The mid-difference hump in forward-masked intensity discrimination[a)]

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Forward-masked intensity-difference limens (DLs) for pure-tone standards presented at low, medium, and high levels were obtained for a wide range of masker-standard level differences. At a standard level of 25 dB SPL, the masker had a significant effect on intensity resolution, and the data showed a mid-difference hump: The DL elevation was greater at intermediate than at large masker-standard level differences. These results support the hypothesis that the effect of a forward masker on intensity resolution is modulated by the similarity between the masker and the standard. For a given masker-standard level difference, the effect of the masker on the DL was larger for a 55-dB SPL than for the 25-dB SPL standard, providing new support for a midlevel hump. To examine whether the masker-induced DL elevations are related to masker-induced loudness changes [R. P. Carlyon and H. A. Beveridge, J. Acoust. Soc. Am. **93**, 2886–2895 (1993)], the effect of the masker on target loudness was measured for the same listeners. Loudness enhancement followed a mid-difference hump pattern at both the low and the intermediate target level. The correlation between loudness changes and DL elevations was significant, but several aspects of the data are incompatible with the predicted one-on-one relation between the two effects.
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I. INTRODUCTION

Nonsimultaneous maskers can strongly affect intensity resolution and produce a rather complex pattern of effects (for a review see Plack and Carlyon, 1995). One of the most prominent findings is the *midlevel hump in intensity discrimination* (Zeng *et al.*, 1991): An intense forward masker (e.g., 90 dB SPL) causes a large elevation in the intensity-difference limen (DL) for a midlevel standard (60 dB SPL), relative to the DL in quiet. The 90-dB SPL masker has only a small effect on the DLs for standards presented at low levels (30 dB SPL) or high levels (90 dB SPL), however.

Three explanations have been proposed for the effects of a nonsimultaneous masker on intensity resolution: the *recovery-rate model* (Zeng *et al.*, 1991), the *referential encoding hypothesis* (Plack and Viemeister, 1992b; Carlyon and Beveridge, 1993; Plack *et al.*, 1995), and the *loudness enhancement hypothesis* (Carlyon and Beveridge, 1993). The former two models attribute the midlevel hump to differences in intensity processing at low and high compared to intermediate standard levels, and the research discussed in this paper is concerned with an alternative or complementary explanation.

According to the recovery-rate model (Zeng *et al.*, 1991), the elevation of the DL at midlevels is a consequence of adaptation of the small population of low spontaneous-rate (SR) auditors nerve neurons, which recover slower than the high-SR population (Relkin and Doucet, 1991). It is assumed that in quiet there is a smooth transition between the operating ranges of the two populations, but that 100 ms after the presentation of an intense forward masker, the high-SR fibers have already recovered, while the threshold of the low-SR fibers is still elevated. The resulting midlevel "coding gap" leads to impairment in intensity resolution at intermediate standard levels. Unfortunately, this model based on peripheral mechanisms is incompatible with the DL elevations caused by contralaterally presented forward maskers (Plack *et al.*, 1995; Zeng and Shannon, 1995; Schlauch *et al.*, 1999), and backward maskers (Plack and Viemeister, 1992b; Plack *et al.*, 1995).

The referential encoding hypothesis (Plack and Viemeister, 1992b; Carlyon and Beveridge, 1993; Plack *et al.*, 1995) assumes that the masker interpolated between the two target tones in a two-interval (2I) intensity-discrimination task degrades the memory trace (Durlach and Braida, 1969) for the target tone presented in the first observation interval (see also Mori and Ward, 1992). Consequently, the listener uses the "context-coding mode" (Durlach and Braida, 1969), in which a temporally stable representation of target intensity is based on a comparison with internal or external references. Referential encoding is assumed to work efficiently at low standard levels, where the internal coding reference detection threshold is available (Carlyon and Beveridge, 1993). At high standard levels, the discomfort level or the level of the intense forward masker may be used as a reference (Braida *et al.*, 1984; Carlyon and Beveridge, 1993). At intermediate standard levels, however, the perceptual distance to these references is large, and discrimination performance will thus

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be inferior (Braida *et al.*, 1984). Therefore, the referential encoding hypothesis can account for the midlevel hump caused by both forward and backward maskers. It can also explain the reduction in the DLs at midlevels found if a notched noise is presented simultaneously with the standard (Plack and Viemeister, 1992a) by assuming that the noise is used as a within-interval coding reference.

At this point however, it is necessary to discuss a methodological problem in previous experiments studying the midlevel hump. Generally, a fixed-level, intense masker was combined with various standard levels. Thus, the *masker-standard level difference* and the standard level were correlated. For a low-level standard, the level difference was always larger than for a medium-level standard. Therefore, the different DL elevations caused by an intense forward masker at different standard levels could in principle be due to the variation in the masker-standard level difference rather than to the variation in standard level. The effect of a forward masker on intensity resolution has been shown to depend on the perceptual similarity between masker and standard (cf. Schlauch *et al.*, 1997, 1999). An alternative explanation for the midlevel hump could thus be that for, e.g., a 30-dB SPL standard combined with a 90-dB SPL masker, the perceptual distance between the masker loudness and the standard loudness is so large that the masker has only a small effect on intensity resolution, while a 60-dB SPL standard and the same masker are sufficiently similar in loudness for the masker to have a significant effect.

The third explanation proposed for the midlevel hump, the loudness enhancement hypothesis (Carlyon and Beveridge, 1993), provides a basis for explaining the influence of the masker-standard similarity. The model assumes that the effect of a forward masker on intensity resolution is related to the effect of the masker on the loudness of the target tones. This idea was based on the observation that *loudness enhancement*, that is, an increase in the loudness of a proximal target caused by a forward or backward masker (e.g., Galambos *et al.*, 1972; Zwislocki and Sokolich, 1974; Elmasian *et al.*, 1980; Oberfeld, 2007), and the masker-induced DL elevation depend in a similar manner on various stimulus parameters. For instance, both loudness enhancement and the DL elevation caused by an intense forward masker are most pronounced at intermediate standard levels (Zeng, 1994; Plack, 1996a), and the two phenomena show a similar dependence on the inter-stimulus interval (ISI) between the masker and the target (Zwislocki and Sokolich, 1974; Zeng and Turner, 1992), on the relation between masker frequency and target frequency (Zwislocki and Sokolich, 1974; Zeng and Turner, 1992), and on the laterality of the masker relative to the target (Elmasian *et al.*, 1980; Plack *et al.*, 1995). Carlyon and Beveridge (1993) suggested that a forward masker impairs intensity resolution because loudness enhancement introduces variability in the loudness of the target tones. Data by Zeng (1994) supported their hypothesis. He presented a 90-dB SPL forward masker and reported loudness enhancement, loudness variability (estimated in an adaptive matching procedure; cf. Jesteadt, 1980; Schlauch and Wier, 1987), and intensity DLs for the same listeners. The effect of the masker on all of the three measures was maximal at intermediate levels (midlevel hump). Plack (1996a) reported that with a 90-dB SPL forward or backward masker, loudness enhancement and loudness variabilitywere significantly correlated for three of the four listeners (Spearman rank correlation coefficient $r_s = 0.5 - 0.76$).

Oberfeld (2007) proposed an explanation for loudness enhancement which is based on an idea by Elmasian *et al.* (1980), who suggested that the loudness representations of the masker and the target are merged automatically. Applied to the three-tone matching task used in most experiments (cf. the lower row of Fig. 1), it follows that the initial value of the target loudness is no longer available at the presentation of the comparison, but that the listener will instead compare a weighted average of the masker loudness and the target loudness with the loudness of the comparison. This explains why the loudness of the target always seems to be shifted toward masker loudness (Zwislocki and Sokolich, 1974; Elmasian *et al.*, 1980). The mergence hypothesis alone cannot account for the midlevel hump in loudness enhancement (Zeng, 1994; Plack, 1996a) because with the masker level fixed at, e.g., 90 dB SPL, loudness enhancement should increase with decreasing target level if a simple weighted average between masker loudness and target loudness was used in the loudness match. This limitation can be overcome, Oberfeld (2007) suggested, by assuming that the effect of the masker depends on the *perceptual similarity* between masker and target, that is, that the masker loudness will receive a smaller weight in the computation of the weighted average if the masker and the target differ strongly in, e.g., spectral content, duration, or loudness. An influence of similarity on the operation of a memory system would not be surprising because effects of the target-distractor similarity are one of the best-established findings in cognitive psychology, for example in experiments studying visual search (e.g., Duncan and Humphreys, 1989), or recognition memory (e.g., Baddeley, 1966). The most prominent evidence for a similarity effect in intensity discrimination is the observation of Schlauch *et al.* (1997, 1999) that adding a 4.133-kHz component to a 1-kHz forward masker strongly reduced the size of the midlevel hump for a 1-kHz standard. Closely related is the reduction in the midlevel DLs if a 10-ms standard was combined with a 250-ms rather than with a 10-ms forward masker (Schlauch *et al.*, 1997).

The *similarity hypothesis* (i.e., loudness enhancement hypothesis extended by the assumption that a reduction in the masker-standard similarity reduces the effect of the masker) predicts that that the effect of a forward masker on intensity resolution is modulated by the similarity between the masker and the standard. To test this prediction, intensity DLs were obtained in Experiment 1 at low, intermediate, and high standard levels (25, 55, and 85 dB SPL) with a wide range of masker-standard level differences (−30 to 60 dB), avoiding the confound between standard level and the masker-standard level difference. According to the similarity hypothesis, it is conceivable that the perceptual distance between the loudness of an 85-dB SPL masker and the loudness of a 25-dB SPL standard is too large for the masker to have a strong effect on intensity resolution. In contrast, a 55-dB SPL masker and the 25-dB SPL standard should be sufficiently similar in loudness for the masker to cause a significant effect. Therefore, a significant elevation of the DLs for a low level standard was expected at intermediate masker-standard level differences, resulting in a *mid-difference hump* pattern.

In Experiment 2, the effect of the forward masker on target loudness was measured for the same listeners and the same conditions as in Experiment 1, to test for the correlation between masker-induced loudness changes and DL elevations predicted by the loudness enhancement hypothesis.

II. EXPERIMENT 1: INTENSITY-DIFFERENCE LIMENS AS A FUNCTION OF THE MASKER-STANDARD LEVEL DIFFERENCE

Intensity DLs were measured for standards presented at 25, 55, and 85 dB SPL, as a function of the level difference between the masker and the standard ($L_M - L_S$). A two-interval, two-alternative forced-choice (21, 2AFC), adaptive procedure was used. $L_M - L_S$ was varied between −30 and +60 dB in 15-dB steps. The lowest masker level was 10 dB SPL. To keep stimulus levels within safe limits, the highest masker level was 100 dB SPL and the maximum sound pressure level was restricted to 105 dB SPL. DLs in quiet were also obtained.

Unfortunately, due to a programming error, listener AL did not receive the 10-dB SPL masker/25-dB SPL standard and the 25-dB SPL masker / 55-dB SPL standard combination, while listener BS did not receive the 70-dB SPL masker combined with the 85-dB SPL standard.

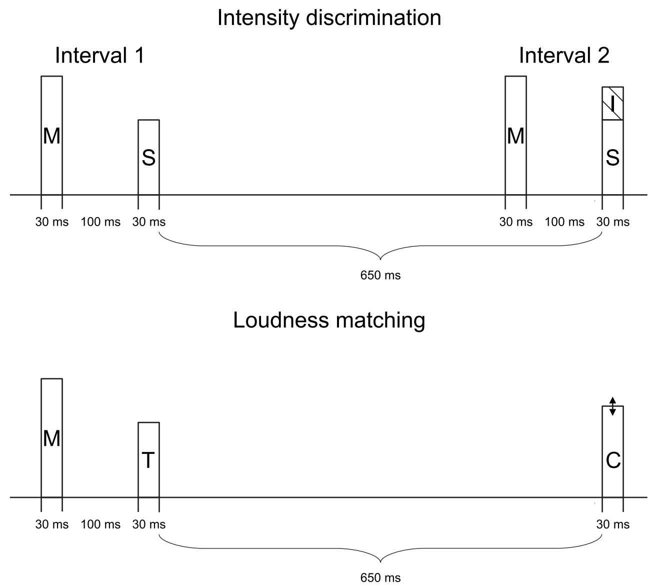

FIG. 1. Upper row: Trial configuration used in the 2I, 2AFC intensity discrimination task in Experiment 1. In each of the two observation intervals, a forward masker *M* and the standard *S* were presented. All stimuli were 30-ms, 1-kHz tone bursts. The silent interval between masker and standard was 100 ms. The level increment *I* was presented in interval 1 or interval 2 with an identical *a priori* probability. Listeners responded whether the increment (i.e., the louder target tone) had occurred in the first or in the second interval. The level of the increment was adjusted by an adaptive procedure with a two-down, one-up rule. Lower row: Trial configuration used in the loudness matching procedure in Experiment 2. Listeners responded whether the target (*T*) or the comparison (*C*) had been louder. The level of the target was fixed. The level of the comparison was adjusted by an interleaved-staircase, adaptive procedure (Jesteadt, 1980).

A. Method

Six volunteers participated in the experiment (three female, three male; age 20–32 years). One of them (DO) was the author, the remaining participants were paid an hourly wage. For the ear tested, all had hearing levels better than 11 dB HL in the frequency range between 125 and 8000 Hz, with one exception (listener AL: HL = 17.6 dB at 8 kHz). All listeners except BS received stimulation to their right ear. For listener BS, the left ear was used because in the right ear, the HL was 19.6 dB at 8000 Hz, while the HLs in the left ear were better than 6.6 dB at all frequencies tested. The listeners were fully informed about the course of the experiment. All except the author were naïve with respect to the hypotheses under test.

The standard and the masker were 1-kHz pure tones with a steady-state duration of 20 ms, gated on and off with 5-ms $\cos^2$ ramps. As the upper row in Fig. 1 shows, there were two observation intervals. In one of the intervals (selected with an equal *a priori* probability), a level increment was added to the standard. The interval between the offset of the first target tone and the onset of the second target tone was 650 ms. In the forward masking conditions, a masker was presented in both intervals. The silent interval between masker offset and standard onset was 100 ms. The target tones were marked by visual signals.

The stimuli were generated digitally and played back via an M-Audio Delta 44 PCI audio-card (sampling rate 44.1 kHz, 24-bit resolution). One channel was used for the masker, a separate channel for the standard/standard-plus-increment. The increment was produced digitally. The masker and the standard/standard-plus-increment were fed into two separate channels of a custom-made programmable attenuator, summed in an inverting summing amplifier, amplified by a headphone amplifier, and fed into one channel of Sennheiser HDA 200 headphones calibrated according to IEC 318 (1970). The experiment was conducted in a single-walled sound-insulated chamber. Listeners were tested individually.

A 2I, 2AFC, adaptive procedure with a two-down, one-up tracking rule (Levitt, 1971) was used to measure intensity DLs corresponding to 70.7% correct. The listeners selected the interval containing the louder target tone. After two consecutive correct responses, the increment was reduced. After each incorrect response, the increment was increased. Up to the fourth reversal, the step size was 5 dB. For the remaining eight reversals, the step size was 2 dB. The difference limen ΔL_{DL} was computed as the arithmetic mean of $10 \log_{10}(1+\Delta I/I)$ at the final eight reversals. A track was discarded if the standard deviation was greater than 5 dB. At least three runs were obtained for each data point. Time permitting, additional tracks were run if the standard deviation of the DLs measured in the first three runs exceeded 5 dB, so that each data point is based on three to nine runs. Visual false/correct feedback was provided after each trial. The experiment was self-paced.

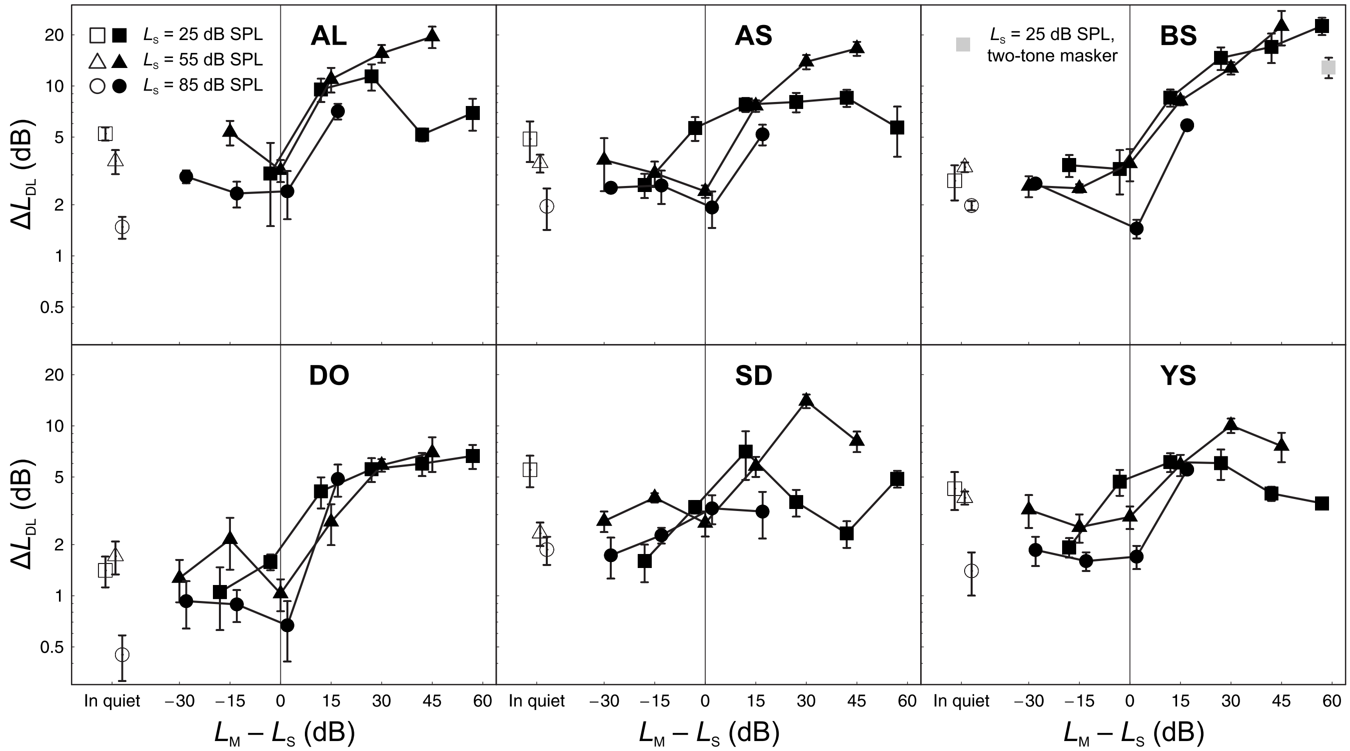

FIG. 2. Experiment 1. Individual intensity-difference limens $[\Delta L_{DL}=10\log_{10}(1+\Delta I_{DL}/ID)]$ for 1-kHz, 30-ms tones as a function of the masker-standard level difference L_M-L_S, and standard level L_S. Panels represent listeners. Open symbols: in quiet. Closed symbols: in forward masking. Squares: 25-dB SPL standard. Triangles: 55-dB SPL standard. Circles: 85-dB SPL standard. Filled gray square: Two-tone masker presented to listener BS in the 85-dB SPL masker/25-dB SPL standard condition. Lines are shifted by 2 dB on the *x* axis. Error bars show plus and minus one standard error of the mean (SEM) for the three or more measurements obtained for each data point.

The listeners were instructed to ignore the maskers. In each block, only one masker-standard level combination was presented. The conditions occurred in pseudorandom order, with the exception that blocks presenting the 100-dB SPL masker were always run at the end of a session.

Listeners received at least 2 h of practice. If necessary, further practice was allowed until performance stabilized. A testing session lasted approximately 1 h with one or two short breaks.

B. Detection thresholds

Detection thresholds were obtained for 30-ms (including 5-ms $\cos^2$ ramps), 1-kHz tones in quiet and under forward masking. A 2I, 2AFC, adaptive procedure (two-down, one-up rule; Levitt, 1971) was used. In one interval (selected randomly), the signal was presented, while no tone was presented in the other interval. In the forward masking conditions, a masker was presented in both intervals. The silent interval between masker offset and signal onset was 100 ms. Masker levels were 25, 55, 85, and 100 dB SPL, except for listener BS, who did not receive the 100-dB SPL masker.

Initially, the signal level was 20 dB SPL. Step size was 5 dB until the fourth reversal, and 2 dB for the remaining eight reversals. Visual trial-by-trial feedback was provided. The threshold level was computed as the arithmetic mean of the signal levels at the last eight reversals. For each condition, at least three measurements were obtained. If the standard deviation was larger than 5 dB within a track, the track was rerun. Time permitting, additional tracks were obtained if the standard deviation of the three threshold estimates exceeded 5 dB.

Thresholds in quiet ranged between 4.5 and 9.2 dB SPL [M=7.0 dB SPL standard deviation (SD) = 1.8 dB]. Thresholds in forward masking were virtually identical to the threshold in quiet for listener BS and elevated by only about 2.5 dB for DO. This finding is compatible with results by Zeng *et al.* (1991). For the remaining listeners, the masker caused an elevation of the detection thresholds that tended to increase with the masker level. The maximum individual elevation of 9.5 dB is comparable to data by Carlyon and Beveridge (1993). Mean thresholds (with *SDs* in parentheses) with the 25-, 55-, and 85-dB SPL masker were 7.9 dB SPL (1.7 dB), 9.9 dB SPL (2.9 dB), and 11.2 dB SPL (4.3 dB), respectively. Five listeners were tested with a 100-dB SPL masker, mean threshold in this condition was 12.9 dB SPL (SD=2.2 dB).

C. Results and discussion

Individual results from the intensity discrimination experiment are displayed in Fig. 2, where ΔL_{DL} is plotted on a logarithmic axis because this measure is compressive at small values. At the 25-dB SPL standard level (squares in Fig. 2), ΔL_{DL} was largest at intermediate masker-standard level differences of 15–45 dB for listeners AL, AS, SD, and YS, resulting in a *mid-difference hump* compatible with the predictions of the similarity hypothesis. The remaining two

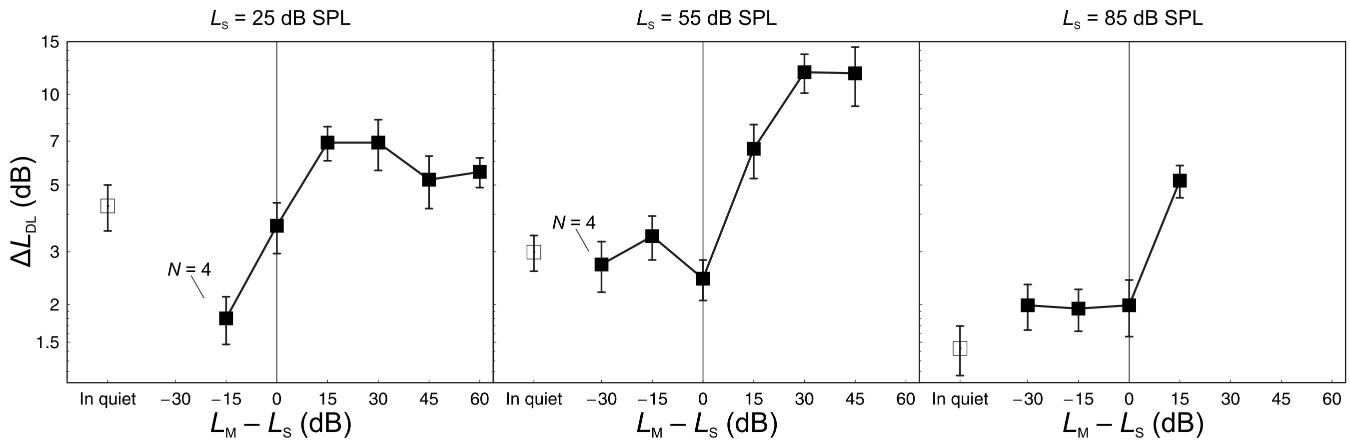

FIG. 3. Experiment 1. Mean intensity-difference limens for five of the six listeners, as a function of the masker-standard level difference $L_M - L_S$, and standard level L_S. The data from listener BS, whose forward-masked DLs for the 25-dB SPL standard strongly deviated from the DLs of the remaining listeners, were excluded. Panels represent standard levels. Open symbols: in quiet. Closed symbols: in forward masking. Error bars show ±1 SEM of the individual values. For the two data points with missing values (see the text), the labels show the number of listeners contributing to the respective data point.

listeners deviated from this pattern. For listener DO (the author), the DL showed a rather small monotonic increase with the masker-standard level difference. For listener BS, the DL increased dramatically with $L_M - LS$. His data are in some aspects similar to the pattern Schlauch *et al.* (1997) reported for one subject in their study, for whom the DLs were even larger (up to 50 dB) for low-level standards combined with a 90-dB SPL masker. Schlauch *et al.* hypothesized that the listener integrated the intensities of the masker and the standard, presumably due to the perceptual similarity between the two tones. Large DLs for a low-level standard combined with an intense masker were also reported by Zeng *et al.* (1991; listener RB), Carlyon and Beveridge (1993; listener LW), and Schlauch *et al.* (1999; listener 2). Schlauch *et al.* (1997) reported that adding a 4.133-kHz component to the masker greatly reduced the DLs in the critical conditions, presumably because the additional component served as a cue helping the listener to differentiate between the masker and the standard. To examine whether the large DLs produced by BS could also be attributed to the perceptual similarity between the masker and the standard, he was tested with a two-tone masker in the 85-dB SPL masker/25-dB SPL standard condition. The two-tone masker consisted of a 1- and a 4.133-kHz tone burst sharing the same temporal envelope. The sound pressure level of the two components was identical so that the overall level was 3 dB higher than the level of the 1-kHz tone. As the gray square in Fig. 2 shows, the two-tone masker resulted in a substantially lower DL than the 1-kHz masker, although the DL was still 10 dB higher than in quiet. Because the data for listener BS deviated strongly from the DLs for the other listeners, his data were excluded from all following analyses.

Mean data for all listeners except BS are displayed in Fig. 3. On average, maskers 15 or 30 dB higher in level than the 25-dB SPL standard caused the largest DLs. Repeated-measures analyses of variance (ANOVAs) were conducted using a maximum-likelihood approach (SAS PROC MIXED; Littell *et al.*, 1996) because there were two missing data points due to a programming error. The Satterthwaite method was used for computing the denominator degrees of freedom for approximate F tests of fixed effects. The "heterogeneous compound symmetry" (CSH) was selected to model the covariance structure. An ANOVA for the data obtained at the 25-dB SPL standard level showed a significant effect of $L_M - L_S [F(6,7.45)=9.71, p=0.0034]$, providing evidence against the recovery-rate model, which predicts the forward masker to have no effect at low standard levels. Paired-samples t-tests indicated that the DL in forward masking was significantly larger than the DL in quiet at the +15-dB masker-standard level difference [$t(4)=5.51$, $p=0.003$, one-tailed], and marginally significantly elevated at $L_M - L_S = 30$ dB [$t(4)=1.96$, $p=0.06$, one-tailed]. At the two highest masker-standard level differences, there was no significant DL elevation. Additional evidence for the expected non-monotonic relation between the DL elevation and the masker-standard level difference was provided by a post-hoc contrast which showed that the DLs obtained at the two intermediate level differences (15 and 30 dB) were marginally significantly higher than the DLs at the two largest level differences (45 and 60 dB) [$F(1,12.8)=3.64$, $p=0.079$, two-tailed].

For the 55-dB SPL standard (triangles in Fig. 2), the DLs at the largest masker-standard level difference (45 dB) were smaller than at the 30-dB level difference for two listeners (SD and YS), resulting in a mid-difference hump. The remaining listeners produced no mid-difference hump at this standard level. It remains unclear whether for them the maximum masker-standard level difference of 45 dB was not large enough for the DL to decrease again. Zeng and Turner (1992) also reported a monotonic increase of the DLs for a midlevel standard as the masker-standard level difference was increased from 0 to 50 dB. In the mean data (center panel in Fig. 3), the DL showed no further increase, but also no decrease, as $L_M - L_S$ was increased from 30 to 45 dB. A one-factorial ANOVA conducted for the data at the 55-dB SPL standard level indicated a significant effect of $L_M - L_S$ [$F(6,6.76)=7.16, p=0.011$]. Paired-samples t-tests showed that all maskers higher in level than the standard had caused a significant DL elevation [$p<0.05$ (one-tailed)].

On average, the effects of the forward maskers higher in level than the standard were more pronounced at the intermediate than at the low standard level. The DL elevations (i.e., the DL in forward masking minus the DL in quiet) were analyzed via an ANOVA with the within-subjects factors L_S (25, 55 dB SPL) and $L_M - L_S$ (15, 30, and 45 dB). The significant effect of L_S $[F(1,12.7)=26.59, p=0.001]$ confirmed the observation of larger DL elevations at the intermediate standard level. The $L_S \times (L_M - L_S)$ interaction was also significant $[F(2,12.8)=7.65, p=0.007]$. These results indicate that forward masking has the strongest effect at intermediate standard levels, even if the masker-standard level difference is not correlated with the standard level as in previous experiments.

Except for listener SD, the 100-dB SPL masker caused an elevation in the DL for the 85-dB SPL standard (circles in Fig. 2). An ANOVA conducted at this standard level indicated a significant effect of $L_M - L_S$ $[F(4,4.13)=7.23, p=0.038]$. The DL obtained with the 100-dB SPL masker was significantly larger than the DL in quiet $[t(4)=5.15$, $p=0.004$, one-tailed]. This effect is not compatible with the recovery-rate model, as a 100-dB SPL masker cannot be expected to shift the threshold of the low-SR fibers to values even near 85 dB SPL. In terms of the referential encoding hypothesis, it seems likely that the DL elevation at the 15-dB level difference should be smaller for an 85-dB SPL standard than for a 55-dB SPL standard, as the distance to the internal reference discomfort level is smaller at high intensities. However, the DL elevation was virtually identical at the two standard levels ($L_S=85$ dB SPL: $M=3.74$ dB, $SD=1.62$ dB; $L_S=55$ dB SPL: $M=3.62$ dB, $SD=2.41$ dB; $t(4)=0.109$, n.s.).

For masker levels lower than or equal to the standard level, the DLs were generally close to those in quiet. For three listeners, the 10-dB SPL masker even caused a reduction in the DL for the 25-dB SPL standard. A potential explanation for this finding is a cueing effect (Moore and Glasberg, 1982).

For comparison with previous studies where a fixed-level, intense masker was used and only the level of the standard was varied, consider the data obtained with the 85-dB SPL masker (data points at $L_M - L_S=60$, 30, and 0 dB in the left, center, and right panel of Fig. 3, respectively). The DL elevation at the intermediate standard level was approximately 9 dB, which is comparable to the value of about 13 dB reported by Plack *et al.* (1995).

To summarize the results, the significant DL elevations observed for 25 and 85-dB SPL standards are incompatible with the recovery rate model.

The mid-difference hump observed at the low standard level is directly compatible with the similarity hypothesis. In terms of the referential encoding hypothesis, the effects of the masker-standard level difference are somewhat difficult to predict as the masker can be assumed to have two effects. First, the amount of trace degradation caused by the masker could be a function of the masker level, although the model contains no explicit assumptions concerning this parameter. It seems reasonable, however, to assume that for example a 60-dB SPL masker should have a stronger detrimental effect on the trace of a 30-dB SPL standard than on the trace of a 90-dB SPL standard. Second, the masker could serve as a within-interval coding reference (Plack, 1996b). Taken together, there should be virtually no trace degradation at masker levels well below standard level. If the masker level is increased to values above the standard level, the trace degradation increases and the system has to rely increasingly on context coding. At the same time, the effectiveness of the masker as a coding reference is reduced according to the perceptual anchor model (Braida *et al.*, 1984). A slightly different prediction can be derived from data by Plack (1996b, 1998), who suggested that the level of the standard is compared to the level of the decaying "temporal excitation pattern" of the masker at the time of occurrence of the standard, so that the optimum level of the masker for referential encoding purposes would be somewhat higher than the standard level. Both variants suggest a maximal effect of the masker at larger masker-standard level differences, but similarity effects are not in principle incompatible with the referential encoding hypothesis. For example, as a reviewer noted, if the masker is grouped into a separate perceptual stream by pairing it with a higher tone (Schlauch *et al.*, 1997), it might cause less trace degradation. Consequently, the assumption that a perceptual difference between masker and standard results in less memory trace interference could be integrated into the referential encoding hypothesis, so that the mid-difference hump could be accounted for.

The data also indicate that there is a midlevel hump not only in the sense that with a fixed-level, intense forward masker the largest DL elevation occurs at medium standard levels, but also in the sense that for a given masker-standard level difference, the effect of the masker on the DL is larger for a medium-level than for a low-level standard. Thus, the masker-standard level difference does not completely determine the effect of the masker. This finding is compatible with the referential encoding hypothesis. On the other hand, at a 15-dB level difference between masker and standard, the DL elevation was not larger for the 55- than for the 85-dB SPL standard, contrary to the predictions of the latter model. It seems possible to integrate the influence of the standard level into the similarity hypothesis by assuming that the effect is due to the compressive behavior of the cochlea that is more pronounced at intermediate than at low levels (for a recent review see Oxenham and Bacon, 2003), and which results in a steeper slope of the loudness function at low levels (e.g., Hellman and Zwislocki, 1964; Yates, 1990). Therefore, it could be argued that the masker-standard level difference at which the difference between the loudness of the masker and the loudness of the target becomes large enough for the effect of the masker to decrease again is smaller at low than at intermediate standard levels. In this line of reasoning, probably the maximum masker-standard level difference of 45 dB presented at $L_s=55$ dB SPL was not large enough for the DL to decrease again, which would explain the absence of a mid-difference hump at this standard level for most listeners.

III. EXPERIMENT 2: LOUDNESS MATCHES AS A FUNCTION OF THE MASKER-TARGET LEVEL DIFFERENCE

A. Rationale

The data from Experiment 1 were in large part compatible with the explanation for loudness enhancement proposed by Oberfeld (2007) combined with the loudness enhancement hypothesis (Carlyon and Beveridge, 1993). If this model is valid, then the masker-target level difference should have a similar effect on target loudness as on the intensity DL: The loudness change caused by the masker should be maximal at intermediate level differences, resulting in a mid-difference hump. Results compatible with the predicted pattern were previously reported by Oberfeld (2007). Additionally, there should be a correlation between the masker-induced loudness change and the masker-induced DL elevation. Experiment 2 was designed to test these hypotheses. A loudness matching task was used to measure the effect of the forward masker on the loudness of a proximal target, for the same listeners as in Experiment 1. The temporal configuration of a trial is displayed in the lower row of Fig. 1. Except for the omission of the masker in the second interval, the temporal structure was the same as in Experiment 1 (upper row in Fig. 1), and the same stimuli and masker-target level combinations were presented.

Note that recent data by Scharf *et al.* (2002), Arieh and Marks (2003), and Oberfeld (2007) suggest that a masker has two effects on a target following it by less than about 400 ms. First, the masker causes a shift in the target loudness toward the masker loudness. At the same time, if the masker level is higher than the target level, the masker causes a reduction in target loudness (loudness recalibration; Marks, 1994). If the comparison is presented at the same frequency as the masker, the masker also induces loudness recalibration in the comparison if the comparison level is lower than the masker level (Scharf *et al.*, 2002; Oberfeld, 2007). According to this two-process model (Arieh and Marks (2003); Oberfeld, 2007), the effect of the masker on the loudness level of the target in a three-tone matching procedure with all tones sharing the same frequency is an estimate of the effect of the process causing loudness enhancement or loudness decrement, because the effect of the process resulting in loudness recalibration is assumed to be constant for at least several seconds following the presentation of the masker (Arieh and Marks, 2003; Oberfeld, 2007), so that its effect on the target loudness and its effect on the comparison loudness cancel.

B. Method

The same listeners as in Experiment 1 took part, except for listener AS, who chose not to participate due to lack of time. For listener BS, the 25-dB SPL target combined with the 85-dB SPL masker again presented a problem. The listener requested comparison levels exceeding the maximum level difference between comparison and target the test equipment could deliver (45 dB), unlike the remaining listeners, for whom loudness enhancement was rather small in this situation. As BS could not be tested in all conditions, his data were excluded from the analyses.

The same stimuli and apparatus as in Experiment 1 were used. Due to a programming error, the 10-dB SPL masker/25-dB SPL target combination was not presented to listener SD. As can be seen in the lower row of Fig. 1, the target was followed by a comparison after a silent interval of 650 ms. The level of the target was fixed. The level of the comparison was adjusted by an adaptive procedure. In forward-masked trials, the silent interval between masker offset and target onset was 100 ms. Listeners responded whether the target or the comparison had been louder. They were instructed to ignore the masker. No feedback was provided.

A 2I, 2AFC, interleaved-staircase procedure (Jesteadt, 1980) was used. Each block comprised two randomly interleaved tracks. The upper track converged on the comparison level corresponding to the 70.7% *Comparison louder* point on the psychometric function. If the listener indicated on two consecutive trials that he or she had perceived the comparison as being louder than the target, the level of the comparison was reduced. After each response indicating that the target had been perceived as being louder, the level of the comparison was increased. In the lower track, a one-down, two-up rule was used to track the 29.3% *Comparison louder* point on the psychometric function. The upper track and the lower track started with a comparison level 11 dB above or below the target level, respectively. The step size was 5 dB until the fourth reversal, and 2 dB for the remaining eight reversals. If in one of the tracks 12 reversals had already occurred before the other track had also reached 12 reversals, trials from the former track were still presented with an *a priori* probability of 0.2.

For each block, the arithmetic mean of the level differences between comparison and target ($L_C - L_T$) at all but the first four reversals was computed separately for the upper and for the lower track, with the restriction that for each track an even number of reversals entered the computation (e.g., if 13 reversals had occurred in one of the tracks, reversal 13 was excluded). The arithmetic mean of these two values was taken as the loudness match, corresponding to the comparison level at the point of subjective equality (PSE) minus the target level. A run was discarded if the standard deviation of $L_C - L_T$ at the counting reversals was greater than 5 dB in either the upper or the lower track. Three runs were obtained in each condition. Time permitting, additional runs were presented if the standard deviation of the loudness matches exceeded 5 dB.

Only one masker-target level combination was presented in each block. Listeners received the conditions in pseudorandom order with the exception that the 100-dB SPL masker was always presented at the end of a session.

C. Results and discussion

Individual loudness matches are displayed in Fig. 4 in terms of the level difference $L_C - L_T$ required to make the comparison sound equally loud as the target. Positive values of $L_C - L_T$ correspond to loudness enhancement of the target,

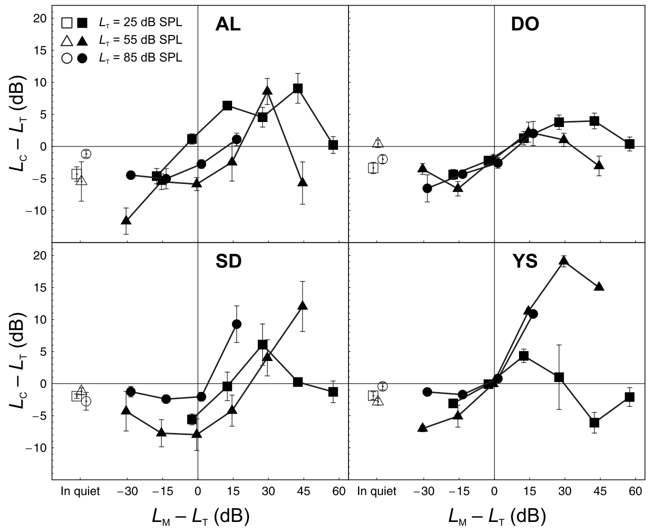

FIG. 4. Experiment 2. Individual loudness matches (comparison level L_C at the PSE minus target level L_T) as a function of the masker-target level difference ($L_M - L_T$) and target level. Same format as Fig. 2.

negative values to loudness decrement. At a target level of 25 dB SPL (squares in Fig. 4), loudness enhancement was a nonmonotonic function of the masker-target level difference for all listeners, consistent with the predicted mid-difference hump. The maximum change in loudness level relative to the match in quiet was found at values of $L_M - L_T$ between 15 and 45 dB, with individual maxima of 6.2–13.4 dB. The 10-dB SPL masker caused loudness decrement. Mean results are shown in the left panel of Fig. 5. On average, loudness enhancement was maximal at intermediate masker-target level differences. A one-factorial repeated-measures ANOVA using a univariate approach with a Huynh–Feldt correction for the degrees of freedom was conducted for the data obtained at the 25-dB SPL target level because PROC MIXED did not converge in this case. The level difference of −15 dB was excluded because of one missing value. There was a marginally significant effect of $L_M - L_T$ $[F(5,15)=2.92, p=0.051]$. Post-hoc paired-samples *t*-tests indicated a significant difference between the loudness match under forward masking and the baseline match (i.e., the match in quiet) at $L_M - L_T = 30$ dB $[t(3)=6.06, p=0.015$ (two-tailed)], and marginally significant differences at the −15- and the +15-dB masker-target level difference $[t(3)=3.17, p=0.087$ (two-tailed), and $t(3)=3.02, p=0.057$ (two-tailed), respectively]. The observation of substantial loudness enhancement for a 25-dB SPL target (on average 6.7 dB relative to the baseline match at a $L_M - L_S = 30$ dB) indicates that the absence of loudness enhancement at low target levels reported in previous studies presenting only an intense masker (Zeng, 1994; Plack, 1996a) cannot be attributed to the low target level, but rather to the large masker-target loudness difference. At the two largest values of $L_M - L_T$, the loudness matches did not differ significantly from the baseline match ($p > 0.15$). The effect of the masker on the loudness match was significantly smaller at the largest masker-target level difference (60 dB) than at the intermediate difference of 30 dB $[t(3)=4.67, p=0.019$ (two-tailed)]. This pattern of results is compatible with the mid-difference hump predicted by the similarity hypothesis.

Mid-difference humps were also present at the 55-dB SPL target level for all listeners except SD (triangles in Fig. 4). At masker-target level differences between 15 and 30 dB, the maximum amounts of enhancement were observed, which showed considerable interindividual variation and ranged between 1.8 and 21.9 dB relative to the match in quiet. An ANOVA conducted at the 55-dB SPL target level showed a significant effect of $L_M - L_T$ $[F(6,18)=4.61, p=0.005]$. On average (center panel in Fig. 5), loudness enhancement was stronger at a masker-target level difference of 30 rather than 45 dB, but this difference was not significant $[t(3)=0.79]$. The average loudness changes induced by the masker (i.e., the match under masking minus the baseline match) were larger at the 55 than at the 25-dB SPL target level (Fig. 5). Yet, in an L_T (25, 55 dB SPL) × $L_M - L_T$ (−15 to 45 dB) ANOVA, neither the effect of L_T $[F(1,7.21)=0.03, p=0.86]$, nor the $L_T \times (L_M - L_T)$ interaction was significant $[F(4,6.46)=0.72, p=0.61]$.

At the 85-dB SPL target level (circles in Fig. 4), loudness decrement was observed at masker-target level differences of −30 and −15 dB, except for listener SD. The 100-dB SPL masker caused loudness enhancement. An

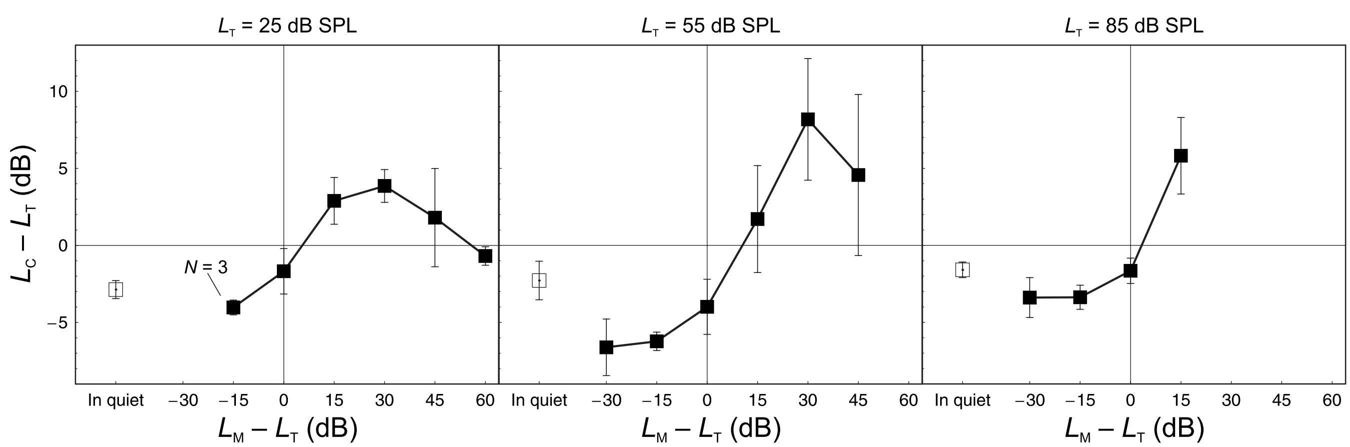

FIG. 5. Experiment 2. Mean loudness matches (comparison level at the PSE minus target level) as a function of the masker-target level difference ($L_M - L_T$) and target level. Same format as Fig. 3.

ANOVA showed that the effect of $L_M - L_T$ was significant at this target level $[F(4,4.14)=9.28, p=0.024]$. The match obtained with the 100-dB SPL masker was marginally significantly higher than the baseline match $[t(3)=2.98, p=0.059]$.

For a level difference of 0 dB ($L_M = L_T$), the mergence hypothesis (Elmasian *et al.*, 1980) predicts no loudness change relative to the condition in quiet. Compatible with this hypothesis, paired-samples *t*-tests showed that at none of the three target levels did the loudness match at $L_M = L_T$ differ significantly from the match in quiet ($p > 0.4$).

Note that the data obtained with the 85-dB SPL masker followed a midlevel hump pattern (right panel of Fig. 5), compatible with the results by Zeng (1994) and Plack (1996a).

IV. GENERAL DISCUSSION

A. Relation between loudness enhancement and intensity DLs

The loudness enhancement hypothesis (Carlyon and Beveridge, 1993) predicts loudness enhancement and the DL elevation caused by the forward masker to be correlated. Two previous studies reported evidence for such a relation (Zeng, 1994; Plack, 1996a), but only for the case of an intense masker, and consequently only for conditions producing loudness enhancement. What can be expected for the case of maskers lower in level than the target, in which loudness *decrement* is observed? The most parsimonious assumption would be that any change in the target loudness induced by the masker, regardless whether enhancement or reduction, increases the variability of the intensity representation. The data from Experiment 1 do not support this hypothesis, however, as only small DL elevations or in some cases even DL reductions were observed if the masker level was lower than the target level. In an experiment by Zeng and Turner (1992), DLs for standards presented at a level between 40 and 60 dB SPL were also unaffected by maskers lower in level than the standard.

Correlational analyses were used to test the prediction of the loudness enhancement hypothesis. In a first step, the parsimonious assumption that both loudness enhancement and loudness decrement should increase the loudness variability was adopted. Consequently, correlations between the DL elevation and the *absolute value* of the masker-induced change in loudness were computed. For each for the four listeners who had participated in both experiments, and each masker-target level combination, the average DL elevation (i.e., ΔL_{DL} in forward masking minus ΔL_{DL} in quiet; Experiment 1) and the average masker-induced change in loudness level (i.e., L_C at the PSE in the presence of the masker minus L_C at the PSE in quiet; Experiment 2) was computed. The Pearson product-moment correlation coefficient for the relation between the DL elevation and the absolute value of the loudness change was significantly greater than zero $[r=0.312, n=62, p=0.014$ (two-tailed)], compatible with the loudness enhancement hypothesis. Note that the proportion of variance accounted for by the linear regression was small ($R^2 = 0.097$).

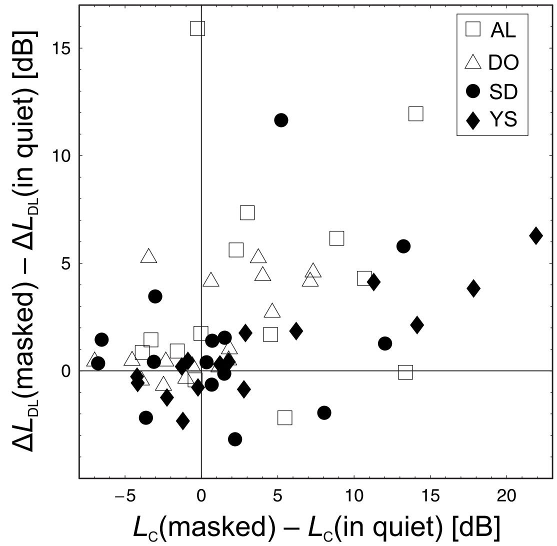

FIG. 6. Scatter plot of the individual masker-induced change in the loudness level of the target measured in Experiment 2 (horizontal axis) and the masker-induced change in ΔL_{DL} measured in Experiment 1 (vertical axis). Each data point represents one listener and one masker-target level combination. Symbols denote listeners.

In a second step, the conditions associated with loudness decrement (i.e., $L_M < L_T$) were excluded. The correlation between the DL elevation and the original rather than the absolute value of the masker-induced loudness change was computed, it was only marginally significant $[r=0.294, n=44, p=0.053$ (two-tailed)]. The data are displayed in Fig. 6, where it can be seen that loudness decrement was associated with small DL elevations, while the DLs tended to increase with the amount of loudness enhancement.

A potential explanation for the correlations being smaller than in the experiment by Plack (1996a) would be that in the latter study the masker level was fixed at 90 dB SPL. In fact, for the data obtained with the 85-dB SPL masker in Experiments 1 and 2 of the present study, the correlation between the DL elevation and the masker-induced loudness change was $r=0.636$ ($n=12$, $p=0.026$).

If one compares the individual patterns of ΔL_{DL} and loudness enhancement (Figs. 2 and 4), several instances are obvious that speak against a simple one-on-one relation between loudness enhancement and intensity resolution. To give an example, the loudness matches produced by listeners AL and DO at the 55-dB SPL target level show a pronounced mid-difference hump, while their DLs increased monotonically with the masker-standard level difference in this condition.

As noted earlier, a masker higher in level than the target can be assumed to cause not only loudness enhancement, but also loudness recalibration (Arieh and Marks (2003); Oberfeld, 2007). Could loudness recalibration rather than loudness enhancement be the mechanism resulting in impairment in intensity resolution? As loudness recalibration is not observed for masker levels lower than the target level, this would explain the absence of a DL elevation in these conditions. Above that, Mapes-Riordan and Yost (1999) reported only 4 dB of loudness recalibration for a 40-dB SPL, 500-Hz target combined with an 80-dB SPL masker, but about 11 dB for the target presented at 60 or 70 dB SPL. In other words, a midlevel hump pattern was observed. Oberfeld (2007) also reported that the amount of loudness recalibration caused by a 90-dB SPL forward masker was slightly stronger for a 60- than for a 30-dB SPL target, but the difference was only about 2 dB, and the data were from two different experiments involving different listeners. Evidence against a relation between loudness recalibration and the DL elevation comes from the observation that the reduction in the loudness of a 30-dB SPL tone increases monotonically with the level of the masker (Oberfeld, 2007), showing no evidence for a mid-difference hump. Still, it would be interesting to measure not only loudness enhancement, but also loudness recalibration in future experiments aimed at examining the relation between masker-induced loudness changes and DL elevations.

B. Implications for models of forward-masked intensity discrimination

In Experiment 1, intensity DLs at different standard levels were for the first time obtained for a wide range of masker-standard level differences, avoiding the confound between the latter difference and the standard level present in previous studies. Three important findings emerged. First, significant DL elevations were observed at low and high standard levels if there was an intermediate level difference between masker and standard. Second, a mid-difference hump was found at the 25-dB SPL standard level where the maximal DL elevations occurred at intermediate masker-standard level differences. Third, the data confirmed that there is a midlevel hump because for a given masker-standard level difference, the effect of the masker on the DL was larger for a medium-level than for a low-level standard. The data are incompatible with the recovery-rate model (Zeng *et al.*, 1991).

The loudness enhancement hypothesis by Carlyon and Beveridge (1993) extended by the assumption that a reduction in the masker-standard similarity reduces the effect of the masker (Oberfeld, 2007) can account for the masker-induced DL elevations at low and high standard levels as well as for the mid-difference hump. The fact that the latter was not observed for all listeners weakens the case for perceptual similarity playing a dominant role, but as discussed in Sec. I, several previous experiments also found pronounced intersubject differences for high-level maskers combined with low-level standards. It is tempting to assume that this finding is related to the "central" nature of the effect of the forward masker assumed by both the referential encoding hypothesis and the similarity hypothesis. Studies on informational masking (which clearly represents a central/cognitive rather than a peripheral effect) also reported a large amount of interindividual variability (for a recent discussion see Durlach *et al.*, 2005). The evidence for a mid-difference hump was more uniform in Experiment 2, where the loudness change caused by the forward masker was a nonmonotonic function of the masker-target level difference for all listeners at the 25-dB SPL target level, and for all but one listener at the 55-dB SPL target level.

The effect of the standard level (midlevel hump) in the intensity discrimination experiment is compatible with the referential encoding hypothesis, which could also account for the mid-difference hump if the assumption is made that a perceptual difference between masker and standard results in less memory trace interference.

To summarize, the data do not provide a basis for definitively deciding between the similarity hypothesis and the referential encoding hypothesis. Therefore, some general remarks concerning the two alternative explanations are in order.

A unique feature of the similarity hypothesis is that it addresses the relation between the effects of a nonsimultaneous masker on loudness and intensity resolution. In line with the predictions, there was a significant correlation between the masker-induced loudness changes (Experiment 2) and the DL elevations (Experiment 1). At the same time, due to several discrepancies between the two effects, the predicted one-on-one relation between loudness enhancement and intensity resolution received only partial support. It should also be noted [as Plack (1996a) pointed out] that even if there had been a perfect correlation between loudness enhancement and the DL elevation, it would still remain to find an explanation of why a masker-induced loudness change should increase the variability of the loudness representations used for example in an intensity discrimination task.

The referential encoding hypothesis is very flexible and thus can account for a broad range of findings as, for example, the effects a tone interpolated between the masker and the target (cf. Plack, 1996b). Plack (1996a) noted that the latter results are difficult to explain in terms of the loudness enhancement hypothesis. On the other hand, the flexibility of the referential encoding hypothesis comes at the cost of many degrees of freedom. For example, to predict the effect of varying the masker-standard level difference, it would be necessary to specify at least qualitatively a functional relation not only between the level difference and the amount of trace degradation, but also between the level difference and the effectiveness of the masker as a within-interval coding reference. Another issue is that if the effect of a forward masker was due to the use of the context coding mode, a midlevel hump should be observed in quiet in a one-interval (absolute identification) paradigm, where listeners are also assumed to use context coding (Durlach and Braida, 1969). If a wide range of different stimulus levels is presented within a block ("roving level"), it is known that intensity resolution is superior at the edges of the intensity range (cf. Berliner *et al.*, 1977). However, in one-interval experiments presenting only a *small* range of intensities, just as in forward-masked intensity discrimination experiments, Braida and Durlach (1972, Experiment 5) found no evidence for a midlevel hump, while in the study by McGill and Goldberg (1968), the DLs for standards presented at 5–15 dB SL were somewhat smaller than in the region 25–35 dB SL. The individual DL differences ranged between only 0.5 and 2.5 dB, however, and were thus considerably smaller than the midlevel DL elevations of up to 13 dB found under forward masking (Plack *et al.*, 1995; Schlauch *et al.*, 1997). Now it could be argued that the maskers create a roving-level situation even if the standard level is fixed. Within a block, a listener encounters, e.g., a 60-dB SPL standard, rather similar standard-plus-increment levels, but also a 90-dB SPL masker, corresponding to a level range of 30 dB. It remains unclear, however, why in this situation the listeners should not be able to use the lower edge of the intensity range (i.e., the intensity of the standard) as an efficient coding reference (Braida *et al.*, 1984), but should have to rely on the detection threshold or the discomfort level.

To conclude, as far as intensity resolution is concerned, the significant masker-induced DL elevations at all standard levels as well as the observed mid-difference hump support the similarity hypothesis, but can also be accounted for by the referential encoding hypothesis.

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Arieh, Y., and Marks, L. E. (**2003**). "Time course of loudness recalibration: Implications for loudness enhancement," J. Acoust. Soc. Am. **114**, 1550–1556.

Baddeley, A. D. (**1966**). "Short-term memory for word sequences as a function of acoustic, semantic and formal similarity," Q. J. Exp. Psychol. **18**, 362–365.

Berliner, J. E., Durlach, N. I., and Braida, L. D. (**1977**). "Intensity perception. VII. Further data on roving-level discrimination and the resolution and bias edge effects," J. Acoust. Soc. Am. **61**, 1577–1585.

Braida, L. D., and Durlach, N. I. (**1972**). "Intensity perception. II. Resolution in one-interval paradigms," J. Acoust. Soc. Am. **51**, 483–502.

Braida, L. D., Lim, J. S., Berliner, J. E., Durlach, N. I., Rabinowitz, W. M., and Purks, S. R. (**1984**). "Intensity perception. XIII. Perceptual anchor model of context coding," J. Acoust. Soc. Am. **76**, 722–731.

Carlyon, R. P., and Beveridge, H. A. (**1993**). "Effects of forward masking on intensity discrimination, frequency discrimination, and the detection of tones in noise," J. Acoust. Soc. Am. **93**, 2886–2895.

Duncan, J., and Humphreys, G. (**1989**). "Visual search and stimulus similarity," Psychol. Rev. **96**, 433–458.

Durlach, N. I., and Braida, L. D. (**1969**). "Intensity perception. I. Preliminary theory of intensity resolution," J. Acoust. Soc. Am. **46**, 372–383.

Durlach, N. I., Mason, C. R., Gallun, F. J., Shinn-Cunningham, B., Colburn, H. S., and Kidd, G. (**2005**). "Informational masking for simultaneous nonspeech stimuli: Psychometric functions for fixed and randomly mixed maskers," J. Acoust. Soc. Am. **118**, 2482–2497.

Elmasian, R., Galambos, R., and Bernheim, A. (**1980**). "Loudness enhancement and decrement in four paradigms," J. Acoust. Soc. Am. **67**, 601–607.

Galambos, R., Bauer, J., Picton, T., Squires, K., and Squires, N. (**1972**). "Loudness enhancement following contralateral stimulation," J. Acoust. Soc. Am. **52**, 1127–1130.

Hellman, R. P., and Zwislocki, J. J. (**1964**). "Loudness function of a 1000 cps tone in the presence of a masking noise," J. Acoust. Soc. Am. **36**, 1618–1627.

International Electrotechnical Commission (IEC). (**1970**). *An IEC Artificial Ear, of the Wide Band Type, for the Calibration of Earphones Used in Audiometry* (IEC 318, Geneva).

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

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

Littell, R. C., Milliken, G. A., Stroup, W. W., and Wolfinger, R. D. (**1996**). *SAS System for Mixed Models* (SAS Institute Inc., Cary, NC).

Mapes-Riordan, D., and Yost, W. A. (**1999**). "Loudness recalibration as a function of level," J. Acoust. Soc. Am. **106**, 3506–3511.

Marks, L. E. (**1994**). "Recalibrating the auditory system: The perception of loudness," J. Exp. Psychol. Hum. Percept. Perform. **20**, 382–396.

McGill, W. J., and Goldberg, J. P. (**1968**). "Pure-tone intensity discrimination and energy detection," J. Acoust. Soc. Am. **44**, 576–581.

Moore, B. C. J., and Glasberg, B. R. (**1982**). "Contralateral and ipsilateral cueing in forward masking," J. Acoust. Soc. Am. **71**, 942–945.

Mori, S., and Ward, L. M. (**1992**). "Intensity and frequency resolution: Masking of absolute identification and fixed and roving discrimination," J. Acoust. Soc. Am. **91**, 246–255.

Oberfeld, D. (**2007**). "Loudness changes induced by a proximal sound: Loudness enhancement, loudness recalibration, or both?," J. Acoust. Soc. Am. **121**, 2137–2148.

Oxenham, A. J., and Bacon, S. P. (**2003**). "Cochlear compression: Perceptual measures and implications for normal and impaired hearing," Ear Hear. **24**, 352–366.

Plack, C. J. (**1996a**). "Loudness enhancement and intensity discrimination under forward and backward masking," J. Acoust. Soc. Am. **100**, 1024–1030.

Plack, C. J. (**1996b**). "Temporal factors in referential intensity coding," J. Acoust. Soc. Am. **100**, 1031–1042.

Plack, C. J. (**1998**). "Beneficial effects of notched noise on intensity discrimination in the region of the 'severe departure'," J. Acoust. Soc. Am. **103**, 2530–2538.

Plack, C. J., and Carlyon, R. P. (**1995**). "Loudness perception and intensity coding," in *Hearing*, edited by B. C. J. Moore (Academic, San Diego), pp. 123–160.

Plack, C. J., Carlyon, R. P., and Viemeister, N. F. (**1995**). "Intensity discrimination under forward and backward masking: Role of referential encoding," J. Acoust. Soc. Am. **97**, 1141–1149.

Plack, C. J., and Viemeister, N. F. (**1992a**). "The effects of notched noise on intensity discrimination under forward masking," J. Acoust. Soc. Am. **92**, 1902–1910.

Plack, C. J., and Viemeister, N. F. (**1992b**). "Intensity discrimination under backward masking," J. Acoust. Soc. Am. **92**, 3097–3101.

Relkin, E. M., and Doucet, J. R. (**1991**). "Recovery from prior stimulation. I. Relationship to spontaneous firing rates of primary auditory neurons," Hear. Res. **55**, 215–222.

Scharf, B., Buus, S., and Nieder, B. (**2002**). "Loudness enhancement: Induced loudness reduction in disguise? (L)," J. Acoust. Soc. Am. **112**, 807–810.

Schlauch, R. S., Clement, B. R., Ries, D. T., and DiGiovanni, J. J. (**1999**). "Masker laterally and cueing in forward-masked intensity discrimination," J. Acoust. Soc. Am. **105**, 822–828.

Schlauch, R. S., Lanthier, N., and Neve, J. (**1997**). "Forward-masked intensity discrimination: Duration effects and spectral effects," J. Acoust. Soc. Am. **102**, 461–467.

Schlauch, R. S., and Wier, C. C. (**1987**). "A method for relating loudness-matching and intensity-discrimination data," J. Speech Hear. Res. **30**, 13–20.

Yates, G. K. (**1990**). "Basilar membrane nonlinearity and its influence on auditory nerve rate-intensity functions," Hear. Res. **50**, 145–162.

Zeng, F.-G. (**1994**). "Loudness growth in forward masking: Relation to intensity discrimination," J. Acoust. Soc. Am. **96**, 2127–2132.

Zeng, F.-G., and Shannon, R. V. (**1995**). "Possible origins of the nonmonotonic intensity discrimination function in forward masking," Hear. Res. **82**, 216–224.

Zeng, F.-G., and Turner, C. W. (**1992**). "Intensity discrimination in forward masking," J. Acoust. Soc. Am. **92**, 782–787.

Zeng, F.-G., Turner, C. W., and Relkin, E. M. (**1991**). "Recovery from prior stimulation. II. Effects upon intensity discrimination," Hear. Res. **55**, 223–230.

Zwislocki, J. J., and Sokolich, W. G. (**1974**). "On loudness enhancement of a tone burst by a preceding tone burst by a preceding tone burst," Percept. Psychophys. **16**, 87–90.