Psychoacoustic correlates of individual noise sensitivity[a)]

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(Received 22 February 2000; accepted for publication 2 January 2001)

In environmental noise surveys, self-reported noise sensitivity, a stable personality trait covering attitudes toward a wide range of environmental sounds, is a major predictor of individual noise-annoyance reactions. Its relationship to basic measures of auditory functioning, however, has not been systematically explored. Therefore, in the present investigation, a sample of 61 unselected listeners was subjected to a battery of psychoacoustic procedures ranging from threshold determinations to loudness scaling tasks. No significant differences in absolute thresholds, intensity discrimination, simple auditory reaction time, or power-function exponents for loudness emerged, when the sample was split along the median into two groups of ''low'' vs ''high'' noise sensitivity on the basis of scores obtained from a psychometrically evaluated questionnaire [Zimmer and Ellermeier, Diagnostica **44**, 11–20 (1998)]. Small, but systematic differences were found in verbal loudness estimates, and in ratings of the unpleasantness of natural sounds, thus suggesting that self-reported noise sensitivity captures evaluative rather than sensory aspects of auditory processing.
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PACS numbers: 43.50.Qp, 43.66.Cb, 43.66.Fe [RVS]

I. INTRODUCTION

A. The concept of noise sensitivity

Individual noise sensitivity is a personality trait covering attitudes towards a wide range of environmental sounds, and is typically assessed by obtaining responses to one or several rating-scale items.

Noise sensitivity is a major antecedent of individual noise annoyance, as has been demonstrated in field surveys and laboratory experiments alike (see Taylor, 1984; Stansfeld *et al.*, 1985; Stansfeld, 1992; Job, 1988, 1999; Staples, 1996). In a review of 27 studies pertaining to railway, aircraft, and construction noise, Job (1988) reported annoyance reactions to be determined most strongly by noise exposure. With noise exposure controlled for, the second most powerful predictor was individual noise sensitivity, with correlations ranging from $r=0.25$ to $r=0.45$. On average, individual noise sensitivity explained 10.2% of variation in noise-annoyance reactions towards a given sound source, as compared to 17.6% of variation explained by noise-exposure measures. Taylor (1984) found an even stronger influence of noise sensitivity on annoyance reactions. Using a path-modeling approach to investigate the impact of noise-exposure measures, attitudes towards aircraft operation, and several personal-background characteristics on annoyance by aircraft noise, Taylor (1984) found noise sensitivity to have the largest single effect overall (as did Langdon, 1976).

It should be emphasized that, conceptually, *noise sensitivity* is clearly distinguishable from *noise annoyance*, as can be seen by their different correlation structures: Whereas measures of annoyance show a clear positive correlation with indices of noise exposure ($r=0.30$), noise-sensitivity measures are independent of exposure ($r=-0.02$; see Taylor, 1984; Job, 1988, 1999). Nevertheless, noise sensitivity has been demonstrated to have direct or indirect effects on health by (a) constituting a stressful psychological condition in its own right (Job, 1999); (b) increasing physiological reactivity of the cardiovascular system (Ising *et al.*, 1980; Stansfeld and Shine, 1993); and (c) being found to covary with the degree of psychopathology (Stansfeld, 1992).

The use of the noise-sensitivity concept is not restricted to clinical or subclinical populations, but refers to a property prevalent in the population at large. There is strong consensus that noise sensitivity constitutes a personality trait that is stable over time (Stansfeld, 1992; Langdon, 1976; Weinstein, 1978; Zimmer and Ellermeier, 1998a, 1999). A definition encompassing all facets of noise sensitivity discussed in the literature has been proposed only recently: Job (1999) defined noise sensitivity as referring to ''*...the internal states (be they physiological, psychological [including attitudinal], or related to life style or activities conducted) of any individual which increase their degree of reactivity to noise in general*'' (p. 59).

B. Evidence for a sensory component in noise sensitivity

While this definition distinguishes several levels at which noise sensitivity might operate, many investigators have conceptualized a crucial component of noise sensitivity to be *perceptual* in nature. Reason (1972) hypothesized a physiologically based disposition that might lead individuals to ''...transduce... input more effectively so that the subjective experience it evokes is more intense than that produced within less 'receptive' individuals by the same level of stimulus energy'' (p. 306). Taylor (1984) conceptualized

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personal sensitivity as related to how individuals ''perceive noisy events'' (p. 259), as opposed to how they evaluate them, and Job (1999) explicitly includes greater ''hearing acuity'' (p. 59) as a possible contributor to noise sensitivity.

The evidence for a sensory component in noise sensitivity is weak, however. We found only four studies addressing the issue, and we will demonstrate that methodological and conceptual shortcomings prevent unequivocal conclusions from the present state of research.

Investigating physiological and psychophysical correlates of noise sensitivity in a female community sample ($n = 72$), Stansfeld *et al.* (1985) found no relationship between noise sensitivity and absolute hearing threshold or uncomfortable loudness level. A small effect of noise sensitivity was found in graphic ratings of the loudness of 2-kHz tones (see their Fig. 1), indicating that highly noise-sensitive individuals exhibit steeper psychophysical functions. This finding, however, did not hold up when instead of a direct self-rating of noise sensitivity the McKennell (1963) scale capturing potential disturbance by seven everyday sounds, was employed. Furthermore, the authors acknowledge the procedure to be flawed, since reversing the polarity of the graphic rating scale was occasionally misunderstood by the participants.

In a laboratory experiment using a student sample of 93 persons, Öhrström, Björkman, and Rylander (1988) had subjects determine the levels at which three artificial sounds became ''unpleasant.'' Noise-sensitive subjects tended to report discomfort at lower sound-pressure levels, resulting in a correlation of $r = -0.25$ (see their Appendix) between discomfort thresholds and noise sensitivity as determined either by a Swedish translation of Weinstein's (1978) questionnaire or a single-item self-rating. Likewise, Dornic, Laaksonen, and Ekehammar (1990) found correlations ranging from $r = -0.44$ to $r = -0.65$ between noise sensitivity as assessed by Weinstein's scale and the level of three different types of noise that respondents from a student sample ($n = 18$) chose as being ''clearly annoying.''

Further evidence for suprathreshold effects of noise sensitivity was presented by Moreira and Bryan (1972). In their Table I, they report a correlation of $r = 0.31$ between self-assessed noise sensitivity and the slope of loudness functions determined in an earlier, unpublished study. Furthermore, they had 34 subjects rate three recorded sounds presented at various levels on a scale mixing adjectives refering to loudness and annoyance. When they contrasted their three most noise sensitive with the three least sensitive subjects, their graphs (Moreira and Bryan, 1972, Figs. 3 and 4) seem to indicate that the former assign higher ratings at low SPLs, thus producing psychophysical functions with shallower slopes, which appears to be at variance with their earlier loudness scaling data.

C. Rationale for the present investigation

In our view, conclusive assessment of the relationship between noise sensitivity and auditory functioning is precluded by two major deficiencies of previous research: (1) Unsatisfactory measurement of noise sensitivity, and (2) insufficient quality and breadth of the psychoacoustical measures employed. These criticisms shall be dealt with in turn.

1. Measurement of noise sensitivity

With the notable exception of the two Swedish studies (Öhrström *et al.*, 1988; Dornic *et al.*, 1990) that used a translation of Weinstein's (1978) 21-item noise-sensitivity questionnaire, the determination of noise sensitivity rested on measures of unknown psychometric quality. In many other studies, noise sensitivity is confounded with noise annoyance, or assessed from single-item self-ratings that have been shown to be inferior to questionnaire-based measurement (Zimmer and Ellermeier, 1999). First of all, such ratings do not meet established psychometric criteria of reliability and validity; second, they are open to *ad hoc* interpretation depending on the context in which they are presented, and finally, they fail to elicit a wide enough range of situations to qualify for the measurement of *general* noise sensitivity (Job, 1999). These properties make them unfit to measure individual differences with the precision needed for correlational analyses.

Therefore, the present investigation employed a recently developed (Zimmer and Ellermeier, 1998a) full-length, German-language noise-sensitivity questionnaire having excellent psychometric properties. Details about this questionnaire are given in Sec. II C 7.

2. Psychoacoustical measurement

A greater hindrance to conclusive assessment of the relationship between noise sensitivity and perceptual acuity is the scarcity of adequate psychophysical measurements in the pertinent literature. The studies reviewed in the previous section clearly do not cover the breadth of psychophysical methods available to assess auditory functioning. They (1) often employ methods that do not represent the state of the art; (2) collect too little data to justify the derivation of individual parameters; (3) make statements based on small numbers of subjects (e.g., selected extreme groups); (4) use stimuli or response categories that confound psychoacoustical performance with noise assessment, and (5) are subject to a host of response biases that makes it difficult to separate sensory from judgmental (or attitudinal) contributions.

Therefore, the present investigation was designed with a test-battery approach in mind: An attempt was made to cover a broad range of methodologies and phenomena including (a) absolute and difference thresholds; (b) suprathreshold reaction-time measurements; (c) a ratio-scaling procedure; and (d) direct ratings of loudness or annoyance. In our view, converging with an integrative perspective recently proposed by Baird (1997, Chaps. 1 and 15), these procedures may be ordered on a hypothetical dimension along which the sensory contribution decreases (from thresholds to ratings, for example) while the judgmental contribution increases accordingly. Furthermore, an effort was made to employ bias-free adaptive procedures which had not been used in this research area thus far, and to include signal-detection analyses which might help to disentangle sensory and judgmental effects of noise sensitivity, if present.

As a result of refining the assessment of noise sensitivity, while simultaneously broadening the collection of psychoacoustical parameters, we hope to make a contribution to the clarification of the concept of noise sensitivity, specifically by probing if it rests on a perceptual basis.

II. GENERAL METHOD

A. Subjects

An unselected sample of 61 volunteers, most of whom were students at the University of Regensburg, participated in the experiments. This sample had a median age of 24 years (range 19–37 years). Care was taken to recruit an approximately equal number of female ($N=33$), and male ($N=28$) participants.

All subjects were audiometrically tested using Békésy tracking at the standard audiometric frequencies (0.5–8 kHz). Two of the 61 subjects had a hearing loss exceeding 30 dB HL with respect to the ANSI (1996) standard for at least one of the frequencies tested; an additional eight subjects showed losses greater than 20 dB HL. These ten slightly impaired subjects were not excluded from the analyses, since restricting the range of audiometric performance might have weakened correlations with noise-sensitivity scores. Separate analyses revealed, however, that the relationships observed in the present study were not affected by the marginal impairments found in the audiometric screening test.

In order to minimize the effect of expectations, the participants were not informed about the central role of self-reported noise-sensitivity in the present investigation. Rather, they were told that the study focused on interrelations between different measures of auditory performance obtained in the laboratory.

B. Apparatus and stimuli

All stimuli—except for the natural sounds used in the annoyance rating experiment (Sec. II C 6)—were computed using a Tucker-Davis-Technologies (TDT) signal processor card (model AP2), and played from a 16-bit digital-analog converter (TDT model DD1) at a sampling rate of 50 kHz. After passing through a low-pass filter set at 10 kHz (TDT model FT5), the signal was adjusted to the proper level by means of two programmable attenuators (TDT model PA4). Upon passing through a headphone buffer (TDT model HB6) the signal was delivered to the subject via audiometric headphones (Beyerdynamic DT 48). A different set of phones (Beyerdynamic DT 550) was used in the annoyance rating experiment. The equipment was calibrated by measuring sound-pressure levels at the headphones using an artificial ear (Bruel & Kjær type 4153) and a sound level meter (Bruel & Kjær type 2610). Subjects were run individually and were seated in a double-walled sound-attenuated chamber throughout the experiments.

C. Procedure

1. Absolute thresholds

Absolute thresholds for 1-kHz tones were determined using a two-interval adaptive forced-choice method as described by Levitt (1971). On each trial, the subject had to decide in which of two observation intervals marked by the consecutive illumination of two LEDs the signal tone had occurred. Immediately after responding via a hand-held unit, the subject received visual feedback as to whether the decision was correct. At the outset of the measurement sequence, the signal—a 200-ms sinusoid having 10-ms rise/decay ramps—was presented well above threshold (at 40 dB SPL). Following two successive correct responses, the level of the signal was decreased; following a single incorrect response, it was increased again (''2-down/1-up rule,'' Levitt, 1971). Initially, level thus varied in steps of 4 dB, but after the first four reversals (changes from decreasing to increasing intensity or vice versa) the step size was reduced to 2 dB. Another eight reversals were collected at this final step size, and their mean was taken as an estimate of the 71%-correct threshold (Levitt, 1971).

Two adaptive threshold determinations were obtained for the right ear of each participant, and two for the left ear with measurements being made in a counterbalanced RLLR (or LRRL) sequence.

2. Intensity discrimination

To obtain a measure of differential sensitivity, we determined each subject's intensity discrimination performance at 1 kHz. An adaptive procedure of identical format as in Sec. II C 1 was used. This time, however, the subject had to tell which of the two observation intervals contained the tone of greater intensity. The standard tone always had a level of 54 dB SPL; the variable comparison was generated by electrically adding the same signal to the standard after passing it through a programmable attenuator. At the outset of the adaptive track, the signal was added in phase at equal level, corresponding to a relative amplitude (RA) of 0 dB, and yielding a level difference ΔL of 6 dB. Subsequently, the relative amplitude was decreased or increased following a two-down/one-up rule (see Sec. II C 1), using an initial step size of 4 dB (RA) which was reduced to 2 dB after the first four reversals. Note, however, that by varying the relative amplitude of the added signal, level differences (ΔL) between standard and comparison amounting to fractions of a dB may be generated (Green, 1988, Table 3-1; leftmost and rightmost columns). Again, the arithmetic mean of the last eight reversals was taken as an estimate of the amplitude difference that would yield 71%-correct responses. For ease of comprehension, the relative amplitudes obtained were converted [Ellermeier, 1996, Eq. (2)] to the intuitively more accessible measure ΔL, the ''just noticeable'' level difference in decibels between standard and comparison.

Again, two adaptive measurements were made for each ear of each participant, with appropriate control of order effects as in Sec. II C 1.

3. Magnitude estimation of loudness

Direct loudness judgments of 1-kHz sinusoids were obtained using the method of magnitude estimation with a fixed standard (also termed ''ratio estimation,'' Gescheider, 1997). On each trial, subjects first heard a 70-dB tone (the ''standard'') which—via instruction—was given a loudness value of ''10'' (the ''modulus''). Following a 2-s interval a second tone was presented, the loudness of which was to be numerically estimated relative to the standard. Both tones had a total duration of 500 ms, including 10-ms rise/fall times. The participants had unlimited time to note their estimate on a chart, then pressed a button to initiate the next trial. In a block of trials, nine sound-pressure levels covering the range from 50 to 90 dB SPL in 5-dB steps were presented in a random sequence. After a block of practice that was discarded, three repetitions of the stimulus set were presented to each subject, in a different random permutation each time.

4. Loudness category scaling

In order to obtain categorical judgments of loudness, the same procedure (stimulus levels, timing, number of trials) as in Sec. II C 3 was used, with the exception that no standard or modulus was presented, and that subjects had to rate their loudness impression on a five-point scale. They entered their judgment by pressing one of five response buttons on a handheld unit which were labeled with the German equivalents of ''very soft,'' ''soft,'' ''medium,'' ''loud,'' and ''very loud.''

5. Simple auditory reaction time

For reaction-time (RT) measurements, the same apparatus and stimuli as in the scaling experiments (Secs. II C 3 and 4) were used with the exception that stimulus duration was shortened to 200 ms. A simple reaction-time paradigm was employed; that is, subjects had to press a key in response to the onset of a tone as fast as they could. Each trial began with the illumination of a warning light for 200 ms. After another 300 ms, an exponentially distributed random foreperiod ranging between 0 and 3000 ms (having an expected value of 500 ms) was initiated which was followed by the presentation of the target tone. Reaction time was measured from the onset of the target tone to the closing of the response key contact. After the subject had made a response, the next trial was started following a 2-s intertrial interval. As in the scaling experiments, trials were permuted in blocks containing all nine sound-pressure levels. Ten such permutations of the nine stimulus levels were presented, yielding a total of 90 RT measurements per subject. Trials resulting in reaction times shorter than 100 ms (anticipations) or longer than 1 s (misses) were repeated at the end of each block.

6. Annoyance ratings

Since annoyance is awkward to assess in a laboratory situation without reference to a focal task with which the annoying sounds may interfere, we decided to have subjects rate the ''unpleasantness'' of ten environmental sounds which a previous study (Ellermeier, Mader, and Daniel, 1997) had shown to be measurable on a unidimensional ratio scale as specified by the ''BTL'' scaling model (Luce, 1959). The ten sounds to be rated were natural, traffic, and industrial noises ranging from ''water running from a faucet'' to the recording of a ''jackhammer.'' The sounds were stored in ''wav'' file format and were—deviating from the general description of the apparatus (see Sec. II B)—played with 16-bit resolution at 22-kHz sampling rate via a ''Soundblaster compatible'' PC sound card. After adequate amplification they were diotically delivered via Beyerdynamic DT 550 headphones. The sounds were presented ''as recorded'' and had vastly different (A-weighted, energy-equivalent $[L_{eq}]$) sound-pressure levels ranging from 60 to 81 dB SPL.

Subjects were asked to rate each sound as either ''not at all unpleasant,'' ''somewhat,'' ''medium,'' ''rather,'' or ''very unpleasant'' by pressing one of five response buttons labeled both verbally and numerically. The ten sounds were presented four times, in a different random order each time.

7. Noise sensitivity questionnaire

Noise sensitivity was assessed using a psychometrically evaluated 52-item questionnaire (''Lärm-Empfindlichkeits-Fragebogen,'' LEF) developed by Zimmer and Ellermeier (1998a). This questionnaire encompasses statements about a wide variety of environmental noises in a range of situations that affects the entire population. The material covers seven content areas: everyday life, recreation, health, sleep, communication, work, and noise in general. The 52 items presented relate to perceptual, cognitive, affective, and behavioral responses towards noise in these contexts. For every item, respondents may choose one of four response options ranging from strong disagreement to strong agreement. In order to correct for response bias, an almost equal number of items is scored in each direction. The questionnaire scores very well on psychometric indices: It has high internal consistency (Cronbach's $\alpha=0.92$) and retest reliability ($r_{tt}=0.91$). Though its scope is somewhat broader, it correlates well with the better-known Weinstein (1978) noise-sensitivity scale ($r=0.79$), and is superior to single-item self-ratings of noise sensitivity (Zimmer and Ellermeier, 1999).

8. Session format

In administering the procedures detailed in Secs. C 1–7, we strictly adhered to the following sequence: In the first session lasting approximately 40 min, data were collected using (1) Békésy audiometry; (2) adaptive intensity discrimination; and (3) category scaling of loudness. The second session lasted 60–70 min including appropriate rest breaks, and involved (4) annoyance ratings of natural sounds; (5) measurement of absolute thresholds; (6) magnitude estimation; (7) simple reaction time; and (8) administering the noise-sensitivity questionnaire (LEF). The two sessions were a minimum of 1 and a maximum of 6 weeks apart. Given the high retest reliability of both noise-sensitivity and psychoacoustical measures, the time lapse between sessions was not considered problematic.

TABLE I. Absolute and difference thresholds for 1-kHz, 200-ms tones as a function of noise sensitivity. Intensity discrimination performance ΔL refers to the level increment in dB required to make a test tone distinguishable from the 54-dB SPL standard.

		N	Mean	Min	Max	s.d.
Absolute thresholds (dB SPL)						
Low noise sensit.	left ear	31	−2.70	−10.05	5.40	4.34
High noise sensit.		30	−0.99	−8.80	23.75	7.08
Low noise sensit.	right ear	31	−2.48	−11.65	6.65	4.98
High noise sensit.		30	0.81	−9.90	30.90	7.98
Intensity discrimination thresholds ΔL [dB]						
Low noise sensit.	left ear	31	1.46	0.52	3.18	0.69
High noise sensit		30	1.38	0.39	3.50	0.80
Low noise sensit.	right ear	31	1.60	0.68	4.31	0.83
High noise sensit.		30	1.57	0.60	5.54	1.10

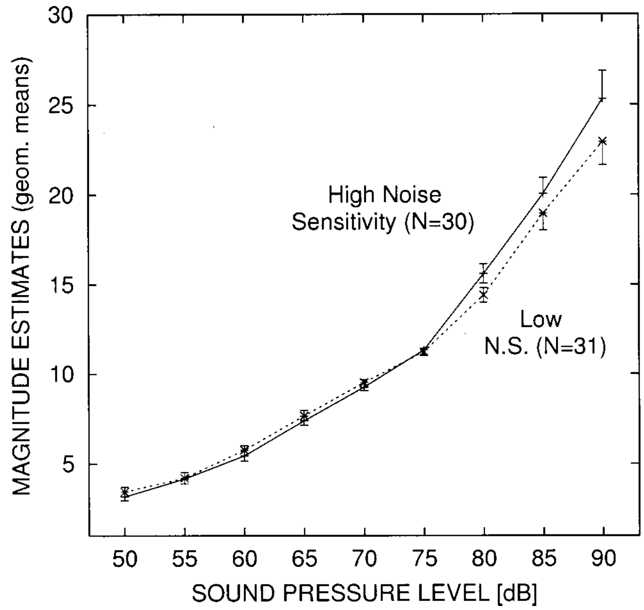

FIG. 1. Mean magnitude estimates made by the two noise-sensitivity groups. Data points are geometric means plus (or minus) one standard error of the mean. These error bars are asymmetric, since they are based on the log transformation of the responses. For legibility, some are plotted in one direction only.

III. RESULTS

A. Noise sensitivity

Overall noise sensitivity, as measured via questionnaire, was normally distributed in the present sample (Kolmogorov–Smirnov test: $z=0.664$, $p=0.77$). The data exhibited a sufficient range of scores (min=44, max=116), and the overall mean ($M=80.18$, s.d.=16.4) agreed well with the mean noise-sensitivity score found in the original student sample ($M=79.4$; Zimmer and Ellermeier, 1998a).

In order to make group-wise comparisons in the various psychoacoustic tasks, the present sample was split along the median ($med=81$) into a group exhibiting "low noise sensitivity" ($M_{\text{low}}=67.45$, s.d.=9.84), and one exhibiting "high noise-sensitivity" scores ($M_{\text{high}}=93.33$, s.d.=10.22). Interestingly, the "high noise-sensitivity" group was dominated by female participants (21 female, 9 male); the "low noise-sensitivity" group contained a majority of males (12 female, 19 male). A χ^2 test confirmed that noise sensitivity and gender may not be considered independent in the present sample [$\chi^2(1)=4.82$; $p=0.028$].

B. Absolute and difference thresholds

Mean absolute thresholds for 1-kHz tones as well as difference limens of intensity are given in Table I for the two noise-sensitivity groups, and for left and right ears, separately. Overall, absolute hearing sensitivity of our sample seems to be quite good, with an average threshold value of −1.36 dB SPL. The fact that this measurement is roughly 8 dB lower than published norms is most likely due to the more sensitive adaptive procedures used in the present experiments (Marshall and Jesteadt, 1986; Kollmeier, Gilkey, and Sieben, 1988). The difference thresholds (ΔL) given in the lower portion of Table I, on the other hand, match published values of intensity-discrimination performance quite well (Jesteadt, Wier, and Green, 1977; Florentine, Buus, and Mason, 1987; Green, 1988). In the most recent comprehensive study, employing the same (two-down, one-up) adaptive procedure as the present investigation (except for a longer stimulus duration of 500 ms), Florentine, Buus, and Mason (1987) reported a mean difference limen (ΔL) of 1.42 dB at 50 as well as at 60 dB SPL (see their Table II).

As is evident in Table I, however, there is no indication that the two noise-sensitivity groups formed on the basis of the questionnaire data differ in absolute or differential sensitivity to 1-kHz tones. In no case do the small apparent differences in mean thresholds reach statistical significance, as is confirmed by between-groups t-tests ($p>0.05$). Likewise, when individual noise-sensitivity scores are correlated with individual thresholds, weak and nonsignificant correlations emerge: $r=0.219$, $p=0.091$, for absolute thresholds (averaged across the two ears), and $r=-0.111$, $p=0.396$, for the relationship between noise sensitivity and intensity discrimination (ΔL).

C. Magnitude estimation of loudness

Suprathreshold data on intensity perception were collected by having subjects make direct numerical estimates of the loudness of sinusoids varying in level. Following Stevens' (1975, Chap. 1) recommendations, these magnitude estimates were geometrically averaged both across the three repetitions of each level, and across individuals. The resulting loudness-growth functions are depicted in Fig. 1, separately for the high and the low noise-sensitivity group. These functions are hardly distinguishable, diverging only at the three highest decibel levels with noise-sensitive individuals showing a steeper growth of loudness. The two curves are well fit by psychophysical power functions $\psi=k\phi^{\beta}$ with exponents of $\beta=0.450$; $r^2=0.9986$ for the low noise-

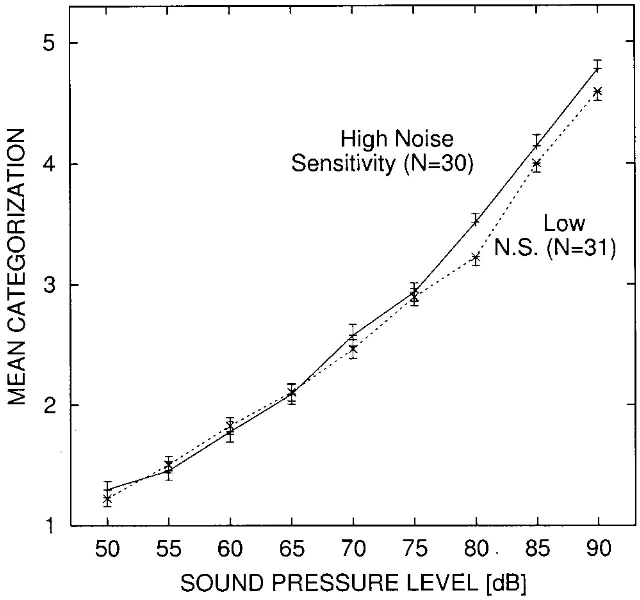

FIG. 2. Mean category ratings of the loudness of 1-kHz tones. Each data point is based on three repetitions of each stimulus level per subject. For better legibility, standard errors are plotted in one direction only at the high sound-pressure levels.

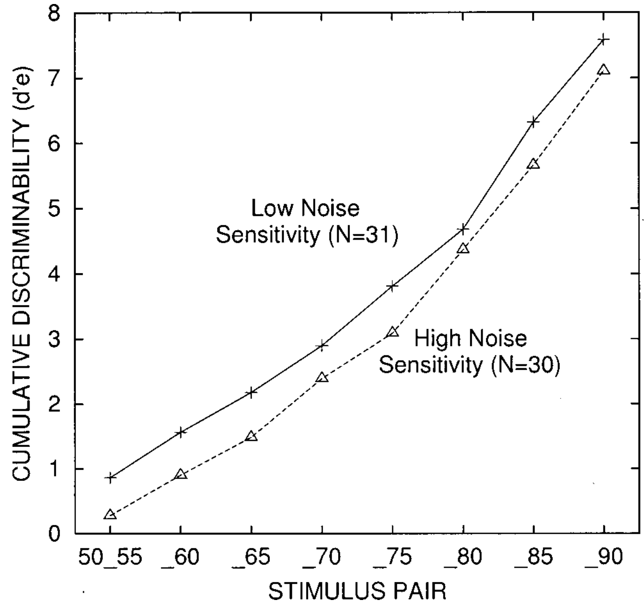

FIG. 3. Cumulative sensitivity (d'_e) computed from the pooled category ratings (see the text). Each entry on the abscissa refers to pair of adjacent stimuli contributing to the cumulative record. For better legibility, only the higher-level member of each pair is given on the abscissa, preceded by a leading underscore.

sensitivity group and $\beta = 0.414$; $r^2 = 0.9964$ for the high noise-sensitivity group. The difference in exponents is not statistically significant, however, as is evident when the individual exponents of the low noise-sensitivity group are compared to those of the high noise-sensitivity group $[t(59) = 1.02]$. More importantly, individually fitted exponents do not correlate significantly with the noise-sensitivity scores obtained by each participant in the questionnaire ($r = 0.10$).

It should be noted, though, that the present ratio estimation experiment may not differentiate groups of subjects or individuals in every respect, since all functions are forced through a fixed point in the center of the curves: the point defined by the standard (70 dB) and the agreed-upon modulus (a judgment of 10). Shifts along the ordinate may not be detected by this implementation. Therefore, other suprathreshold methods were investigated as well.

D. Loudness category scaling

Figure 2 shows the loudness categorizations made by the two groups of participants: Individuals expressing high noise sensitivity appear to assign slightly higher loudness ratings when presented with sound-pressure levels exceeding 75 dB SPL. Using the standard analysis of variance approach in order to evaluate the statistical significance of this divergence was ruled out, since the data showed significant deviations from the normality assumption, especially towards the extreme categories of the rating scale. Therefore, a nonparametric equivalent of a two-factor mixed analysis of variance (Bortz, Lienert, and Boehnke, 2000, Sec. 6.2.5.2) based on Kruskal and Wallis' (1952) H-statistic was performed. In the absence of a main effect of noise sensitivity, it revealed a significant (groups by SPL) interaction, $H^*_{A\times B} = 21.541$; $p < 0.01$, thus confirming the statistical significance of the divergence seen at high SPLs.

In order to assess whether the divergence in loudness ratings observed when comparing the two noise-sensitivity groups is due to a true sensory difference or merely to a judgmental artifact, the data were subjected to a signal-detection analysis (see Irwin and Whitehead, 1991; Ellermeier, 1997, for analogous applications in the psychophysics of pain). This is achieved by treating the pooled loudness ratings of the two groups like ''confidence ratings'' in a signal-detection experiment. These serve to trace out ''receiver-operating curves'' (ROCs) from which two parameters may be computed: (1) A discriminability index d'_e indicating the sensory distance between stimuli, and (2) an entirely independent ''bias'' parameter β reflecting a tendency to assign high ratings.

A maximum-likelihood method (Alf and Grossberg, 1987) was used to estimate d'_e for each adjacent pair of stimuli, separately for the two noise-sensitivity groups.[1] Figure 3 shows these measures of sensitivity, cumulated over the stimulus range. There is no indication that the highly noise-sensitive subjects show a greater growth in cumulative discriminability than do the less-sensitive subjects. If anything, the latter group exhibits a slight advantage due to an offset generated by superior discrimination of the two lowest sound-pressure levels. The slopes of the two curves, however, which may be interpreted as indicating the growth in sensation magnitude unbiased by judgmental tendencies (Irwin and Whitehead, 1991), do not seem to differ between the two noise-sensitivity groups, $t(14) = 0.308$, $p = 0.763$.

E. Simple auditory reaction time

Simple reaction time (RT) is often seen as a dependent variable that might tap the underlying sensory processes more directly than various verbal measures used in psychophysics. Furthermore, as a long research tradition has shown

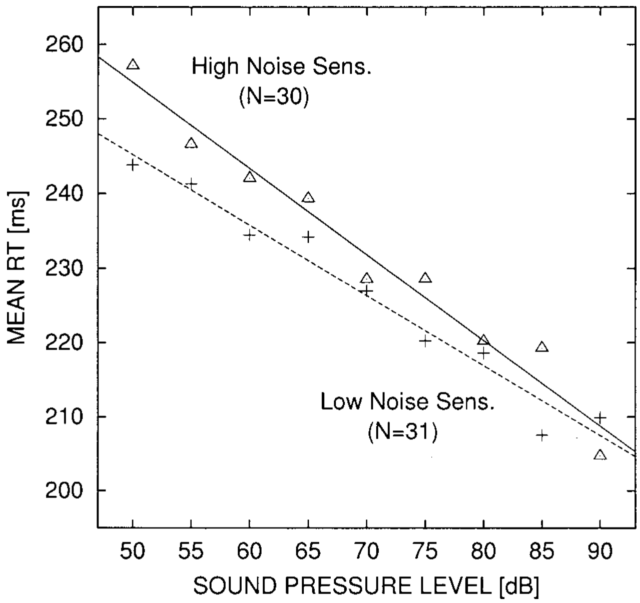

FIG. 4. Mean auditory reaction time (RT) to the onset of tones having SPLs given on the abscissa. Linear functions relating RT and sound-pressure level are fitted to the data of groups of subjects reporting high (triangles) and low (crosses) noise sensitivity. Each data point is based on at least 300 RT measurements.

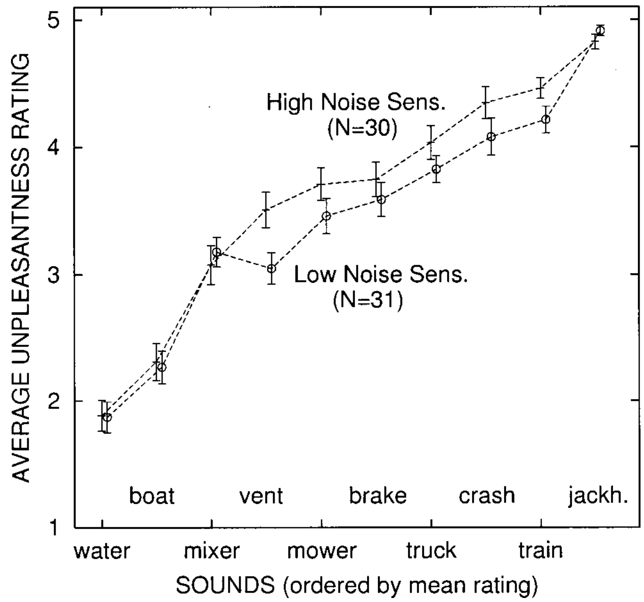

FIG. 5. Unpleasantness ratings of the ten natural sounds identified at the bottom of the figure (for details, see the text). Mean ratings plus/minus one standard error of the mean are given. Note that the abscissa is not metric; sounds are merely ordered according to the mean rating received.

(Chocholle, 1944; Luce, 1986; Kohfeld, Santée, and Wallace, 1981), it may be seen as an indirect way of scaling sensory magnitude via ratio-scale physical measurements. Therefore, reaction times were measured in response to the same stimuli as in the scaling experiments. The parameter of interest is the slope of the function relating decreasing response times to increasing sound-pressure levels.

As is evident in Fig. 4, this slope appears to be somewhat steeper for the subjects reporting high noise sensitivity in the questionnaire. Note that while in the literature (e.g., Kohfeld *et al.*, 1981) Piéron functions (power functions accounting for the steep rise in RT at very low intensities) are used to describe data like these, starting at a clearly audible 50 dB SPL takes us into the linear portion of the RT function (cf. Kohfeld *et al.*, 1981, Fig. 4). Therefore, we fitted functions that are linear over sound-pressure levels (dB) to the group data which are plotted in Fig. 4. The function describing the mean data of the low noise-sensitivity group is $\mathrm{RT} = -0.943 \times \mathrm{SPL} + 292.33$; the function accounting for the high noise-sensitivity data is $\mathrm{RT} = -1.153 \times \mathrm{SPL} + 312.54$. The difference in slope, however, is not statistically significant; either when the two sets of individual slope parameters are compared [$t(59) = 1.368$; $p = 0.177$], or when these parameters are correlated with the individual noise-sensitivity scores obtained from the questionnaires ($r = -0.138$, $p = 0.29$).

F. Unpleasantness ratings

Figure 5 shows mean unpleasantness ratings of ten natural sounds ranging from the sound of water running from a faucet to the noise of a jackhammer. The entries on the abscissa are ordered according to the mean rating given by all 61 subjects. This ordering does not correspond perfectly to the ordering obtained from a paired-comparison methodology in a previous study using the same sounds (Ellermeier, Mader, and Daniel, 1997); the rank correlation between the two orderings, however, is $\rho = 0.81$.

When the ratings of the two noise-sensitivity groups are considered separately (as in Fig. 5), it is evident that the high noise-sensitivity group tends to assign higher unpleasantness ratings once the middle category of the scale is exceeded. The convergence at the top end of the scale is most likely due to a ceiling effect: the sound of the jackhammer receives mean ratings almost indistinguishable from the maximum value of 5. Since this entails violations of the homogeneity-of-variance assumption, a nonparametric test (two-way analysis of variance on ranks; Bortz, Lienert, and Boehnke, 2000) was performed to statistically evaluate the unpleasantness ratings. Both the main effect of noise sensitivity ($H_A^* = 2.66$; $p \approx 0.10$) and its interaction with the stimuli to be rated ($H_{A \times B}^* = 13.975$; $p \approx 0.08$) just failed to reach statistical significance.

Analysis on an individual-subjects level, however, shows unpleasantness ratings to be systematically related to noise sensitivity: When each participant's mean rating (averaging across all ten sounds) is paired with his/her noise-sensitivity score from the questionnaire, a correlation of $r = 0.26$ ($p = 0.042$) emerges between the two measures.

IV. DISCUSSION

The present investigation found noise sensitivity as measured by a psychometrically evaluated questionnaire to be largely unrelated to psychoacoustic indices of auditory functioning. Small, but significant effects of noise sensitivity only emerged in loudness scaling and in ratings of the unpleasantness of sounds; that is, in those tasks most closely related to annoyance (which noise sensitivity was originally conceived to predict).

These findings shall be discussed with respect to (a) the (lacking) psychoacoustical basis of noise sensitivity; (b) the role of gender effects; and (c) the potential of combining indicators to predict increased noise sensitivity.

A. Psychoacoustic correlates of noise sensitivity

Our finding that individuals expressing high or low noise sensitivity do not differ in absolute thresholds agrees well with the two relevant earlier studies (Moreira and Bryan, 1972; Stansfeld *et al.*, 1985). Whereas these studies used classical methods for threshold measurement, the present finding is based on more rigorous, bias-free adaptive procedures. Furthermore, it extends to difference thresholds (see Table I). Thus, there is no indication that individuals expressing increased susceptibility to noise differ in absolute or differential hearing sensitivity. If anything, there is a slight trend (though statistically not significant) for subjects having higher absolute thresholds to express greater noise sensitivity.

It may be argued that most of our more sophisticated psychophysical analyses (adaptive thresholds, scaling, RT) are restricted to data collection at 1 kHz. It is of course possible that noise sensitivity is mediated by increased auditory acuity at other (e.g., higher) frequencies. An attempt was made to assess this possibility by analyzing the Békésy tracking data obtained from all subjects at the standard audiometric frequencies (0.5 to 8 kHz). Those subjects, however, that showed evidence for slight hearing losses in this screening test were roughly equally distributed across the two noise-sensitivity groups: 6 (low) vs 4 (high noise sensitivity) subjects showed hearing losses exceeding 20 dB for at least one of the audiometric frequencies. Reanalyzing the scaling data while excluding these participants did not change the general outcome.

The suprathreshold data collected over a large sound-pressure range encompass (a) magnitude estimation and (b) category scaling of loudness, as well as (c) reaction-time measurements and (d) unpleasantness ratings. Despite the breadth of methodologies used, significant effects of noise sensitivity only emerged in loudness category scaling and in the unpleasantness ratings of natural sounds. The general tendency of noise-sensitive subjects to assign higher loudness categories or greater unpleasantness ratings was largely restricted to higher sound-pressure levels, and thus contradicts the earlier finding by Moreira and Bryan (1972), who found their extreme groups (of $N=3$ each) to *converge* at high SPLs.

To further explore the nature of the small suprathreshold differences emerging in the present investigation, the loudness category ratings were subjected to a signal-detection analysis which enabled us to disentangle sensory and judgmental aspects in the data. Cumulative sensitivity (d') was shown to grow at the same rate for sensitive and nonsensitive participants (see Fig. 3), while computing a bias measure (B; McNicol, 1972) showed the same divergence at high SPLs as did the ''raw'' mean ratings. Thus, from a detection-theory perspective (MacMillan and Creelman, 1991; Irwin and Whitehead, 1991) the apparent noise-sensitivity effect in the loudness scaling data might be interpreted as judgmental rather than sensory in nature: a tendency to assign higher ratings in the absence of a true difference in auditory processing.

This interpretation is consistent with the fact that in the present investigation, it is only in the ''softer,'' more judgmental psychophysical tasks that noise-sensitivity effects are observed, while objectively measured thresholds, RT measurements, and ratio estimates do not show systematic differences. Taken together, the evidence suggests that self-reported noise sensitivity is not related to auditory acuity, but reflects a judgmental, evaluative predisposition towards the perception of sounds.

This predisposition should not be interpreted as simply reflecting a ''response style,'' e.g., a tendency to use extreme categories of a rating scale, as discussed by Job (1999). While individual differences of this sort might indeed create spurious correlations, when single-item ratings of annoyance and sensitivity are related, for example, such an explanation seems unlikely for the present results (a) since different response formats and settings (questionnaire items versus psychophysical judgments obtained in the course of a laboratory experiment) are being compared and (b) since noise sensitivity is measured using a psychometrically sound questionnaire, constructed explicitly to cancel out biases resulting from idiosyncratic response styles.

B. Gender effects

An unusual finding related to the present sample is that we found a significant majority (roughly two-thirds) of women in the noise-sensitive group (see Sec. III A). This is atypical, both for research published by other investigators, who found no effects of sex on noise sensitivity (Moreira and Bryan, 1972; Weinstein, 1978; Taylor, 1984), and for a vast amount of data collected in our own laboratory. In four different samples, three of which were drawn from a similar student population, and all of which consisted of a far greater number of participants (ranging between 117 and 213), we never found a significant effect of gender (Zimmer and Ellermeier, 1997, 1998a, 1998b). Therefore, we tend to interpret the gender imbalance found in the present investigation as a peculiarity of that particular sample.

Interestingly, however, the present data occasionally show significant effects of sex on the form of the psychophysical functions obtained. To distinguish these effects from the consequences of increased noise sensitivity which are the focus of this article, additional analyses were performed. The general strategy was to make gender another factor in the analyses of variance;[2] that is, to inspect effects of noise sensitivity, gender, and sound-pressure level, and their respective interactions. Significant main effects of, or interactions with the participant's gender emerged for only two psychophysical tasks: (1) loudness category scaling, and (2) unpleasantness ratings of natural sounds. The case of loudness category scaling is instructive, since here the effect of gender consists of a discrepancy at *low* sound-pressure levels, evident in a significant interaction [$H^{*}_{A\times B}=17.04$; $p<0.05$] between the effects of sex and SPL, which is qualitatively different from the divergence at *high* sound-pressure levels found if subjects are grouped according to their noise-sensitivity scores (see Fig. 2). When rating the unpleasantness of natural sounds, female participants tended to assign higher categories to all sounds presented, leading to a significant main effect of gender [$H_A^* = 7.769$; $p < 0.01$] in that data set. In no case, however, did a two-way or three-way interaction involving both noise sensitivity and gender reach statistical significance, implying that the effects of noise sensitivity are the same in both genders with no need to consider differential effects for male and female participants.

Observing effects of gender in psychoacoustic measures is by no means unusual. Whether they are biological in nature, as the evidence compiled by McFadden (1998) suggests, or whether they reflect different judgmental styles is still a matter of debate. The fact that in the present investigation gender effects show up in the same ''soft'' psychophysical tasks as do the effects of noise sensitivity seems to suggest a similar, judgmental origin.

C. Combining psychoacoustical predictors

Since individual indices of psychoacoustic performance showed only occasional and weak relationships with noise sensitivity, one may ask whether a combination of these indices provides a better prediction. To address this question, a multiple regression analysis was performed, into which potential predictors from all psychoacoustical tasks were entered: (1) mean absolute threshold; (2) the threshold produced by the poorer ear alone; (3) the difference threshold (ΔL); (4) the individual magnitude-estimation exponent; (5) the slope parameter of the loudness category-scaling function; (6) the mean unpleasantness rating of ten sounds; and (7) the slope of the function relating reaction time to SPL. All seven variables in combination account for 15.2% (R^2) of the variance in noise-sensitivity scores. Note, however, that this value is the optimal prediction to be made from the present *sample*. If it is corrected for potential measurement errors to estimate the relationship in the *population*, a disappointingly low ''adjusted'' R^2_{adj} of approximately 0.04 results.

Furthermore, when in a ''stepwise multiple regression'' those parameters that contribute least to the prediction are successively excluded (''backward approach,'' Bernstein, Garbin, and Teng, 1988), we are left with a model according to which (a) the mean unpleasantness rating ($\beta = 0.256$); (b) the threshold in the poorer ear ($\beta = 0.197$); and (c) the category-scaling slope ($\beta = -0.129$) provide the best prediction of individual noise sensitivity. Even though the prediction provided by this model is statistically significant [$F(3,57) = 2.947$; $p = 0.04$]; given the small proportion of variance accounted for ($R^2 = 0.134$; $R^2_{adj} = 0.089$), it is of little practical relevance. The best thing that may be said for it is that it comes up with the same psychoacoustical parameters as did looking at each task in turn.

V. CONCLUSIONS

The present results clearly refute the conjecture—often traced back to Reason (1972)—that for noise-sensitive individuals ''the world is a brighter, louder, smellier, tastier, heavier, faster, and more painful place than it is for less 'receptive' people'' (Reason, 1972, p. 306). There is no indication in the present data set that noise sensitivity may be attributed to a predisposition to perceive sound events more intensely, or to discriminate between them more accurately. Nevertheless, noise-sensitive participants systematically tended to *judge* the same stimuli as louder or more unpleasant than the less sensitive group, suggesting that what is psychophysically tractable in the concept of noise sensitivity might primarily reflect attitudinal/evaluative rather than sensory components. Furthermore, as an earlier study (Ellermeier and Zimmer, 1997) employing the irrelevant speech paradigm had shown, individual noise sensitivity is only weakly related to objectively measured performance decrements under noise.

Hence, laboratory experiments may help to clarify the concept of noise sensitivity by providing some of the empirical evidence, Job (1999) had called for in his recent review. Even though the central outcome of the present study is negative, showing that self-reported noise sensitivity is *not* related to auditory acuity, the effects observed suggest it to reflect a judgmental, evaluative predisposition towards the perception of sounds. This is consistent with the vast literature relating noise sensitivity to the annoyance produced by unwanted sounds. Some of that work might have to be re-evaluated, however, in the light of the both conceptually, and psychometrically more evolved measures of noise sensitivity available today, which provide better protection against the risk of circularity involved in assessing an individual's noise sensitivity and his or her annoyance produced by an environmental source by posing two very similar questions. Furthermore, the issue of ''specificity'' will have to be addressed, in order to clarify whether noise sensitivity is specific to acoustic nuisances or represents a broader, more general tendency (e.g., Winneke, Neuf, and Steinheider, 1996) to be bothered by environmental stressors.

ACKNOWLEDGMENTS

We would like to thank Till Pfeiffer at Regensburg for providing us with a program to perform the nonparametric equivalents of analyses of variance. Furthermore, we are grateful for the comments made by two anonymous reviewers which helped to improve the quality of the paper.

[1]Actually, d'_e, a measure allowing for different variances of the signal and noise distributions [cf. Macmillan and Creelman, 1991, Eq. (3.8)], was computed. Since overall, however, the ratio of the two variances did not differ significantly from one, d'_e was taken as an index of the more familiar d'.

[2]As in Sec. III D., due to violations of the homogeneity-of-variance assumption, nonparametric equivalents of analyses of variance (Bortz, Lienert, and Boehnke, 2000, Sec. 6.2.5.2) are reported. Using parametric or nonparametric analyses, however, did not affect the statistical conclusions to be drawn from the data analyzed here.

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