only, and the filled triangles represent the jnd's reflecting the variability caused by forward masking.

support to this "equal-loudness, equal-jnd" hypothesis (Hellman *et al.*, 1987; Schlauch and Wier, 1987; Stillman *et al.*, 1993). As a third point of view, Viemeister and Bacon (1988) favored a "no relationship" hypothesis, because they argued that the jnd in intensity is objectively measurable and quantifies primarily a sensory process, whereas the measurement of loudness function involves cognitive contextual effects and nonsensory processes.

Using a 2IFC, adaptive procedure, the present study measured both loudness function and intensity jnd function in forward masking. Both functions were significantly different from the normal, quiet conditions, but whether they are related is not apparent and needs to be examined. First, according to the "proportional-jnd" hypothesis, the symmetrical shape of the jnd function in forward masking (the midlevel hump) would produce an antisymmetric, cubic loudness function as shown by the dotted line in Fig. 4. This cubic function is inconsistent with the derived loudness function in forward masking. Second, the "equal-loudness, equal-jnd" hypothesis does not hold because there is no level in quiet which would produce the large midlevel jnd's observed in forward masking. However, the unsuccessful accounting for a relationship between loudness and jnd by the above two hypotheses does not necessarily mean that the third "no-relationship" hypothesis is correct. The similarity between the loudness enhancement effect and the midlevel jnd hump in forward masking may be more than just coincidental and needs further investigation. At any rate, current hypotheses relating the loudness to the jnd must be modified to account for the loudness and jnd data in forward masking.

Let us examine what role, if any, loudness enhancement may have played in the midlevel hump of the forward-masked intensity discrimination function. Figure 5 shows four sets of intensity discrimination functions. The two dashed lines represent intensity discrimination functions measured in the absence (open circles) and presence (inverted open triangles) of forward masking (Zeng and Shannon, 1994). The two solid lines represent two derived jnd functions from the present data.

The first derived function represents the effect of loudness enhancement only on forward-masked intensity discrimination. To do so, we interpolate the level of the forward-masked tone to an equivalent level without forward masking using the loudness balance function in Fig. 2. We then assume that intensity discrimination is performed on the transformed level as if there were no forward masking (i.e., the open circles in Fig. 5). The filled squares represent the jnd function after such a transformation, which shows a rather flat function with better than the no-masking performance at low levels and poorer performance at high levels. This flat function indicates that loudness enhancement by itself plays little role in the midlevel hump of the jnd function in forward masking.

The filled triangles represent the second derived jnd function (half of the bracket)—the variability measure of the loudness in forward masking. This jnd differs from the jnd's measured in the traditional forward masking experiment (e.g., Zeng *et al.*, 1991) in that the standard tone had no forward masker in the present study. It is reasonable to assume that the midlevel hump in this jnd function is caused by the forward masker preceding the masked tone, and the contribution is negligible from the variability of the standard tone presented alone. In other words, the loudness variability caused by forward masking is likely the main factor that contributes to the midlevel jnd hump in the forward-masked intensity discrimination experiments. Carlyon and Beveridge (1993) also suggested a relation of the enhancement and the variability to the midlevel jnd hump in forward masking, but their experimental paradigm did not allow them to separate the contribution of one factor from the other.

3. Possible physiological mechanisms

Two questions are discussed in this section. First, how is it physiologically possible that loudness can be enhanced or "increased" at medium levels in forward masking? If we assume that loudness is encoded by the overall rate from both high- and low-SR neurons, then the loudness should be less at the midlevels, because the low-SR neurons are not recovered from forward masking and cannot contribute to the overall rate. In other words, loudness enhancement effect must be due to some central mechanism which may compensate for the decrement of the overall rate in forward masking. Coats and Dickey (1972) suggested a similar compensation mechanism to account for the loudness recovery from forward masking.

Second, what physiological mechanisms might be responsible for the large variability of the loudness of the forward-masked tones at midlevels? There is some indirect evidence indicating a peripheral origin of the large variability in forward masking. Taub and Raab (1969) showed that the variance of compound action potential is the primary factor in determining the midlevel jnd hump for clicks. In addition, forward masking alters the normal threshold distribution of low-SR neurons in the midlevel region (Relkin and Doucet, 1991) and may increase the variance of the overall rate at midlevels. At present, we do not have any physiological data to speculate on the specific mechanisms, nor do we know that these two effects, the loudness enhancement and the large variability caused by forward masking, are related phenomena.

D. Conclusion

The loudness balance function is measured between a forward-masked tone and a tone without masking, using a 2IFC, adaptive procedure. The present study demonstrates that both the loudness enhancement effect and the loudness variability caused by forward masking are nonmonotonic, being the largest at medium levels and smallest at low and high levels.

Based on the loudness growth data of Hellman and Zwislocki (1963), we derive that loudness in forward masking grows more steeply at low-medium sensation levels, and merges with normal growth at high levels. By comparing intensity discrimination with and without forward masking, we suggest that loudness enhancement does not contribute to the midlevel hump on the forward-masked jnd function, *per se*. What is likely to be responsible at the psychophysical level is the loudness variability caused by forward masking.

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