Suprathreshold effects of adaptation produced by amplitude modulation[a)]

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This work extends the study of adaptation to amplitude modulation (AM) to the perception of highly detectable modulation. A fixed-level matching procedure was used to find perceptually equivalent modulation depths for 16-Hz modulation imposed on a 1-kHz standard and a 4-kHz comparison. The modulation depths in the two stimuli were compared before and after a 10-min exposure to a 1-kHz tone (adaptor) 100% modulated in amplitude at different rates. For modulation depths of 63% ($20 \log m = -4$) and smaller, the perceived modulation depth was reduced after exposure to the adaptor that was modulated at the same rate as the standard. The size of this reduction expressed as a difference between the post- and pre-exposure AM depths was similar to the increase in AM-detection threshold observed after adaptation. Postexposure suprathreshold modulation depth was not appreciably reduced when the modulation depth of the standard was large (approached 100%). A much smaller or no reduction in the perceived modulation depth was also observed when the modulation rates of the adaptor and the standard tone were different. The tuning of the observed effect of the adaptor appears to be much sharper than the tuning shown by modulation-masking results. [DOI: 10.1121/1.1593067]

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I. INTRODUCTION

Dynamic changes in amplitude and frequency are important features used in perception of speech, music, and other sounds. For this reason, numerous studies have investigated mechanisms that might be involved in the processing of these dynamic changes. In particular, it has been suggested that there exist channels that specialize in the processing of specific features of sound. Evidence for existence of the ‘‘feature channels’’ is from experiments showing that prolonged exposure to a specific feature of sound, such as amplitude or frequency modulation, decreases sensitivity to that feature but does not influence sensitivity to other features or affects them to a much lesser extent. The observed decrease in sensitivity is presumed to reflect a decrease in response due to selective adaptation of neural channels tuned to a specific feature (Kay and Matthews, 1972; Regan and Tansley, 1979; Gardner and Wilson, 1979; Tansley and Suffield, 1983).

Later studies have cast doubt on such interpretation of the results obtained from experiments that were presumed to show the effects of adaptation. Wakefield and Viemeister (1984) measured psychometric functions for detection of FM upsweeps before and after exposure to adapting upsweeps. They found that threshold elevation observed after the exposure (expressed in terms of percent of the pre-exposure threshold frequency sweep) corresponds to a relatively small change in performance, and that this change could be explained in terms of nonsensory factors such as the use of an ‘‘inappropriate’’ reference for the detection of the signal. Moody *et al.* (1984) observed strong training effects in the detection of FM upsweeps. They found that elevated thresholds observed after long exposure decreased more rapidly with the amount of training than pre-exposure thresholds. After a sufficient number of experimental blocks no difference between pre- and postexposure thresholds was observed. Thus, the effect that was interpreted as selective adaptation and was taken as a strong support for the existence of a sensory channel sensitive to frequency sweeps, disappeared with training. In the study of Regan and Tansley (1979), which used tones modulated sinusoidally in amplitude and frequency, each subject completed as many as 90 sessions but no strong training effects that would eliminate the difference between pre- and postexposure thresholds were mentioned.

Support for the notion that channels specializing in the processing of AM may exist in the auditory system was provided by studies that recorded neural responses to stimuli with fluctuating envelopes. Langner and Schreiner (1988) found a map of best modulation frequencies in the inferior colliculus of the cat that resembled the tonotopic map of responses to auditory frequencies at different stages of auditory processing. Consistent with the tuning in the modulation-frequency domain, it was found that modulation-masking patterns measured psychophysically show a clear peak around the modulation frequency of the masker (Bacon and Grantham, 1989; Houtgast, 1989). These masking results inspired development of models that use a bank of modulation filters to process envelope fluctuations (Dau *et al.*, 1996; Ewert and Dau, 2000). Existence of modulation channels that selectively process different modulation rates implies that if these channels adapt as a result of prolonged stimulation, the observed adaptation should be modulation-rate specific, i.e., an adapting sound modulated at a given rate would affect sensitivity to similar rates but not to rates remote from

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[a)] A portion of this work was presented at the 22nd ARO meeting [M. Wojtczak and N. F. Viemeister (1999), ‘‘Adaptation produced by amplitude modulation,’’ p. 59].

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the adapting rate. We are not aware of any study that systematically examined the effect of the adaptor as a function of the difference between the adapting and test modulation rate.

Richards *et al.* (1997) used two different modulation rates for the adapting tone, and found that when the adaptor and the test tone were modulated at the same rate, threshold for detecting AM was elevated by about 7.5 dB ($20 \log m$). In contrast, only about 1-dB elevation was observed when the adapting modulation rate (56 Hz) differed substantially from the test rate (16 Hz). Thus, the effect of the modulated adaptor appears to be modulation-rate specific. Richards *et al.* also measured pre- and postadaptation AM detection for different frequency separations between the adapting carrier and the test carrier, both modulated at the same rate. For a carrier frequency of 1500 Hz of the adapting tone, no effect of adaptation was observed for test tones with carrier frequencies two octaves below and one octave above the frequency of the adaptor. This suggests that AM detection threshold is elevated by an adapting sound when the carrier frequency and the modulation rate of the adaptor are similar to those of the test tone.

All experiments aimed at investigating the effects of adaptation to modulation have measured differences between pre- and postexposure thresholds for the detection of modulation. Detection threshold is a measure of sensitivity, and as such it provides information about the limits of the auditory processing. More directly related to the daily tasks that the auditory system performs is information about how prolonged exposure to modulated stimuli affects perception of well-detectable (suprathreshold) modulations. The present study used a subjective matching procedure to investigate this issue. In experiment 1, the adapting stimulus and the test stimulus had the same carrier frequencies and modulation rates and thus, presumably, they were processed by the same "feature channel." The comparison had a carrier frequency two octaves higher than the adapting tone and a modulation rate identical to the modulation rate of the adaptor. Because of the large separation between the carrier frequencies, the frequency channel processing the comparison was unaffected by the adapting stimulus, as was shown by Richards *et al.* and confirmed in our experiment 1. Thus, it was reasoned that if the adaptor has an effect on the perceived modulation depth in the test tone, changes in the subjectively equivalent modulation depth of the comparison would be observed. In experiment 2, different modulation rates of the adapting stimulus were used to examine whether the effect of the adaptor is modulation-rate specific.

II. EXPERIMENT 1: THE EFFECT OF THE SAME-RATE ADAPTING AM

A. Stimuli and procedure

A fixed-level modulation-matching procedure was used to study the effect of prolonged exposure to AM. Listeners were asked to compare modulation depths between a 1-kHz AM standard and a 4-kHz AM comparison, both presented for 500 ms at 60-dB SPL and both modulated at a rate of 16 Hz. The adapting stimulus was a 60-dB 1-kHz tone, 100% modulated in amplitude by a 16-Hz sinusoid. The adaptor was played for 10 min before the testing began. A warning signal was displayed on a computer screen 30 s before the first trial was presented.

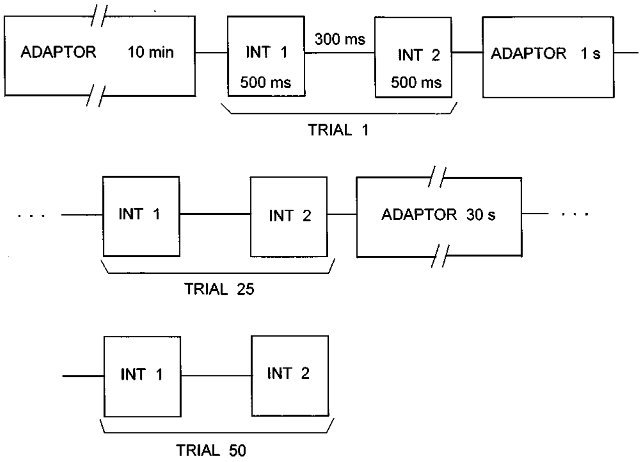

FIG. 1. Schematic illustration of the experimental procedure used with the adapting stimulus.

Three modulation depths of the 1-kHz standard and eight modulation depths of the 4-kHz comparison were used within a block. The standard modulation depths were −4, −6, and −8 dB ($20 \log m$) in one set of blocks, and 0, −1, and −2 dB in another. For the three smaller standard modulation depths, the comparison modulation depths were selected so that they bracketed the point of subjective equality (PSE) estimated for each subject during pilot testing. Blocks with the three larger modulation depths used comparison modulation depths from −14 through 0 dB in steps of 2 dB because this range covered the PSE estimates observed in pilot runs for all subjects. On each trial, one standard and one comparison modulation depth were drawn randomly for presentation. The order in which the 1-kHz standard and the 4-kHz comparison were presented within a trial was also random. The listener made a judgment as to whether the first or the second interval contained stronger fluctuations.[1] Because the task was subjective in nature, no feedback indicating the correct response was provided. The schematic illustration of the experimental procedure in the adapting condition is presented in Fig. 1. After each trial, the adapting sound was reintroduced for 1 s, and after the first 25 trials, testing was interrupted and the adapting stimulus was played for 30 s to reinforce possible adaptation to modulation. Each block consisted of 50 trials. Each subject completed 25 blocks that were used to estimate the PSE.

The same fixed-level matching procedure was used to find the pre-exposure PSEs for amplitude modulation imposed on the 1- and 4-kHz carriers. Prolonged exposure to the unmodulated adaptor was not used because other studies have demonstrated that silence is an equivalent reference for the adaptation condition, since the unmodulated tone has no effect on AM detection (Regan and Tansley, 1979; Tansley and Suffield, 1983), and using such a tone would unnecessarily extend the duration of the experiment.

To compare the effect of the adapting stimulus on the perceived suprathreshold AM with its effect on modulation detection, pre- and postexposure AM detection thresholds were measured using an adaptive 2-down, 1-up, three-interval forced-choice (3IFC) procedure. In this task, a visual feedback indicating the correct response was provided. The adaptor and the standard tone were the same as in the matching task, except that the modulation depth of the standard was varied adaptively to obtain threshold. The step sizes used in the adaptive procedure were 4 dB for the first four reversals and 2 dB for the remaining eight reversals. AM-detection threshold from a single run was computed based on the last eight reversals. The final threshold estimate was obtained by averaging thresholds from three separate runs. Pre- and postexposure AM-detection thresholds were also measured with the 4-kHz test tone. This was done to assess whether the 1-kHz AM adaptor affects the processing of AM in the frequency channel tuned to 4 kHz.

The stimuli were generated digitally with a sampling rate of 44.1 kHz on a NeXT computer equipped with a 16-bit D/A converter. They were attenuated to the desired level and directed to a Sony MDR-V6 earphone for monaural presentation.

B. Subjects

Four listeners participated in the study. Their hearing thresholds were normal as determined by comparing the thresholds measured at octave frequencies between 250 and 8000 Hz to the lab norms. Not all listeners were run in every condition. Three listeners were compensated for their services. One listener (S1) was the first author.

C. Results

Pre- and postexposure thresholds for detecting AM confirmed the finding by Richards *et al.* (1997) that the adapting modulated tone increases thresholds by about 8 dB for the standard with a carrier frequency identical to that of the adaptor (1 kHz), but does not affect sensitivity to AM measured for the standard with a carrier frequency two octaves above (4 kHz) that of the adaptor.

For suprathreshold AM, PSEs were estimated from functions which showed the proportion of responses, for which the comparison was judged more modulated than the standard, plotted for each of the eight comparison depths used in a given set of blocks. Because three standard modulation depths were used within each block, three functions were obtained, one for each modulation depth of the standard.

Figure 2 shows an example of pre- (left panel) and postexposure results (right panel) for one listener. Data for each standard modulation depth were separately fitted with a sigmoidal function and the PSE was estimated based on this fit

$$P(m_c > m_{st}) = \frac{1}{1+\left(\frac{m_c}{m_{c(0.5)}}\right)^{\alpha}}, \tag{1}$$

where P is the predicted proportion of responses where the modulation depth of the comparison (m_c) sounded like a larger modulation depth than that of the standard (m_{st}). The parameters $m_{c(0.5)}$ and α were varied until the sum of squared deviations between the predicted P values and the data was minimum.[2] The value of $m_{c(0.5)}$ that produced the best fit was taken as the PSE between the standard and the comparison modulation depths. This value represented the predicted modulation depth of the comparison that would be evaluated by the listener as greater than the modulation depth of the standard on 50% of trials.

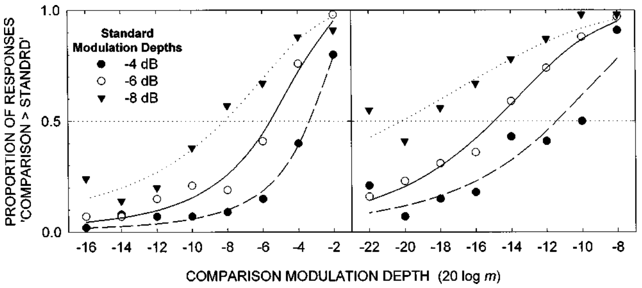

FIG. 2. The ordinate is the proportion of times the listener chose the comparison modulation depth, plotted on the abscissa, as larger than the standard modulation depth. Different symbols show data for different standard modulation depths. The left panel shows pre-exposure matching results; the right panel shows results obtained after exposure to a 10-min 1-kHz tone that was 100% modulated at a rate of 16 Hz.

The pre-exposure PSEs fall very close to the standard modulation depths, -4, -6, and -8 dB (left panel in Fig. 2). This result implies that the same physical modulation depth imposed on a 1-kHz carrier and a 4-kHz carrier produces a similar percept of the depth of fluctuations. Other listeners showed very similar results that indicated no dependence of the perceived modulation depth on the carrier frequency, at least for the carrier frequencies of 1 and 4 kHz tested within this study. Paired t-tests performed separately for each standard modulation depth on the data from all the listeners show no significant difference ($p < 0.01$) between the perceived modulation depths in the 1- and 4-kHz carriers prior to adaptation.

The three functions in Fig. 2 are shifted relative to one another with the leftmost function representing results for the smallest standard modulation depth and the rightmost function representing results for the largest standard modulation depth. This suggests that the listener actually used the standard to make judgments about the fluctuation depth in the comparison.

The right panel of Fig. 2 shows data obtained after the listener has been exposed to an adapting AM tone. All three functions are shifted toward smaller modulation depths, suggesting that the adapting sound had an effect of reducing the perceived fluctuations. For each of the three standard modulation depths, the PSE was smaller than the standard modulation depth. Paired t-tests performed separately for each standard modulation depth using data from all subjects revealed a significant effect due to the exposure to the adapting stimulus (obtained t-values corresponded to $p > 0.01$).

Similar analysis was performed on the results obtained from the set of blocks that used the standard modulation depths of 0, -1, and -2 dB. In this case, all three listeners who performed the task showed a very small shift in the perceived modulation toward smaller depths, indicating very little or no reduction of the perceived depth of fluctuations

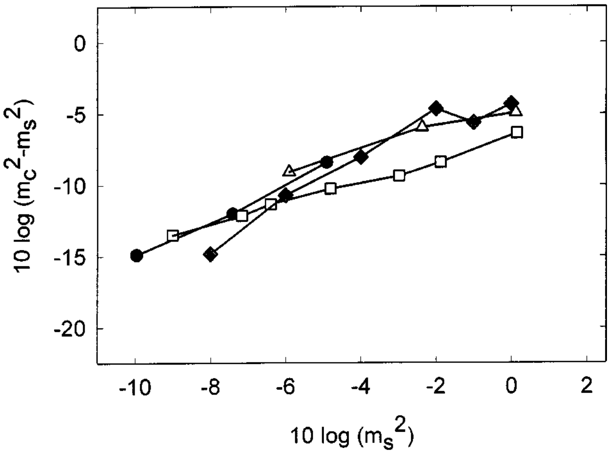

FIG. 3. Modulation-depth discrimination thresholds estimated from the curves fitted to pre-exposure AM matching data (diamonds). The estimated thresholds for the modulation depth of 0, -1, and -2 dB correspond to detecting a decrement, whereas the thresholds for -4, -6, and -8 dB, correspond to detecting an increment in modulation depth. For comparison, data from objective modulation-depth discrimination tasks are plotted: open squares (von Fleischer, 1980), open triangles (Ozimek and Sek, 1988), and filled circles (Wakefield and Viemeister, 1990). (From Fig. 5 in Wakefield and Viemeister.)

after the 10-min exposure to the 100% modulated tone. Paired t-tests showed that for these standard modulation depths the effect of the adaptor was not significant ($p < 0.01$).

Since before adaptation, no significant difference was found between the standard modulation depth in the 1-kHz carrier and the perceptually equivalent modulation depth in the 4-kHz carrier, the pre-exposure functions obtained from the modulation-matching procedure could be used to estimate modulation-depth discrimination thresholds. These thresholds were computed by solving Eq. (1) for the modulation depth of the comparison (m_c) and assuming $P(m_c > m_{st}) = 0.707$ for the standard modulation depths of -4, -6, and -8 dB, and $P(m_c > m_{st}) = 0.293$ for the standard modulation depths of 0, -1, and -2 dB. Thus, for the three lower modulation depths, depth discrimination was estimated for an increment in the modulation depth, while for the large modulation depths, depth discrimination thresholds were estimated for a decrement in modulation depth. Figure 3 shows modulation-depth discrimination thresholds estimated from the preadaptation matching functions (diamonds) presented along with published modulation-depth discrimination thresholds for increments and decrements in modulation depth (von Fleischer, 1980; Ozimek and Sek, 1988; Wakefield and Viemeister, 1990), for a range of the standard modulation depths relevant to the present data. The thresholds for modulation-depth discrimination estimated from the subjective AM matching procedure fall very close to the thresholds measured directly in the objective modulation-depth discrimination tasks. This supports the validity of the subjective procedure and also provides further support for the inference that prior to adaptation, equal physical modulation depths in the 1-kHz and 4-kHz carriers are perceptually equivalent.

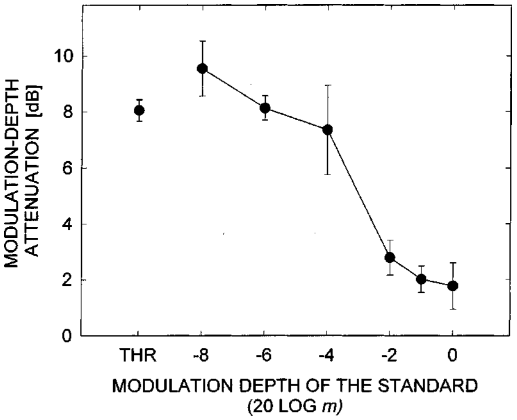

FIG. 4. Attenuation of the perceived modulation depth computed from the difference between the pre- and postexposure PSE, averaged across listeners. The leftmost unconnected point shows the difference between pre- and postadaptation AM detection thresholds. The vertical bars show ± one standard deviation from the mean.

Comparison of the pre- and postexposure PSEs allows for estimation of the attenuation in the perceived (output) modulation depth. This can be evaluated indirectly by computing the reduction in terms of the physical (input) modulation depth. For each subject and every standard modulation depth, a difference between the PSE obtained before the exposure to the adapting stimulus and the PSE obtained after the 10-min exposure was computed to represent the reduction in perceived modulation depth. Attenuations averaged across listeners, plotted as a function of the modulation depth of the standard are shown in Fig. 4.

For standard modulation depths of -4 dB and smaller, an average reduction between 7 to 9 dB was observed. There was a tendency for the attenuation to decrease with increasing standard modulation depth. A shift in AM detection threshold, shown by the unconnected point on the left, also falls within that range, i.e., after a 10-min exposure to the adapting modulated tone, the modulation depth at AM-detection threshold was 8 dB higher than the modulation depth measured pre-exposure. As the modulation depth of the standard approaches the modulation depth of the adapting stimulus (0 dB), the reduction in the perceived modulation depth becomes statistically insignificant. For standard modulation depths of 0, -1, and -2 dB the computed attenuation is only around 2 dB, with a slight tendency to decrease with increasing modulation depth.

For the three lower modulation depths of the standard, the postexposure PSEs were computed for each individual listener based on separate successive sets of five blocks (the results are not shown here). This was done to make sure that no major shifts in the obtained PSEs occurred with increasing amount of training. No systematic shifts of the PSE toward the modulation depth equal to that of the standard were observed for any of the subjects and any of the three standard modulation depths. In fact, the PSEs exhibited a high degree of stability across all sets of blocks.

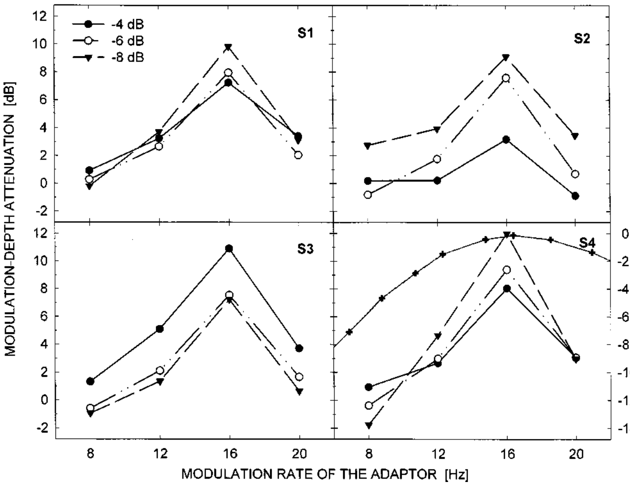

FIG. 5. Attenuation of the perceived modulation depth, estimated from the difference between the pre- and postexposure PSE, plotted as a function of the modulation rate of the adapting stimulus. The modulation rate of the standard was 16 Hz. Each panel shows results for a different subject. Different symbols and types of connecting lines correspond to different modulation depths of the standard. The cross-hair symbols connected by the gray solid line (bottom right panel) represent the transfer characteristic of a 16-Hz modulation filter with a Q-value of 2. The rightmost *y* axis shows the attenuation by the modulation filter.

III. EXPERIMENT 2: TUNING IN SUPRATHRESHOLD EFFECTS OF ADAPTATION

A. Method

In this experiment, three different modulation rates (8, 12, and 20 Hz) of the adaptor whose carrier frequency was 1 kHz were used to examine rate specificity of the effects observed in experiment 1. The 1-kHz standard and the 4-kHz comparison were modulated at 16 Hz. Only the three lower modulation depths of the standard (-4, -6, and -8 dB), for which the effect of the adaptor was significant, were used to study tuning. The method, the equipment, and the subjects used were the same as in experiment 1.

B. Results

Figure 5 shows differences between the pre- and postexposure PSEs plotted as a function of the modulation rate of the adapting tone, for each individual listener. These differences, representing the magnitude of adaptation, are the largest when the modulation rate of the adapting tone is the same as that of the standard. When the adapting modulation rate differs from the rate of modulation in the standard, prolonged exposure to the adaptor produces a smaller reduction of the perceived standard modulation depth.

As shown by all these individual data, even a difference in modulation rate between the adaptor and the standard as small as 4 Hz causes a substantial reduction in the effect of the adaptor. The ‘‘tuning’’ of the effect of the adapting tone appears symmetrical around the modulation rate of the standard. For the adapting rate of 8 Hz, no consistent effect of the adapting stimulus is observed. As will be discussed later, the lower right panel also shows the transfer characteristic of a modulation filter centered on 16 Hz, with a Q-value of 2 (cross-hair symbols).

IV. DISCUSSION

This study examined whether adaptation, a phenomenon that has been observed for threshold modulation depths, is general, i.e., whether it is also present in the processing of well-detectable fluctuations. Large fluctuations are important in everyday listening and thus, studying mechanisms that affect their perception is crucial for characterizing the envelope processing in the auditory system. The experiments performed within this study used a 10-min adapting modulated stimulus. While in everyday listening we may not be exposed to a constant-rate modulations continuously over such a long period of time, previous studies have shown that adaptation asymptotes after about 10 min of exposure. Thus, the magnitude of adaptation reported in this study should be the maximum adaptation produced by AM tonal stimuli.

The results indicate that the magnitude of adaptation produced by a 100% AM adaptor depends on the modulation depth of the standard. This indicates that the effect of the adaptor is not equivalent to a simple, fixed attenuation of the envelope fluctuations of the standard: As the modulation depth of the standard approaches that of the adaptor, the amount of attenuation of the modulation becomes negligible (Fig. 4). One explanation is that the attenuation is, in fact, fixed, but that because of threshold/floor effects the perceived modulation of the standard is not appreciably affected at large modulation depths of the standard. More specifically, if the effect of the adaptor is primarily to reduce the effective depth of the envelope minima, then for large modulation depths these minima may be below threshold, either from forward masking by the envelope maxima or the absolute detection threshold for the minima. Thus, an increase in the ‘‘internal’’ minima produced by adaptation may have a negligible effect on perceived modulation depth at large modulation depths because the elevated minima are obscured by threshold/floor effects. This conjecture relies upon a differential effect of adaptation on envelope minima and maxima. How such a differential effect might occur is unclear.

Another explanation is in terms of ‘‘intensity’’-dependent adaptation. If the attenuation of the perceived modulation depth is due to adaptation, it is possible that the amount of adaptation would decrease as the intensity of the adapted stimulus approaches the intensity of the adaptor. (Intensity is meant here as the magnitude of the parameter that is subjected to adaptation.)

The crucial issue is whether or not the reduction of the perceived modulation depth after prolonged exposure to a modulated tone with a similar carrier frequency and modulation rate is indeed a result of fatigue (adaptation) of neural channels that specialize in the processing of this modulation. As mentioned in the Introduction, Wakefield and Viemeister (1984) suggested that increased thresholds for detection of frequency sweeps might result from the use of an improper reference after exposure to a highly detectable adapting frequency sweep. Their conclusion was based on the observation that the increase in threshold corresponded to a change in performance from 75% to only 65%. In the present study, psychometric functions for AM detection were not measured. However, it has been shown that for AM detection, $d' = k\,m^2$ (Moore and Sek, 1992; Edwards and Viemeister, 1994). The 8-dB increase in threshold after exposure thus corresponds to a decrease in d' of 0.8 log units, a factor of 6.3. In terms of a change in performance, this is a large effect [d' would decrease from 1.28 to 0.2; $P(C)$ would decrease from 70.7% to 39%]. It seems unlikely that such a large change results from the use of an improper reference. It is possible that neural fatigue or adaptation is responsible for the elevation of AM-detection threshold. The same mechanism is likely to cause a reduction in the perceived suprathreshold modulation depth.

Within the present study, postexposure AM detection thresholds were not measured for modulation rates of the adaptor that differed from the modulation rate of the test stimulus. However, the results in Fig. 5 show clearly that the reduction in the perceived suprathreshold modulation is much less for adaptor rates differing by only 4 Hz from the test modulation rate. This tuning in the effect of the adaptor resembles the tuning observed in modulation masking (Bacon and Grantham, 1989; Takahashi and Bacon, 1992). A direct comparison of sharpness of the tuning between the present data and the modulation-masking data is difficult. Bacon and Grantham used a signal modulation rate of 16 Hz, but only relatively remote masker modulation rates (4 and 64 Hz) were used in their study to measure the amount of masking. For these two masker rates, negligible or no masking was observed. Takahashi and Bacon used a range of masker modulation rates but they used only a signal modulation rate of 8 Hz. Their data for young adults show that maskers with modulation rates one octave below (4 Hz) and slightly more than a half-octave above (12 Hz) the signal rate still produce about 12 to 15 dB of masking. The data in Fig. 5 show no effect of adaptation for the adaptor rate an octave below the modulation rate of the standard, and only a very small effect (less than 4 dB) for the adaptor modulation rate only 0.3 octave above the rate of the standard. Under the assumption that the internal amplitude of the standard modulation after adaptation is proportional to the amplitude of the adapting modulator at the output of the ''adaptation filter'' in the modulation frequency domain, the derived tuning of the hypothetical adaptation filter is sharper than tuning of the modulation filter derived based on modulation-masking data. To illustrate this, the transfer characteristic of a modulation filter centered on 16 Hz, with a Q-value of 2 is plotted with the adaptation data in Fig. 5. Typically, modulation filters symmetrical on a log frequency scale with a Q-value of 2 or 1 are used to account for modulation masking (e.g., Ewert and Dau, 2000).

The differences in the observed tuning between modulation-masking and modulation adaptation data may reflect two different levels of modulation processing. For example, a sharper tuning in adaptation would be observed if adaptation followed the modulation-filtering process and if the magnitude of adaptation decreased with decreasing level at the output of the modulation filter. Different tuning may also result from the different nature of the detection (objective) and matching (subjective) tasks. It should be noted, however, that the magnitude of adaptation estimated by comparing pre- and postexposure AM detection thresholds was very similar to the magnitude of adaptation estimated from the subjective matching task for three lower modulation depths of the standard. This result suggests that the subjective nature of the task probably was not responsible for the observed differences in tuning.

V. FINAL REMARKS

In summary, the size of AM-detection threshold elevation suggests that the decreased sensitivity likely does not reflect a nonsensory effect such as a change in the detection criterion or the use of the adaptor rather than a comparison as a reference for detection. The reduction in the perceived suprathreshold AM, and the robustness of the results (lack of considerable training effects) appears to support the notion that there may be a primary neural basis for the observed effects. Tuning of the effect is generally consistent with the idea that there exist ''hard-wired'' channels tuned to specific modulation rates, and that those channels are associated with specific auditory-frequency channels. The difference between the degree of tuning observed for the effect of adaptation versus that for modulation masking is probably due to different levels at which the two processes occur.

The similarity between the amount of adaptation seen in the detection and the matching data at the lower modulation depths, and the size and robustness of the effect argue for its sensory basis. Although we believe that the adaptation effects shown in these experiments are primarily sensory, a cognitive component, based on perceived adaptor-standard similarity, cannot be dismissed. Since the matching task is subjective and requires judgments across different dimensions (carrier frequency), fairly complex cognitive strategies are likely to be involved. Further investigation using objective psychophysical techniques should help to evaluate the sensory basis for adaptation to suprathreshold AM.

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[1] After several unsuccessful attempts at using adaptive matching procedures, a fixed-level procedure with multiple standards and comparisons was adopted. It was observed when using matching procedures, that because of a difference in the perceptual quality between the standard and the comparison, some listeners did not use the standard as a reference but instead, provided consistent responses by apparently matching each comparison to some memorized ''internal standard.'' In the fixed-level procedure, on a given trial the modulation depths of the standard and the comparison were chosen randomly, thus encouraging the listener to compare the two stimuli. A monotonic relation between the pre-exposure standard modulation depths and the perceptually equivalent comparison modulation depths confirmed that the standard modulation depths were used as references in evaluating the perceived modulation depths in the comparison.

[2] Sometimes pre-exposure comparisons during runs that used standard modulation depths of 0, -1, and -2 dB did not yield even one comparison modulation depth producing larger than 0.5 proportion of responses where the comparison was judged to be more modulated. In those cases, the sigmoidal function defined by Eq. (1) was fit to the data and the PSE was estimated by extrapolation of the function toward larger modulation depths with the constraint that the modulation depth in dB could not exceed zero. In these cases, the portion of the matching function representing values

above 0.5 was very steep. In the postexposure condition, there was always at least one modulation depth of the comparison that was evaluated as producing stronger perceived fluctuations than the standard on more than 50% of trials.

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