The decision process in forward-masked intensity discrimination: Evidence from molecular analyses[a)]

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In a two-interval forced-choice intensity discrimination task presenting a fixed increment, the level of the forward masker in interval 1 and interval 2 was sampled independently from the same normal distribution on each trial. Mean and standard deviation of the distribution were varied. Correlational analyses of the trial-by-trial data revealed different decision strategies depending on the relation between mean masker level and standard level. If the two levels were identical, listeners tended to select the interval containing the higher-level masker, behaving like an energy detector at the output of a temporal window of integration. For mean masker level higher than the standard level, most listeners showed a negative correlation between the masker level in a given interval and the probability of selecting this interval, indicating a strategy of comparing the masker loudness and the target loudness in each of the two observation intervals, and voting for the interval where the loudness difference was smaller. Implications for models of forward-masked intensity discrimination and differences from decision strategies reported for forward-masked detection tasks [Jesteadt *et al.*, (2005). "Effect of variability in level on forward masking and on increment detection," J. Acoust. Soc. Am. **118**, 325–337] are discussed.

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I. INTRODUCTION

Nonsimultaneous masking produces a rather complex pattern of effects on intensity resolution (e.g., Carlyon and Beveridge, 1993; Plack *et al.*, 1995; Zeng, 1998; Oberfeld, 2008b). The present study for the first time not only examined the effects of a forward masker on performance levels or intensity-difference limens (DLs) ("molar psychophysics;" see Green, 1964) but also assessed the decision process in a forward-masked intensity discrimination task by introducing within-trial variability in masker level and analyzing the trial-by-trial data ("molecular psychophysics;" see Green, 1964; Gilkey and Robinson, 1986; Berg, 2004). The results demonstrate different decision strategies for different combinations of masker level and standard level.

To summarize previous findings, an important result is that with an intense forward masker [e.g., 90 dB SPL (sound pressure level)], intensity DLs are strongly elevated for a midlevel standard, relative to the DL in quiet. On the other hand, there is only a small effect of the masker on the DLs for standards presented at low and high levels, resulting in the so-called *midlevel hump in intensity discrimination* (Zeng *et al.*, 1991).

Three explanations have been proposed for these effects (for an in-depth discussion see Oberfeld, 2008b). Zeng *et al.* (1991) suggested that the effect is due to adaptation of the (small) population of low spontaneous-rate (SR) auditory-nerve neurons showing slower recovery from prior stimulation than high-SR neurons (Relkin and Doucet, 1991). However, in subsequent experiments a midlevel hump was also found for backward maskers and contralaterally presented maskers (e.g., Plack and Viemeister, 1992; Plack *et al.*, 1995; Schlauch *et al.*, 1999), which precludes mechanisms in the auditory periphery as the origin of the effect.

The *referential encoding hypothesis* by Plack and Viemeister (1992) and Carlyon and Beveridge (1993) can account for the effects of backward maskers and contralaterally presented maskers. It assumes that the masker presented between the targets in a two-interval (2I) task degrades the memory trace of the target presented in the first observation interval, so that the listener is forced to switch to the "context-coding mode" (Durlach and Braida, 1969; Braida and Durlach, 1988), in which he or she remembers a categorical/verbal representation of the sensation, based on a comparison with internal or external references.[1] Referential encoding is assumed to work efficiently at low and high standard levels, where the detection threshold, the discomfort threshold, or the level of the intense forward masker can be used as a coding 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 is thus predicted to be poor (Braida *et al.*, 1984). Consequently, for a midlevel standard, the model predicts a strong effect of an intense masker. For low-level and high-level standards, on the other hand, it predicts essentially no effect of the masker due to the assumed efficiency of referential encoding.

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Thus, the referential encoding hypothesis can account for the midlevel hump. Yet, it cannot easily explain the reduced midlevel humps observed if a masker differing from the standard in duration or spectral content is presented (Schlauch *et al.*, 1997, 1999). Even more important, the referential encoding hypothesis predicts essentially no effect of the masker at low and high standard levels. However, Oberfeld (2008b) found significant masker-induced DL elevations at standard levels of 25 and 85 dB SPL. At the low standard level, a *mid-difference* hump was observed: the DL elevation was larger at intermediate than at large masker-standard level differences. The latter result and the effects of masker duration and spectrum indicate that the *perceptual similarity* between the masker and the standard modulates the effect of the masker. Such similarity effects can be integrated into a third explanation proposed for the midlevel hump, which is based on the finding that a forward masker has an effect not only on intensity resolution but also on loudness. Maskers higher in level than a temporally proximal target result in an increase in target loudness (loudness enhancement; see Zwislocki and Sokolich, 1974 and Oberfeld, 2007). Now, Carlyon and Beveridge (1993) suggested that the masker-induced change in target loudness introduces loudness variability, which in turn results in impaired performance in an intensity discrimination task (*loudness enhancement hypothesis*). In fact, both a midlevel hump (Zeng, 1994; Plack, 1996) and a mid-difference hump (Oberfeld, 2008b) have been reported for loudness enhancement. One possible explanation for loudness enhancement is that listeners cannot access the "isolated" loudness of the target but will instead use a weighted average of masker loudness and target loudness when making their decision ("mergence;" see Elmasian *et al.*, 1980 and Oberfeld, 2007). Oberfeld (2007, 2008b) proposed that the observed similarity effects can be incorporated into such a model by assuming that maskers strongly differing from the target in at least one dimension (e.g., level, duration, or spectrum) will receive only a relatively small weight. Thus, the third model considered in this paper is the combination of the loudness enhancement hypothesis and the *similarity hypothesis* proposed by Oberfeld (2008b).

The "molar" data (i.e., DLs) collected in previous studies are compatible with the latter model, but as Oberfeld (2008b) noted, the referential encoding hypothesis could also be extended by the assumption that a perceptual difference between masker and standard results in less memory trace interference, accounting for the observed similarity effects. The current study provides a "molecular" analysis of the data from an intensity discrimination task. The levels of the masker in interval 1 and the masker in interval 2 were independently and randomly perturbed on each trial. The influence of the masker intensity information on the decision of the listener was measured in terms of the correlation between the within-trial difference in masker level and the response (*increment in interval 1 or increment in interval 2*).

Now the three different explanations for the effect of a forward masker on intensity resolution predict rather distinct patterns of correlations. For instance, a decision strategy compatible with the loudness enhancement hypothesis combined with the similarity hypothesis (Oberfeld, 2008b) would be that the listeners behave as an energy detector, comparing the output level of a "temporal window" for the first interval (representing a weighted sum of masker level and target level in that interval) with the output level of a temporal window for the second interval and responding that the increment was presented in the interval where the output level was higher (Plack and Oxenham, 1998).[2] These assumptions result in the hypothesis that the response be positively correlated with the within-trial difference in masker level. For example, listeners should tend to respond "*Increment in interval 2*" if the masker presented in interval 2 is higher in level than the masker in interval 1. The recovery-rate model and the referential encoding hypothesis predict different patterns of correlations, which will be detailed in Sec. IV.

The assumptions about the decision process in forward-masked intensity discrimination have not yet been tested using a molecular approach. Concerning intensity discrimination in quiet, Jesteadt *et al.* (2005) reanalyzed data from an experiment by Jesteadt *et al.* (2003) in which external variability was added by randomly varying the pedestal level in each of the two observation intervals. The relation between the level of the tone in the interval containing the standard only and in the interval containing the standard-plus-increment and performance was compatible with the pattern an energy detector would produce (see Green and Swets, 1966). Listeners voted for the interval containing the tone higher in level. For a forward-masked detection task with randomly perturbed masker levels, on the other hand, analysis of the trial-by-trial data demonstrated a decision strategy incompatible with energy detection at the output of a temporal window of integration (Plack and Oxenham, 1998; Nizami, 2003) because the subjects did not vote for the interval containing the higher-level masker.

It was hoped that an insight into the decision process could also provide an explanation for an additional aspect of the previous data currently not well understood, namely, the considerable intersubject variability, which is most notable for the case of an intense masker combined with a low-level standard. As pointed out above, most listeners show no or only a small DL elevation in this condition. In several studies, however, a large increase in the DL was observed for some listeners (Zeng *et al.*, 1991, listener RB; Zeng and Turner, 1992, listener RB; Carlyon and Beveridge, 1993, listener LW; Schlauch *et al.*, 1997, listener S4; Schlauch *et al.*, 1999, listener 2; Oberfeld, 2008b, listener BS). Could these differences be due to the use of different decision strategies?

II. METHOD

A 2I, two-alternative forced-choice (2AFC) intensity discrimination procedure was used. The levels of the standards remained constant at 25 dB SPL throughout the experiment. Listeners were tested in quiet and with forward maskers presented at mean levels of 25, 55, and 85 dB SPL. Three different values of the masker level variance were presented. Either the masker level was identical in the two observation intervals (i.e., the masker level was constant) or a small or large within-trial masker level variability was introduced. The performance of an energy detector operating at the output of a temporal window of integration would decrease with the variability in masker level because the latter variability would contribute to the variance of the decision variable, which is assumed to be the difference in output level of the temporal window for the two observation intervals.

In order to make the task more similar to the "classical" 2I intensity discrimination task used in previous experiments, the level of the target tones (standard and standard-plus-increment) was not perturbed. In an adaptive procedure, for example, there are only two alternative target levels (standard or standard-plus-increment), standard level is constant, and increment level remains relatively stable toward the end of a run. To approximate these conditions, a fixed level increment was presented in each block. The task obviously still differed from a classical intensity discrimination task due to the within-trial variation in masker level. This level variation of the to-be-ignored masker seemed less likely to introduce a decision strategy other than in the classical task than if the target levels had been perturbed. Second, the presentation of only two fixed target levels (standard and standard-plus-increment) per condition made it possible to use a signal detection approach for calculating sensitivity.

A. Listeners

Four students at the Johannes Gutenberg–Universität Mainz participated in the experiment voluntarily (three females, one male, age 19–24 years). They either received partial course credit or were paid for their participation. All listeners reported normal hearing. For the right ear (the ear tested), detection thresholds measured by a 2I, 2AFC adaptive procedure with a 3-down, 1-up rule (Levitt, 1971) were better than 10 dB HL at all octave frequencies between 0.5 and 8 kHz. Listeners were naïve with respect to the hypotheses under test. Only listener KD had previous experience in an intensity discrimination task.

B. Stimuli and apparatus

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 cosine-squared ramps. Each sinusoid started at zero phase. On each trial, there were two observation intervals. Except in no-increment trials (see below), an increment—that is, a pure tone of the same frequency, duration, and temporal envelope—was added in-phase to the standard in one of the observation intervals (selected with an equal *a priori* probability). In the forward masking conditions, a masker was presented in both intervals. On each trial, the sound pressure level of the masker presented in interval 1 and of the masker presented in interval 2 was sampled independently from the same normal distribution. Mean masker level μ_M was 25, 55, or 85 dB SPL. The standard deviation (SD) was 0 (fixed masker level), 2, or 6 dB. Masker level was limited to a range of $\mu_M \pm 2.5$ SD.

The silent interval between masker offset and standard onset was 100 ms. The interval between the offset of the first target and the onset of the second target was 650 ms. A similar stimulus configuration has been used in previous experiments (e.g., see Plack *et al.*, 1995; Zeng, 1998; Oberfeld, 2008b).

A trial started with a visual attention signal. The targets (standard and standard-plus-increment) were also marked by visual signals. The intertrial interval was 2000 ms, with the restriction that the next trial never started before the response and the feedback to the preceding trial had been given.

The stimuli were generated digitally, played back via one channel of an RME ADI/S digital/analog converter ($f_s = 44.1$ kHz, 24-bit resolution), attenuated by a TDT PA5 programmable attenuator, buffered by a TDT HB7 headphone buffer, and presented to the right ear via Sennheiser HDA 200 circumaural headphones calibrated according to IEC 318 (1970). The attenuator setting remained constant within a trial. The experiment was conducted in a single-walled IAC sound-insulated chamber. Listeners were tested individually.

C. Procedure

The listeners participated in two training sessions, followed by three sessions in which intensity DLs were measured using an adaptive procedure. On the basis of these DLs, individual increments corresponding to 70%–85% correct were selected for each combination of mean masker level and masker level SD. The so-selected increments were used in the main experiment in which the increment was constant within each block.

1. Adaptive measurement of intensity-difference limens

Prior to the main experiment, intensity DLs were measured using a 2I, 2AFC adaptive procedure with a 3-down, 1-up tracking rule (Levitt, 1971). A level increment was added to the standard in one of the two observation intervals (selected randomly). Listeners were instructed to ignore the maskers. Visual trial-by-trial feedback was provided. The initial level of the in-phase intensity increment, $10 \log_{10}(\Delta I/I)$, was 8 dB. The step size was 5 dB until the fourth reversal and 2 dB for the remaining eight reversals. For each track, the arithmetic mean of $10 \log_{10}(\Delta I/I)$ at the eight final reversals was converted to $\Delta L_{\mathrm{DL}} = 10 \log_{10}[1 + \Delta I/I]$. A track was discarded if the SD of $10 \log_{10}(\Delta I/I)$ at the eight final reversals was greater than 5 dB. At least three tracks were obtained for each Mean Masker Level × SD combination. Time permitting, additional tracks were run if the SD of the DLs estimated in the first three tracks exceeded 5 dB.

2. Intensity discrimination task with a fixed level increment

In a 2I, 2AFC procedure, a level increment was added to the standard in one of the two observation intervals (selected randomly). The increment was fixed within each block. Listeners indicated the interval containing the louder target. They were instructed to ignore the maskers.

Based on the DLs obtained in the adaptive procedure, a level increment ΔL was selected individually for each Mean Masker Level × SD combination that would correspond to percent correct in the range from 70% to 85%. Across listeners and conditions, ΔL ranged from 1.3 to 7.2 dB. Due to sizeable individual DL elevations caused by the 55-dB SPL and the 85-dB SPL maskers, it was not always possible to test a single intensity level increment resulting in the targeted performance level for all conditions. Therefore, for most listeners, the conditions differed not only in mean masker level and masker level variability, but also in increment level. This variation in the increment level presents a potential problem for the analyses of the trial-by-trial data because different correlation coefficients observed at, e.g., two different mean masker levels could be either due to the difference in masker level or to the difference in increment level. For example, Dai *et al.* (1996) demonstrated that the increment level has a pronounced effect on the expected and observed correlations in a spectral-shape discrimination task. To solve this problem, additional trials presenting the standard in both observation intervals (i.e., trials without an increment) were included in each block (Green, 1964; Dai *et al.*, 1996), except for the in-quiet condition. If the two targets are identical, any correlation between, e.g., the response and the difference between masker level in interval 2 and masker level in interval 1, can be attributed to the variation in masker level.

Only one Mean Masker Level × SD combination was presented in each block. Each block comprised 35 trials with the level increment presented in the first interval, 35 trials with the increment presented in the second interval, and 35 trials without an increment. Visual trial-by-trial feedback was provided, except following a no-increment trial. Additionally, the percentage of correct responses was displayed at the end of each block. Listeners were informed that they would receive both trials with feedback and trials without feedback, but they were not told that there would be no-increment trials without any difference in target level. Within each block, the three types of trials were presented in random order. For each combination of mean masker level and masker level SD, six blocks of 105 trials each were run in separate sessions, resulting in a total of 210 trials per condition (Mean Masker Level × SD × Increment Position). The main experiment comprised nine sessions. A testing session lasted approximately 1 h. Listeners took one short break in each session.

III. RESULTS AND DISCUSSION

A. Effect of mean masker level and masker variability on intensity resolution

The data from the intensity discrimination task using a fixed level increment were analyzed in terms of a signal detection theory model assuming equal-variance Gaussian distributions (Green and Swets, 1966). The no-increment trials were excluded from the analysis. For each observer, the sensitivity index applicable to a 2I forced-choice (2IFC) task, $d'_{\mathrm{2IFC}}=(1/\sqrt{2})(z_{\mathrm{hit}}-z_{\mathrm{FA}})$,[3] was computed for each block.[4]

In 7 of the total of 240 blocks obtained across listeners and conditions, the proportion of hits was 1.0. As d' is not defined in this case, the "log-linear correction" for extreme proportions was used (see Goodman, 1970; Hautus, 1995; Jesteadt, 2005).

As the level increment was not constant across listeners and conditions, it was not possible to analyze the sensitivity in terms of d' directly. Instead, the level increment resulting in $d'=1.16$ was estimated for each block. This value of d' corresponds to the performance level targeted by a 3-down, 1-up adaptive procedure (79.4% correct; see Macmillan and Creelman, 2005), under the assumption of unbiased responding. In the first step, resolution-per-dB was computed as $\delta' = d'/\Delta L$ (Durlach and Braida, 1969), where ΔL is the size of the level increment presented in a given block. The estimate of the level increment corresponding to $d'=1.16$ was then computed as $\Delta L_{\mathrm{DL}}=1.16/\delta'$, with the subscript DL denoting the correspondence to the DL in a 3-down, 1-up adaptive intensity discrimination task. Note that this analysis rests on the assumption that d' is proportional to the difference in level (ΔL) between standard-plus-increment and standard (Rabinowitz *et al.*, 1976; Buus and Florentine, 1991; Jesteadt *et al.*, 2003; for a discussion see Green, 1993).

In one block, d' was slightly negative so that no meaningful value of δ' could be computed. This block was excluded from the analysis. If for a given block the distance between the estimated ΔL_{DL} and the closer of the two quartiles of the six individual estimates obtained in the respective condition was larger than three interquartile ranges, this data point would be as an outlier (Lovie, 1986), resulting in the exclusion of four data points. Across the remaining 235 blocks, the percentage of correct responses ranged between 0.56 and 0.96 ($M=0.73$, SD=0.084). Mean d' was 0.95 (SD=0.40).

Figure 1 displays the individual estimates of the level increment ΔL_{DL} corresponding to $d'=1.16$, as a function of mean masker level and masker level variance. In the condition with fixed masker level (SD=0; open symbols in Fig. 1), the effect of the masker was small (maximum DL elevation of 2.6 dB), except for listener LE who produced a DL elevation of more than 7 dB at the two higher masker levels. For comparison, Oberfeld (2008b) using an adaptive procedure observed a mean DL elevation of 2.7 dB for a 55-dB SPL masker combined with a 25-dB SPL standard. For listeners KD and LE, the effect of the midlevel masker was slightly larger than the effect of the intense masker, representing weak evidence for a *mid-difference hump* pattern (Oberfeld, 2008b), which was also present in the mean data shown in Fig. 2. Listeners KD and LE showed a mid-difference hump in the presence of variability in masker level, while in these conditions ΔL_{DL} tended to increase monotonically with the masker level for listeners AZ and NH. The data were analyzed via repeated-measures analyses of variance (ANOVAs). The Huynh–Feldt correction for the degrees of freedom (Huynh and Feldt, 1976) was used where applicable and the value of $\tilde{\varepsilon}$ is reported. For the conditions with fixed masker level (SD=0), a one-factorial repeated-measures ANOVA indicated no significant effect of masker level $[F(3,9)=2.24]$. There was a significant quadratic trend, however, $[F(1,3)=10.26, p=0.049]$, compatible with the observation of a mid-difference hump. For the data obtained under forward masking, the DLs tended to be larger if the masker levels were varied rather than fixed (Fig. 2). Such a pattern is compatible with energy detection at the output of a temporal window of integration. However, an ANOVA with the within-subject factors mean masker level (25, 55, and

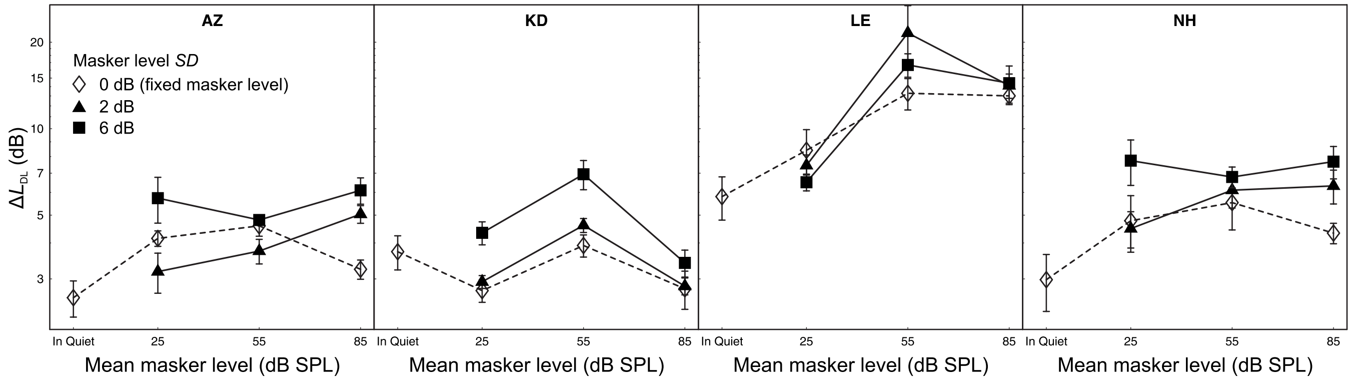

FIG. 1. Individual level increments (ΔL_{DL}, plotted on a log scale) corresponding to $d'=1.16$ as a function of mean masker level, estimated from resolution-per-dB in a 2IFC intensity discrimination task presenting a fixed level increment. The different symbols indicate different masker level SDs. Open diamonds: SD=0 dB (fixed masker level). Triangles: SD=2 dB. Boxes: SD=6 dB. Panels represent listeners. Error bars show ±1 standard error of the mean (SEM) of the six estimates per data point.

85 dB SPL) and masker level SD (0, 2, and 6 dB) showed neither a significant effect of mean masker level $[F(2,6)=1.64]$ nor an effect of masker level SD $[F(2,6)=3.50]$ nor a Mean Masker Level × SD interaction $[F(4,12)=0.94]$.

B. Correlational analyses of the trial-by-trial data

A correlational approach was used for molecular analyses of the trial-by-trial data (see Richards and Zhu, 1994 and Lutfi, 1995; see also Berg, 1989).[5] In the first analysis, point-biserial correlations were computed between the within-trial difference between the masker levels in interval 2 and interval 1 ($L_{\mathrm{M2}}-L_{\mathrm{M1}}$) and the binary response of the listener (1 or 2, indicating that he or she detected the increment in interval 1 or interval 2, respectively). This made it possible to test the hypothesis that the listeners use energy detection at the output of a temporal window of integration, that is, tend to respond that the increment was presented in the interval in which the masker was higher in level.

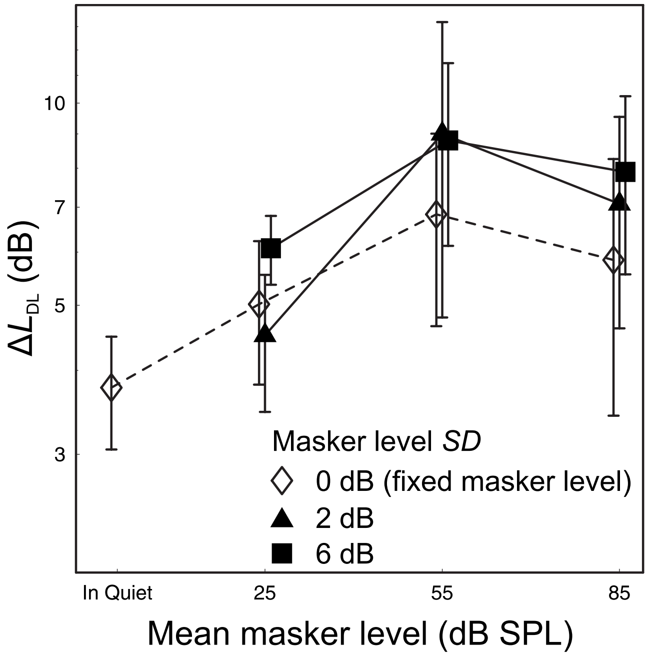

FIG. 2. Mean estimated level increments (ΔL_{DL}) corresponding to $d'=1.16$ as a function of mean masker level. Same symbols as in Fig. 1. Error bars show ±1 SEM of the four individual estimates.

In the second analysis, correlations of the correctness of the response (correct or incorrect) on individual trials with the masker level in the interval containing the standard and the level of the masker in the interval containing the standard-plus-increment were computed separately in order to answer the question whether the pattern Jesteadt *et al.* (2005) found for a forward-masked detection task also applies to a forward-masked intensity discrimination task, or if detection and discrimination show different characteristics in this regard.

1. Correlations between the within-trial difference in masker level and the response

Separate point-biserial correlations between the within-trial difference in masker level and the binary response were computed for the increment presented in interval 1, for the increment presented in interval 2, and for the no-increment trials.

An energy detector showing temporal integration will vote for the interval containing the higher overall level. As can be seen in Fig. 3, all listeners showed positive correlations if the mean masker level equaled the standard level (25 dB SPL), compatible with the behavior of an energy detector. All correlation coefficients were significantly different from 0 at the masker level SD condition of 6 dB (each coefficient based on 210 trials; t-test for correlation, $p<0.05$, two tailed; see Hays, 1988, p. 589). With a masker level SD of 2 dB, 8 of the 12 coefficients differed significantly from 0.

The data obtained in the conditions where the mean masker level was higher than the standard level indicated a decision strategy not compatible with energy detection, except for listener LE, who showed positive correlations between $L_{\mathrm{M2}}-L_{\mathrm{M1}}$ and the response at all mean masker levels. For the remaining listeners, 28 of the 36 correlation coefficients were significantly *smaller* than 0 at the 55-dB SPL and the 85-dB SPL mean masker levels (Fig. 3). A negative correlation between the difference in masker level and the response means that the listeners tended to vote for the interval

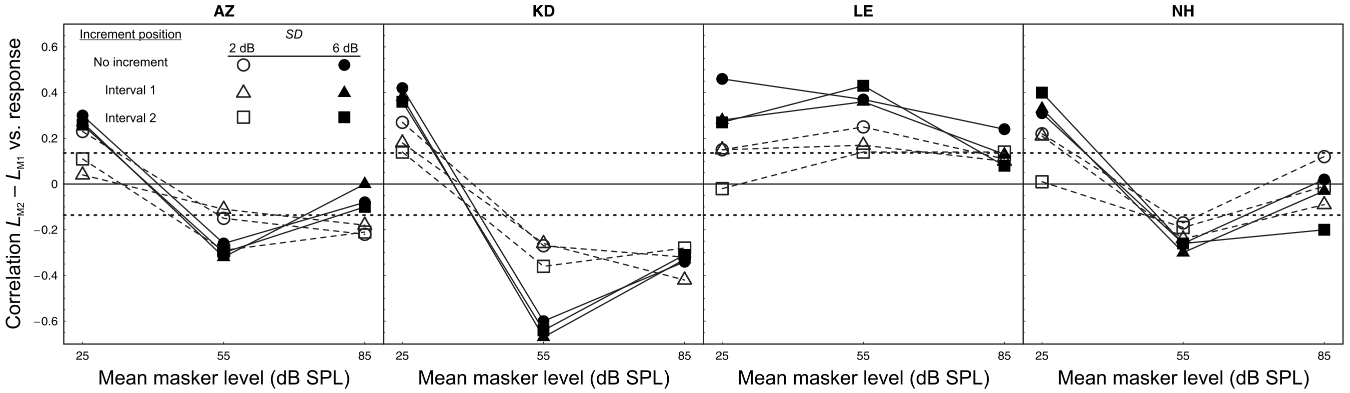

FIG. 3. Individual point-biserial correlations between the within-trial difference in masker level ($L_{M2}-L_{M1}$) and the response of the listener (1 or 2, indicating that he or she detected the increment in interval 1 or interval 2, respectively). Open symbols: SD=2 dB. Filled symbols: SD=6 dB. Circles: no increment. Triangles: increment in interval 1. Boxes: increment in interval 2. Panels represent listeners. Each data point is based on 210 trials. Correlation coefficients above or below the dotted horizontal lines are significantly different from zero (t-test for correlation, $p<0.05$, two tailed).

containing the *softer* masker. Such a behavior is compatible with a decision strategy of comparing the masker loudness and the target loudness in each of the two observation intervals and voting for the interval in which this difference in loudness was smaller.

A simple explanation for the zero correlations observed in several cases would be that the listener was effectively ignoring the maskers.

The correlations were stronger at a mean masker level of 55 dB SPL, especially so for the larger masker level SD. At the intermediate mean masker level, 23 of the 24 coefficients were significantly different from 0. At the largest mean masker level, only 12 of the 24 correlation coefficients differed significantly from 0. In principle, this pattern is consistent with the idea that a large loudness difference between masker and target should reduce the influence of the masker level on the decision (Oberfeld, 2008b), although the loudness enhancement hypothesis combined with the similarity hypothesis, of course, predicts positive rather than negative correlations.

At this point, a general cautionary note concerning the interpretation of the correlations as decision weights is in order. As Richards and Zhu (1994) showed, the correlation coefficients are identical in sign to the decision weight assigned to the parameter of interest (in the current case, the within-trial difference in masker level). Their magnitude, on the other hand, depends not only on the decision weight but also on parameters such as response bias, the (external) variability in masker level, and additional sources of variability in the decision variable (internal noise). Therefore, for a meaningful comparison of the magnitudes of the weight assigned to masker levels between, e.g., different mean masker levels, it would be necessary to analyze estimates of the decision weight rather than correlation coefficients. Unfortunately, the weight estimation would require rather strong assumptions about, for example, sources of internal noise and the weight assigned to target level. In part, these assumptions could be relaxed if the target levels were also randomly perturbed. In the current experiment, this was not done in order to make the task more similar to the classical intensity discrimination task. As a consequence, only the qualitative patterns of the correlations, most importantly the signs of the correlation coefficients, provide unequivocal information concerning differences in decision strategies. The *magnitude* of the correlations does not necessarily reflect the magnitude of the decision weights assigned to masker level information, however.

Mean data are displayed in Fig. 4. As discussed, the use of different level increments in the different Mean Masker Level × SD combinations poses a problem for the comparison of the correlations (see Dai *et al.*, 1996). Therefore, only the data from the common no-increment condition (circles in 4) were analyzed using a repeated-measures ANOVA with the factors mean masker level (25, 55, and 85 dB SPL) and masker level SD (2 and 6 dB). There was a significant effect of mean masker level [$F(2,6)=6.48$, $p=0.032$, $\tilde{\varepsilon}=1.0$], indicating different decision strategies for mean masker level

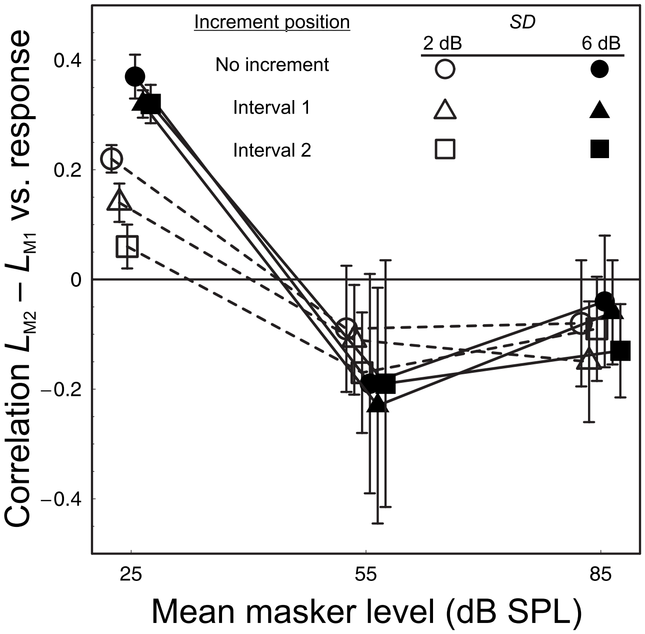

FIG. 4. Mean point-biserial correlations of the difference between masker level in interval 2 and masker level in interval 1 ($L_{M2}-L_{M1}$) with the response of the listener. Same format as Fig. 3. Error bars show ±1 SEM of the four individual correlation coefficients.

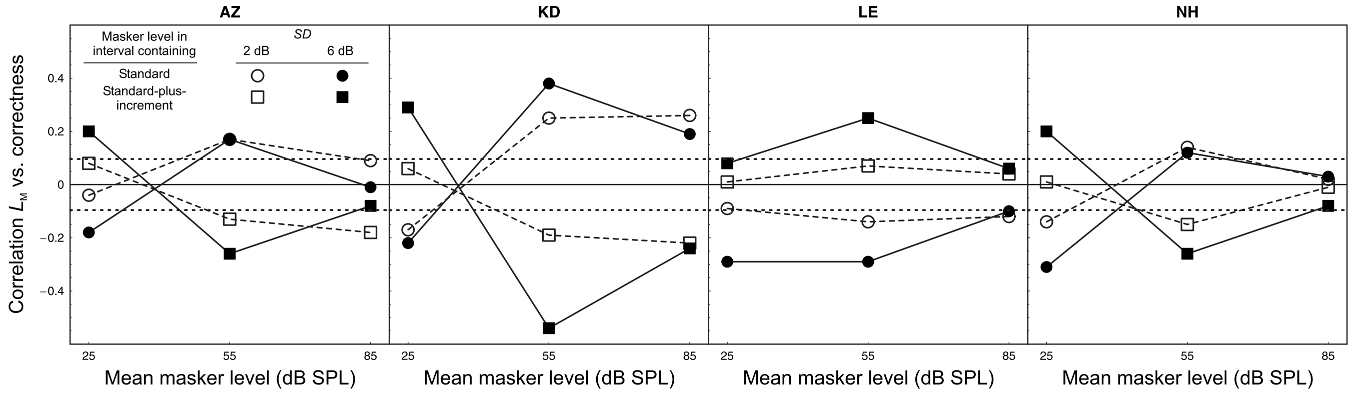

FIG. 5. Individual point-biserial correlations between the masker level and the correctness of the response as a function of interval and mean masker level. Circles: masker level in the interval containing the standard (M_S). Boxes: masker level in the interval containing the standard-plus-increment (M_{S+I}). Open symbols: masker level SD=2 dB. Filled symbols: SD=6 dB. Panels represent listeners. Each data point is based on 420 trials. Correlation coefficients above or below the dotted horizontal lines are significantly different from zero ($p < 0.05$, two tailed).

equal to or greater than standard level, respectively. The observation of a stronger correlation at the larger masker level SD was confirmed by a significant Mean Masker Level × SD interaction [$F(2,6)=6.53$, $p=0.031$, $\tilde{\varepsilon}=1.0$]. The main effect of masker level SD was not significant [$F(1,3)=0.275$], reflecting the fact that the correlation coefficients obtained at the two higher masker levels were more negative in the 6-dB SD condition for listeners AZ and KD, but more positive for listener LE.

2. Correlations between the masker level in the interval containing the standard or the standard-plus-increment and the correctness of the response

Correlations of the correctness of the response (correct or incorrect) on individual trials with the masker level in the interval containing the standard (M_S) and the masker level in the interval containing the standard-plus-increment (M_{S+I}) were computed separately. Jesteadt *et al.* (2005) reported that the level of the masker in the interval containing the signal was negatively related to performance, while the level of the masker in the nonsignal interval had only a very small effect on the correctness of the response. The performance of an energy detector at the output of a temporal window of integration would be equally affected by the masker levels in both intervals, albeit in opposite directions. A higher masker level in the interval containing the increment would increase the probability of voting for this interval, thereby increasing the probability of a correct response. A higher masker level in the interval containing the standard would also increase the probability of voting for this interval, but as a result *reduce* the probability of a correct response. For the current experiment, this raises the question whether the corresponding correlations differed as a function of mean masker level. As shown above, for mean masker level equal to standard level, the correlations between the within-trial difference in masker level and the response (increment in interval 1 or 2) were compatible with energy detection. Thus, it was expected that the masker level in both intervals be correlated with the correctness of the response in this condition. In contrast, for the higher masker levels, where a different decision strategy was observed, it seemed conceivable that the correctness was correlated mainly with the masker level in the interval containing the increment, which would parallel the results by Jesteadt *et al.* (2005).

An incorrect answer was coded as 0, a correct answer as 1. The no-increment trials were excluded from the analysis. The individual data are shown in Fig. 5. At a mean masker level of 25 dB SPL, all correlation coefficients for the relation between M_{S+I} and the correctness of the response were positive, although only three of the eight coefficients differed significantly from 0 (each coefficient was computed on the basis of 420 trials). In contrast, all correlation coefficients for the relation between M_S and the correctness of the response were negative (six of the total of eight were significantly different from zero). The positive correlations for the interval containing the increment and the negative correlations for the intervals containing the standard are compatible with energy detection.

For the two higher mean masker levels, the opposite relations were found for all listeners except LE (e.g., a *positive* correlation between M_S and the correctness of the response). For the interval containing the standard (S) and the interval containing the standard-plus-increment ($S+I$), 13 and 10, respectively, of the 16 correlation coefficients were significantly different from 0.

To test whether the strength of association between masker level and correctness differed between the standard interval and the standard-plus-increment interval, the *absolute values* of the correlation coefficients were analyzed in a repeated-measures ANOVA with the factors mean masker level (25, 55, and 85 dB SPL), SD (2 and 6 dB) and interval (interval containing the standard and interval containing the standard-plus-increment). Mean data are displayed in Fig. 6. There was no significant effect of interval [$F(1,3)=0.11$, $p=0.76$], showing that the correctness of the response was equally affected by the masker level in the interval containing the standard (S) as well as by the masker level in the interval containing the increment ($S+I$). The association between masker level and correctness was stronger at the larger masker level SD, confirmed by a significant effect of SD [$F(1,3)=22.63$, $p=0.018$]. There was also a significant Mean Masker Level × SD interaction [$F(2,8)=8.51$, $p=0.026$, $\tilde{\varepsilon}=0.85$] because the difference between the two SDs was not present at the highest mean masker level. Mean

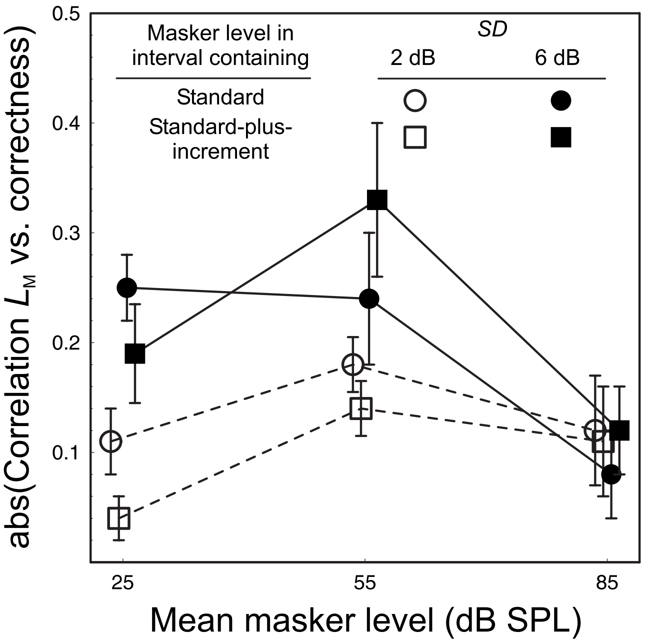

FIG. 6. Mean absolute values of the point-biserial correlation coefficients for the relation between masker level and the correctness of the response, as a function of interval and mean masker level. Same symbols as in Fig. 5. Error bars show ±1 SEM of the four individual values.

masker level had a significant effect, with the correlation being largest at the intermediate masker level $[F(2,6)=8.77,\ p=0.046,\ \tilde{\varepsilon}=0.59]$. The remaining effects were not significant at an alpha level of 0.05.

Taken together, the correlations between masker level in the two types of interval and the correctness of the response were incompatible with the behavior of an energy detector for conditions where mean masker level was higher than the standard level. Different from what Jesteadt *et al.* (2005) observed for a forward-masked detection task, the influence of masker level in the nonsignal interval (i.e., the interval containing the standard *S*) on the correctness of the response was not significantly smaller than the influence of masker level in the interval containing the increment. It can thus be concluded that different decision strategies are used in forward-masked detection and forward-masked intensity discrimination tasks.

IV. GENERAL DISCUSSION

The decision process in a 2I, 2AFC forward-masked intensity discrimination task was studied by introducing within-trial variability in masker level and analyzing the trial-by-trial data. Correlations between the within-trial difference in masker level and the response of the listener indicated the use of different decision strategies for different masker-standard level combinations. If the mean masker level equaled the standard level, the correlation was positive, compatible with a strategy of integrating the loudness of the masker and the target in each observation interval and voting for the interval in which the overall loudness was larger (i.e., energy detection at the output of a temporal window of integration). On the other hand, for three of the four listeners, the correlations were *negative* if the mean masker level was higher than the standard level. This result is compatible with a decision strategy of comparing the masker loudness and the target loudness in each of the two observation intervals and voting for the interval in which this difference in loudness was smaller. One of the listeners used the same strategy ("energy detection") at all mean masker levels. For this listener, the forward masker also had the strongest effect on intensity resolution. It remains to be shown whether and why using the "energy detection" rather than the "differencing" strategy could be related to this interindividual difference in sensitivity.

How do the results relate to the three explanations for the effects of a forward masker on intensity resolution discussed in the Introduction? If the effect of the masker was due to peripheral adaptation, as Zeng *et al.* (1991) assumed, then in principle negative correlations between the masker level presented in a given interval and the probability of selecting this interval should result. The reduction in the neural response (spike count) of auditory-nerve fibers to a test tone is proportional to the response to the masker (Smith, 1977; Abbas and Gorga, 1981). Therefore, the masker-induced reduction in the neural response to the target should be weaker in the interval containing the masker lower in level, introducing a tendency to vote for the interval containing the softer masker. On the other hand, as the output from high-SR fibers saturates at moderate sound pressure levels, a variation of ±5 dB in the level of a forward masker with a mean level of 85 dB SPL (as in the SD=2 dB condition of the current experiment) should have virtually no effect on the neural response to the test tone. However, based on a model of auditory-nerve responses that explicitly takes into account the differences between high-SR and low-SR neurons (Sumner *et al.*, 2002), Meddis and O'Mard (2005) concluded that for low-SR neurons, the amount of depression in the response to the test tone does not saturate even at masker levels of 90 dB SPL. In any case, the *positive* correlations between the within-trial level difference and the response observed for mean masker level equal to standard level are at odds with the physiological characteristics of the auditory nerve, where maskers identical in level to the test tone produce adaptation rather than enhancement (Smith, 1977).

Negative correlations are in principle also compatible with the referential encoding hypothesis, but only if it is assumed that the listeners use the intense masker as the coding reference. If now the intensity of the targets is coded by "measuring" the distance to the reference intensity (Braida *et al.*, 1984), then the distance will be larger in the interval containing the masker higher in level, so that the target presented in this interval will be coded as being softer. It appears very unlikely, though, that the listeners used the masker as a coding reference. As the level of the standard was fixed to 25 dB SPL throughout the experiment, this was the lowest level in all blocks presenting the 55 and the 85-dB SPL mean masker level, thus representing a sharp gradient in the stimulus set. This should have made the standard level useful as a coding reference according to the model by Braida *et al.* (1984), specifically so as the perceptual distance between the targets and the standard was much smaller than the distance between the targets and the intense masker. Second, to explain the different correlations observed for mean masker level equal to standard level, it could be assumed that the masker causes no trace degradation. On the other hand, only zero correlations would have been directly compatible with the referential encoding hypothesis in this situation, while the observed positive correlations cannot be explained in terms of the model.

The loudness enhancement hypothesis (Carlyon and Beveridge, 1993) combined with the idea that loudness enhancement occurs because the percept of target loudness is the weighted average of the separate sensation masker and target would produce if presented in isolation (mergence; see Elmasian *et al.*, 1980; Oberfeld, 2008b) predicts positive correlations between the within-trial level difference and the response. Compatible results were found only for mean masker level equal to standard level, however, while the negative correlations at higher masker levels are evidence against this hypothesis. The data show that at least in the latter conditions the listeners do not behave as an energy detector at the output of a temporal window of integration.

Taken together, it has to be concluded that none of the three explanations for the effects of a nonsimultaneous masker on intensity resolution is strictly compatible with the results of the present experiment. Instead, the decision strategies identified via molecular analyses should motivate the formulation of alternative models. To this end, it would, of course, be desirable to apply the molecular approach to a wider variety of conditions than in the current experiment. Generally, the findings indicate that it is not appropriate to assume that one and the same decision strategy is used in all conditions and by all listeners.

In order to gain meaningful information about not only the direction of the influence of masker level on the decision but also about the strength of the association between the within-trial difference in masker level and the response, it would be necessary to estimate decision weights rather than to analyze the correlations (see Richards and Zhu, 1994). In this context, a sensible step for future experiments would be to also perturb the target levels, which could simplify the derivation of the weights. The magnitudes of the decision weights in different conditions (e.g., mean masker levels) could provide further information about, for example, the relation to inter-and intraindividual differences in sensitivity.

Correlations of the correctness of the response on individual trials with either the masker level in the interval containing the standard or the masker level in the interval containing the standard-plus-increment showed that the masker level in both types of interval had an effect on performance, contrary to what Jesteadt *et al.* (2005) observed for a forward-masked detection task. The data are thus further evidence for the characteristics of discrimination and detection differing from one another (see Laming, 1986; Zeng *et al.*, 1991).

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[1] If trace degradation prevents across-interval comparisons, then the 2I task is effectively transformed into a one-interval (1I) task. Sensitivity (in terms of d') in a 1I task is approximately two times lower than in a 2I task [e.g., see Viemeister (1970), Jesteadt and Bilger (1974), and Braida *et al.* (1984)]. As there are two observations per trial (one per interval), however, sensitivity should decrease only by a factor of $\sqrt{2}$ if across-interval comparisons are prevented [see Green and Swets (1966), p. 238ff]. If the masker-induced decline in intensity resolution was only due to the latter decrease in sensitivity predicted by signal detection theory, a forward masker should have no effect in a 1I task, however, where the same decision mode would be assumed in quiet and in forward masking. Yet, Oberfeld (2006) found that the effect of a forward masker on intensity resolution in a 1I task was very similar to the effect in a 2I task. Thus, it is necessary to consider additional factors such as an increased variance in the coding process introduced by the change in decision mode [see Braida *et al.* (1984) and Plack and Viemeister (1992)].

[2] The temporal window effective here must be considerably longer than the window with a duration of approximately 40 ms assumed for a detection task (Plack and Oxenham, 1998) because an effect of a forward masker on intensity resolution is observed at masker-target ISIs up to 400 ms (Zeng and Turner, 1992). Therefore, it is not likely that the temporal integration operates at early processing stages. Instead, it is conceivable that the integration of masker and target level information represents properties of the decision process operating on memory representations of the targets.

[3] For d' derived from a one-point receiver operating characteristic (ROC) curve to be a valid measure of sensitivity, it must be assumed that the ROC curve is symmetric (i.e., linear and of unity slope in z-coordinates; see Macmillan and Creelman, 2005). As Green and Swets (1966) (p. 68) have shown on theoretical grounds, the ROC curve for a 2IFC experiment can be expected to be symmetric about the negative diagonal, even if the yes-no ROC curve for the same condition is asymmetric. This prediction was supported empirically (see Norman,1964; Atkinson and Kinchla, 1965; Markowitz and Swets, 1967; see also Luce and Green, 1974).

[4] Alternatively, the frequencies of hits and false alarms could have been pooled across all blocks presenting the same condition. Hautus (1997) showed that computing d' from pooled data can be more efficient than computing average d' across blocks, albeit not in all situations (for a discussion see Macmillan and Creelman, 2005). It is likely that for a given condition the sensitivity of a listener varies from session to session. In fact, Jesteadt (2005) showed that the variability of repeated measurements of d' is larger than the variance associated with the binomial distributions of the proportions underlying the computation of d', indicating additional sources of variance. Computing d' per block and presenting the average sensitivity and the associated SD provide information about the block-to-block variability that would be concealed when computing d' from pooled data.

[5] The techniques used to estimate perceptual weights range from maximum-likelihood estimation of the weights based on the slopes of psychometric functions (Berg, 1989) to point-biserial or Pearson correlations (Ahumada and Lovell, 1971; Lutfi, 1995) and multiple logistic regression (Alexander and Lutfi, 2004; Oberfeld, 2008a). All techniques are based on a similar decision model (for a recent discussion see Lutfi and Jesteadt, 2006). Multiple logistic regression has the advantage of controlling for (spurious) correlations between multiple predictors. In the present experiment, however, only one predictor (the within-trial difference in masker level) was involved. Therefore, the correlational approach was selected because it is computationally simple and its properties have been thoroughly analyzed by Richards and Zhu (1994). Plank (2005) and Tang *et al.* (2005) demonstrated that the weight estimates produced by the different techniques are very similar.

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