Perception of amplitude modulation by hearing-impaired listeners: The audibility of component modulation and detection of phase change in three-component modulators

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Two experiments were conducted to assess whether hearing-impaired listeners have a reduced ability to process suprathreshold complex patterns of modulation applied to a 4-kHz sinusoidal carrier. Experiment 1 examined the ability to “hear out” the modulation frequency of the central component of a three-component modulator, using the method described by Sek and Moore [J. Acoust. Soc. Am. 113, 2801–2811 (2003)]. Scores were around 70–80% correct when the components in the three-component modulator were widely spaced and when the frequencies of the target and comparison differed sufficiently, but decreased when the components in the modulator were closely spaced. Experiment 2 examined the ability to hear a change in the relative phase of the components in a three-component modulator with harmonically spaced components. The frequency of the central component, $f_c$, was either 50 or 100 Hz. Scores were about 70% correct when the component spacing was $\leq 0.5f_c$, but decreased markedly for greater spacings. Performance was only slightly impaired by randomizing the overall modulation depth from one stimulus to the next. For both experiments, performance was only slightly worse than for normally hearing listeners, indicating that cochlear hearing loss does not markedly affect the ability to process suprathreshold complex patterns of modulation. © 2006 Acoustical Society of America. [DOI: 10.1121/1.2139631]

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I. INTRODUCTION

The perception of amplitude modulation (AM) plays an important role in many aspects of auditory perception, including speech perception (Plomp, 1983; Shannon et al. 1995) and the ability to analyze mixtures of sounds arising from different sources (Darwin and Carlyon, 1995). Hearing-impaired people often have difficulty in understanding speech in the presence of background sounds (Plomp, 1978, 1994; Moore, 1998) and it is possible that part of this difficulty stems from abnormalities in the processing of amplitude modulation. This possibility is assessed in the present experiments.

Previous studies of AM perception by hearing-impaired people have mostly focused on the detection of AM (Formby, 1982; Bacon and Gleitman, 1992; Moore et al., 1992; Moore and Glasberg, 2001) or the discrimination of AM rate (Formby, 1986; Grant, 1998). Overall, the results from these studies suggest that performance is not usually adversely affected by cochlear hearing loss, except when a portion of the carrier is inaudible. Here, we focus on the perception of complex patterns of modulation applied to a single carrier for modulation depths well above threshold. We start with a review of previous related studies.

Moore et al. (1996) tested listeners with unilateral hearing loss. They were presented with an amplitude-modulated sinusoid to one ear, and were asked to adjust the AM depth of a sinusoid presented alternately to the other ear, so as to match the perceived modulation depth. The results indicated that the perceived amount of modulation in the impaired ear was “magnified” compared to that in the normal ear, and it was argued that this was a manifestation of loudness recruitment (Steinberg and Gardner, 1937), probably resulting from the loss of fast-acting compression on the basilar membrane (Rhode and Robles, 1974, Moore and Glasberg, 1997, 2004).

Tandetnik et al. (2001) measured second-order modulation detection thresholds in normally hearing and hearing-impaired listeners. Second-order modulation is modulation applied to the modulation depth of an AM signal, i.e., modulation of the modulator. The second-order modulation thresholds were measured as a function of the frequency of the modulation applied to the modulation depth (referred to as $f_m^2$), using values of $f_m$ from 1 to 11 Hz, and a fixed first-order modulation frequency of 16 Hz. The audio-frequency carrier was broadband white noise. The thresholds for the hearing-impaired listeners were within the normal range for $f_m=3.5$, and 11 Hz, and were higher (poorer) than normal for $f_m=1$ and 7 Hz. These results suggest that cochlear hearing loss may have some deleterious effect on the ability to
process complex temporal envelopes, but the effect is not large. In a later study using a 2-kHz sinusoidal carrier, detection thresholds for second-order AM were found to be essentially the same for normally hearing and hearing-impaired listeners (Füllgrabe et al., 2003).

Turner et al. (1995) used “noise-vocoder” processing to compare the ability of hearing-impaired and normally hearing listeners to identify speech on the basis of temporal envelope cues in a few spectral regions. They found that performance did not differ significantly for the two groups. However, recent unpublished data obtained in our laboratory indicate that hearing-impaired listeners often perform more poorly than normally hearing listeners when trying to understand “noise-vocoder” speech when background sounds are present.

Although most of the studies described above suggest that the ability of hearing-impaired listeners to process amplitude modulation is nearly normal, there is at least one study suggesting that this may not be the case. Lorenzi et al. (1997) measured the ability to detect 100-Hz sinusoidal AM applied to a white noise carrier, as a function of the frequency of a masking sinusoidal AM applied to the same noise carrier. For listeners with normal hearing, the modulation masking patterns had a broad bandpass characteristic with a peak at 100 Hz. One listener with a moderate hearing loss also showed a broadly tuned pattern with a peak at 100 Hz. However, the two other listeners with moderate or mild-to-severe hearing loss showed broader patterns with more of a lowpass characteristic. These results suggest that frequency selectivity in the modulation domain can be reduced in listeners with sensorineural hearing loss.

In the present experiments, we examine the ability of hearing-impaired listeners to process complex patterns of suprathreshold modulation imposed on a single sinusoidal carrier, i.e., we examine within-channel modulation processing. The two tasks used (Sek and Moore, 2003) were originally designed to test the concept that the envelopes of the outputs of the auditory filters are fed to a second array of overlapping bandpass filters tuned to different envelope modulation rates. This set of filters is usually called a “modulation filter bank” (MFB) (Dau et al., 1997a, 1997b). The main purpose of the present experiments was not to test the concept of the MFB, but rather to use the two tasks as measures of the ability of hearing-impaired listeners to process complex suprathreshold patterns of AM imposed on a single sinusoidal carrier. This allowed us to examine modulation processing while avoiding possible confounding effects of reduced frequency selectivity in hearing-impaired listeners. It also allowed us to avoid confounding effects of variations in audibility with frequency, which can occur when a broadband carrier is used.

II. EXPERIMENT 1: “HEARING OUT” COMPONENT MODULATION

In our first experiment, we assessed the extent to which hearing-impaired listeners can “hear out” the component modulations in a complex modulator, in the same way that spectral components in a complex sound can be heard out in the audio-frequency domain (Plomp, 1964; Plomp and Mimpfen, 1968; Soderquist, 1970; Moore and Ohgushi, 1993). Performance was measured as a function of the frequency separation of the modulator components. The method was identical to that used by Sek and Moore (2003) with normally hearing listeners, so it is described only briefly here.

A. Listeners and test levels

Eight hearing-impaired listeners were tested. All were paid for their services. The air-bone gap in the audiogram was always $\leq$10 dB, indicating that the hearing losses were sensorineural, presumably cochlear, in origin. Only one ear was tested for each listener. This was the ear that had a hearing loss closest to 50 dB at the test frequency of 4 kHz. The hearing loss at 4 kHz ranged from 40 to 80 dB. The level of the 4-kHz sinusoidal carrier was chosen to give a comfortable loudness for each listener. Initially, the carrier was presented with a level of 80–85 dB SPL for listeners with hearing loss at 4 kHz up to 65 dB, and 85–90 dB SPL for listeners with hearing loss at 4 kHz greater than 65 dB. Listeners were asked to indicate whether the carrier was at a comfortable level. If the carrier was judged too soft, the level was increased, while if it was judged too loud, the level was decreased.

Generally, the required adjustments were small ($\pm$2 to 4 dB). Table I shows, for each listener, the hearing loss at 4 kHz, the test level, the gender and age, and the probable etiology of the hearing loss.

Listeners were trained both on the task for this experiment and the task for experiment 2 (described later), on alternate days. Training lasted 4–6 days with about 2.5 h of training per day. Following training, performance appeared to be stable for all listeners.

B. Method and stimuli

To maximize the likelihood that listeners could perform the task, we used a modulator containing only three components, with relatively wide frequency spacings between the components. We assessed whether listeners could hear out the central component of this complex modulator. The carrier was a 4-kHz sinusoid. To avoid any influence of resolvable spectral sidebands (Sek and Moore, 1994; Kohlrausch et al., 2000; Moore and Glasberg, 2001), the highest modulation frequency used was 190 Hz, which is less than one-half of the “normal” bandwidth of the auditory filter, $\text{ERB}_N$, at
4 kHz (Glasberg and Moore, 1990). Since hearing-impaired listeners usually have auditory-filter bandwidths that are larger than normal (Pick et al., 1977; Glasberg and Moore, 1986), it was very unlikely that the listeners would be able to “hear out” any spectral sidebands (Moore and Glasberg, 2001).

The task was designed so that listeners could not perform it by judging the mean rate of the complex modulator. On each trial, three modulated stimuli were presented. The modulator of the first stimulus contained three components. Within a run, the frequencies of the outer two components (called “flanking” components) were fixed and the frequency of the central (“target") component, \( f_{\text{target}} \), was drawn randomly from one of five possible values: 80, 89.4, 100, 111.8, and 125 Hz. The modulators of the second and third stimuli contained just one single component. In one of these, selected at random, the modulation frequency was equal to that of the target. In the other, the (“comparison”) modulation frequency, \( f_{\text{comp}} \), was randomly selected from one of the four other possible values of the target. Listeners were required to indicate whether the second or third stimulus contained a modulation component that was present in the first stimulus. Feedback was provided by lights on the response box indicating the correct interval. Listeners were seated in a double-walled sound-attenuating chamber.

The results were analyzed in terms of the ratio between \( f_{\text{target}} \) and \( f_{\text{comp}} \), taking as the numerator whichever of these two was the larger. The smallest ratio was equal to 1.118. This was chosen as it is somewhat larger than the threshold for detection of a change in modulation frequency of a sinusoidal carrier (Lee, 1994; Lemanska et al., 2002; Füllgrabe and Lorenzi, 2003). A run started with five trials using the easiest condition, with the largest ratio of \( f_{\text{target}} \) and \( f_{\text{comp}} \). Scores for these initial five trials were discarded. Then each possible value of \( f_{\text{target}} \) was paired with each possible value of \( f_{\text{comp}} \) two times, giving a total of 40 scored trials per run. Data presented are the result of at least 17 runs per listener (more usually, 20–23 runs).

Stimuli were generated using a Tucker-Davis Technologies (TDT) array processor (TDT-AP2) in a host PC, and a 16-bit digital-to-analog converter (TDT-DD1) operating at a 50-kHz sampling rate. The stimuli were attenuated (TDT-PA4) and sent through an output amplifier (TDT-HB6) to a Sennheiser HD580 earphone. Each modulator component had a modulation index of 0.33. This was chosen so as to avoid overmodulation of the three-component modulator, while ensuring that the modulation was clearly audible. The starting phase of each modulator component was chosen randomly for each and every stimulus.

On each trial, the carrier was presented in three bursts separated by silent intervals of 400 ms. Each burst had a 20-ms raised-cosine rise and fall, and an overall duration (including rise/fall times) of 1000 ms. The modulation was applied during the whole of the carrier. The flanking component modulation frequencies were 10 and 190 Hz, 30 and 170 Hz, and 52.6 and 190 Hz. These values were also used by Sek and Moore (2003). The first pair of flanking frequencies was chosen to be widely spaced, so that it would be possible to hear out the middle component even if selectivity in the modulation domain was very poor. The components were equally spaced from the central target component (100 Hz) on a linear frequency scale. The second pair was chosen to be closer in modulation frequency to the target component, while keeping the components symmetrically placed (on a linear frequency scale) around the frequency of the central target component. This was done to assess the ability to hear out the central modulation component under more difficult conditions. For the third pair, the components were equally spaced from the central target component on a logarithmic scale.

C. Results and discussion

The pattern of the results was similar across the eight listeners, and mean results across listeners are shown in the left panel of Fig. 1; the right panel shows the mean results for normally hearing listeners obtained by Sek and Moore (2003) for the same stimuli, but using a carrier level of 70 dB SPL. Percent-correct scores are plotted as a function of the ratio \( f_{\text{target}}/f_{\text{comp}} \), with the frequencies of the flanking components as parameter. For the smallest ratio \( f_{\text{target}}/f_{\text{comp}} \), scores for the hearing-impaired listeners are close to the chance level of 50%. However, scores increase as the ratio increases, and for a ratio of 1.56 the mean scores are all above 50%. Performance was better for the widest spacing of the flanking modulator components (10 and 190 Hz) than for the two smaller spacings.

A within-subjects analysis of variance (ANOVA) was
conducted on the percent correct scores for the hearing-impaired listeners, with factors ratio $f_{\text{target}}/f_{\text{comp}}$ and frequencies of the flanking components. There was a significant main effect of the ratio $f_{\text{target}}/f_{\text{comp}}$; $F(3,21)=28.55$, $p<0.001$. This suggests an ability to hear out the target modulation in the complex modulator when $f_{\text{target}}$ and $f_{\text{comp}}$ differ sufficiently. There was also a significant main effect of the frequencies of the flanking components; $F(2,14)=18.74$, $p<0.001$. Post hoc tests, based on the least-significant differences test, showed that performance was significantly better ($p<0.01$) for the 10- and 190-Hz flanking components than for either of the other two combinations of flanking components. There was no significant difference in scores between the 30- and 170-Hz combination and the 52- and 190-Hz combination. There was a significant interaction between the two main factors; $F(6,42)=2.42$, $p=0.042$. This reflects the fact that the improvement in performance with increasing value of the ratio $f_{\text{target}}/f_{\text{comp}}$ was greater for the 10- and 190-Hz combination of flanking components than for either of the other two combinations. However, post hoc tests showed that the improvement in performance with increasing value of the ratio $f_{\text{target}}/f_{\text{comp}}$ was significant ($p<0.01$) for all three pairs of flanking components.

The pattern of results was very similar for the hearing-impaired listeners tested here and the normally hearing listeners tested by Sek and Moore (2003). For the largest ratio $f_{\text{target}}/f_{\text{comp}}$, the normally hearing listeners performed slightly better than the hearing-impaired listeners when the flanking component frequencies were 10 and 190 Hz, and 30 and 170 Hz, but the reverse was true when the flanking component frequencies were 52.6 and 190 Hz. To assess whether the difference between the two groups was significant, an ANOVA was conducted on the mean percent correct scores for each group, with the following factors: ratio $f_{\text{target}}/f_{\text{comp}}$, frequencies of the flanking components, and group membership. The error variance was estimated from the three-way interaction term. The main effect of group membership was significant; $F(1,6)=6.39$, $p=0.045$. There was also a significant interaction between group membership and the frequencies of the flanking components; $F(2,6)=11.77$, $p=0.008$. This reflects the finding that performance was affected more by the frequencies of the flanking components for the normal than for the impaired listeners.

In summary, the results indicate that the hearing-impaired listeners had some ability to hear out the target modulation in the complex modulator when the flanking components were widely spaced in frequency from the target, and when $f_{\text{target}}$ and $f_{\text{comp}}$ differed sufficiently. The ability is comparable to, but slightly worse than, that found for normally hearing listeners. Performance for both groups was never perfect even for the widest spacing of the modulator components, which is consistent with the relatively broad tuning of the modulation filters inferred from experiments on modulation masking (Dau et al., 1997a, 1997b; Ewert and Dau, 2000) and on forward masking of AM (Wojtczak and Viemeister, 2005).

### III. EXPERIMENT 2: THE DETECTION OF CHANGES IN MODULATOR COMPONENT PHASE

#### A. Background

In the audio-frequency domain, listeners are more sensitive to within-channel phase changes than to across-channel phase changes (Zwicker, 1952; Patterson, 1987; Uppenkamp et al., 2001; Moore, 2003). Hence, changes in phase sensitivity with changes in the frequency spacing of the components probably reflect the influence of the frequency selectivity of the auditory system. Applying this rationale to the modulation domain, one would expect high sensitivity to component phase for closely spaced modulator components, and poorer sensitivity for widely spaced components. Such a pattern of results was observed by Sek and Moore (2003) for normally hearing listeners in a task requiring detection of a change in relative modulator phase of a three-component modulator.

One complicating factor when interpreting phase effects in the modulation domain is that the internal representation of the envelopes of sounds may be distorted by the presence of nonlinearities in the auditory system, such as basilar-membrane compression (Rhode and Robles, 1974) and neural saturation and adaptation effects (Shofner et al., 1996). These nonlinearities can result in the introduction of components in the effective modulation spectrum that were not present in the stimulus itself (Moore et al., 1999; Verhey et al., 2003; Sek and Moore, 2004; Füllgrabe et al., 2005), and they can also result in differences in effective “internal” root-mean-square (RMS) value of the modulator when the relative phases of modulator components are changed. Like Sek and Moore (2003), we included a condition in which the modulation depth of all components was fixed, and a condition in which the effective modulation depth was made unreliable as a cue by randomizing the overall modulation depth from one stimulus to the next. Comparison of the results for the two conditions provides an indication of the extent to which effective modulation depth was used as a cue when there was no randomization of modulation depth.

#### B. Listeners

Eight hearing-impaired listeners were tested; they were the same as for experiment 1. All listeners were paid for their services.

#### C. Stimuli

The equipment and earphone were the same as for experiment 1. The carrier was again a 4-kHz sinusoid, and its level for each listener was the same as for experiment 1. Listeners were required to discriminate two three-component complex modulators differing only in the relative phases of their components. Each modulator component was of equal amplitude. The center component of the modulator had a frequency, $f_c$, of 50 or 100 Hz. The spacing of the components was 5, 15, 25, 35, or 45 Hz for the 50-Hz $f_c$, and 10, 30, 50, 70, or 90 Hz for the 100-Hz $f_c$. For one modulator, the starting phase was 0° (sine phase) for all components. We refer to this as 0-phase. The waveforms for the 0-phase...
modulator had relatively high peak factors; see Sek and Moore (2003) for details. For the other modulator, the lowest component was phase-shifted by 180° or π radians (the other two components starting at 0°). We refer to this as π-phase. The waveforms for this modulator had lower peak factors than for the 0-phase modulator.

On each trial, three stimuli were presented. Durations and levels were the same as for experiment 1. In one set of conditions, the modulation index \( m \) of each component was fixed at 0.2. In another set of conditions, each modulator component had the same value of \( m \), but the value of \( m \) was randomly varied from one stimulus to the next, over a range of ±3 dB in terms of 20 \( \log m \) on a uniform scale in terms of \( \log m \); the value of \( m \) varied between 0.1416 and 0.2825.

D. Procedure

A three-interval three-alternative forced-choice task was used. Two intervals contained the 0-phase stimulus. The other interval, selected at random from the three intervals, contained the π-phase stimulus. The task of the listener was to select the interval that was different from the other two. Feedback was given via lights on the response box. A run started with five trials using the smallest frequency spacing of the modulator components; pilot trials indicated that performance was relatively good for this spacing. Then, in successive trials, stimuli with each frequency spacing were presented once, in ascending order. This sequence was repeated ten times to give a total of 55 trials per run. Results from the first five trials of each run were discarded. For each listener, each modulator center frequency, and each modulation-depth condition (fixed or randomized), 20 runs were obtained.

E. Results

The pattern of results was reasonably similar across listeners, and mean results across listeners are shown in the top two panels of Fig. 2. Performance worsened with increasing frequency separation of the modulator components, for all listeners. However, even for the largest frequency separation, scores for all listeners remained above the score that would be achieved by guessing (33.3%). For \( f_c = 100 \) Hz, performance for listeners 1 and 2 was somewhat poorer when the modulation depth was randomized (squares) than when it was fixed, suggesting that, when the modulation depth was fixed, these listeners may have made some use of a cue related to the change in “internal” modulation depth. For the other listeners, and for all listeners when \( f_c = 50 \) Hz, there was no consistent effect of randomizing the modulation depth.

The data for the hearing-impaired listeners were subjected to a within-subjects ANOVA with factors modulator center frequency (50 or 100 Hz), spacing of the components relative to the center frequency (five values), and randomization of modulation depth (absent or present). The main effect of center frequency was significant; \( F(1,7) = 10.49, p = 0.014 \). Overall performance was a little better for \( f_c = 100 \) Hz (64%) than for \( f_c = 50 \) Hz (59%). The main effect of frequency spacing of the components was significant; \( F(4,28) = 85.88, p < 0.001 \). The main effect of randomization was also significant; \( F(1,7) = 13.21, p = 0.008 \). The mean score was 63.5% with no randomization and 59.5% with randomization. Finally, the interaction of randomization and frequency spacing of the components was significant, reflecting the fact that randomization of the modulation depth had a larger effect for small spacings than for large spacings; \( F(4,28) = 4.47, p = 0.006 \). No other interactions were significant.

The lower two panels of Fig. 2 show the mean results for the normally hearing listeners tested by Sek and Moore (2003) using a carrier level of 70 dB SPL. The results are similar for the two groups, except that the hearing-impaired listeners performed slightly more poorly overall than the normally hearing listeners. To assess whether the difference between the two groups was significant, an ANOVA was conducted on the mean percent correct scores for each group, with such factors as modulator center frequency (50 or 100 Hz), spacing of the components relative to the center frequency (five values), randomization of modulation depth (absent or present), and group membership. The error variance was estimated from the three-way and four-way interaction terms. The main effect of group membership was significant; \( F(1,17) = 85.81, p < 0.001 \). There was also a significant interaction between group membership and spacing of the components; \( F(4,17) = 11.47, p < 0.001 \). This reflects the finding that performance changed more with spacing of the components for the normal than for the impaired listeners.

F. Discussion

Sek and Moore (2003) considered various possible cues that might be used in the phase-discrimination task. Given
the small size of the effect of randomization of modulation depth, they argued that listeners did not perform the task using a cue based on the effective internal depth of the modulation. Another possible cue introduced by nonlinearities in the auditory system is a distortion component at the envelope or “beat” rate of the modulation, which is determined by the spacing between modulator components (Sek and Moore, 2004; Füllgrabe et al., 2005). The strength of this component might vary with the phase of the modulator components, and this could be used as a cue to discriminate the phase changes (possibly mediated via analysis with an MFB). However, in several of the conditions of our experiment, the distortion component would have coincided in frequency with a component that was already present. Given that the distortion component appears to be weak in amplitude relative to the primaries, it is unlikely that the change in effective modulation depth of the distortion component would provide a useful cue in the phase discrimination task, especially in the condition where the modulation depth was randomized.

Sek and Moore (2003) also considered and rejected as possible cues the ratio of the maximum value to the minimum value of the modulator (max-min) (Forrest and Green, 1987; Strickland and Viemeister, 1996) and the crest factor or the skewness of the modulator (Lorentzen et al., 1999).

It seems likely, as argued by Sek and Moore (2003) and Ewert et al., 2002, that listeners are sensitive to changes in the shape of the modulator waveform at the output of the modulation filter centered on (or close to) the central component of the modulator. This shape would be influenced by the relative phase of the components. When the modulator components are widely spaced (spacing greater than 0.5/fc), they interact less at the output of the modulation filter, so the sensitivity to modulator phase is reduced. However, because of the broad tuning of the modulation filters, some interaction occurs even for wide spacings. This can explain why performance remained above chance for the largest spacing used. It was not possible to use much larger spacings, since if the spacing exceeds fc, one of the modulator components has a negative frequency.

**IV. GENERAL DISCUSSION**

In both experiments, the pattern of results obtained for the hearing-impaired listeners was similar to that obtained previously for normally hearing listeners. This suggests that the processing of suprathreshold complex patterns of modulation is not greatly affected by cochlear hearing loss. However, for both experiments, the hearing-impaired listeners tested here did perform slightly and significantly more poorly overall than the normally hearing listeners tested by Sek and Moore (2003). Also, for both experiments, performance of the hearing-impaired listeners was affected less by the frequencies of the flanking components than performance of the normally hearing listeners. This is consistent with the idea that the hearing-impaired listeners had slightly reduced frequency selectivity in the modulation domain, consistent with the modulation-masking results of Lorenzi et al. (1997).

It is not obvious why this should be the case, since the MFB is usually assumed to occur relatively centrally in the auditory system (Rees and Møller, 1983; Liegeois-Chauvel et al., 2004), and there is no obvious reason why the operation of central mechanisms should be affected by cochlear hearing loss (Füllgrabe et al., 2003). While poorer selectivity in the modulation domain for hearing-impaired listeners might explain the reduced effect of the spacing of the flanking components in experiment 2, it does not account for the poorer overall performance; reduced selectivity would lead to more interaction of components, which would be expected to lead to better discrimination of the relative phase of the components.

It is of interest to consider other factors that might have affected the performance of the impaired listeners tested here. As described in the Introduction, cochlear hearing loss usually leads to a loss of fast-acting compression on the basilar membrane (Ruggero et al., 1997). For suprathreshold modulation depths, this can lead to a perceived amount of modulation that is greater than normal (Moore et al., 1996). One might argue that in a person with cochlear hearing loss, the effective modulation depth at the input to central mechanisms is greater than normal. This might lead to an advantage in some modulation-processing tasks, and may account for why detection of AM is sometimes better than normal when the comparison is made at equal (low) SLs (Bacon and Gleitman, 1992; Moore et al., 1992). On the other hand, for normally hearing listeners, the high-frequency side of the excitation pattern is processed almost linearly, at least for high characteristic frequencies (Robles and Ruggero, 2001). If a large effective modulation depth is beneficial in a specific task, a normally hearing listener can obtain that benefit by using information from the high-frequency side of the excitation pattern (Zwicker, 1956), at least when the carrier is at a relatively high level. The normally hearing listeners of Sek and Moore (2003) were tested using a carrier level of 70 dB SPL, which would have been sufficient to allow them to use information from the high-frequency side of the excitation pattern. One might therefore argue that differences in basilar-membrane compression between normal and hearing-impaired listeners should have little effect on performance.

Another factor that may have affected the relative performance of the normally hearing listeners tested by Sek and Moore (2003) and the hearing-impaired listeners tested here is the relatively low SL of the stimuli for the latter, which ranged from 15 to 43 dB SL (mean=27 dB SL). Performance on many tasks, including the detection of AM, worsens at very low SLs (Kohrausch et al., 2000). However, there is little information on the influence of SL on the processing of suprathreshold amounts of AM. The relatively low SL of the stimuli in our experiments might have led to slightly poorer-than-normal performance simply because relatively few neurons are excited at low SLs, so the neural code is relatively sparse. Put another way, neural “noise” may have a greater influence at low SLs than at high SLs.

A final possible reason for the slightly poorer-than-normal performance of the hearing-impaired listeners is connected with the fact that they were older than the normally hearing listeners tested by Sek and Moore (2003). It has been
suggested that age can have adverse effects on temporal processing (Wingfield et al., 1985). However, Takahashi and Bacon (1992) found that there were no significant effects of age on performance in a variety of modulation processing tasks once the effect of hearing loss was taken into account (except for a very modest correlation between age and modulation detection sensitivity at low modulation frequencies). Furthermore, in our data there was no clear trend for the older listeners (S7 and S8, aged 73 and 71, respectively) to perform more poorly than the younger listeners (S4 and S5, aged 47 and 53, respectively). Thus it seems unlikely that age had a major influence on the results.

Overall, the results of the present experiments indicate that hearing impairment has relatively little effect on the ability to process complex suprathreshold patterns of modulation, although the impaired listeners may have slightly reduced frequency selectivity in the modulation domain.

V. CONCLUSIONS

We have described two experiments assessing the ability of listeners with cochlear hearing loss to process suprathreshold amounts of AM applied to a 4-kHz sinusoidal carrier presented at a comfortable listening level. Experiment 1 examined the ability to “hear out” the modulation frequency of the central component of a three-component modulator. All listeners showed some ability to perform the task when the components in the modulator were widely spaced and when the frequencies of the target and comparison differed sufficiently. Scores were poorer when the two flanking components were closer to the central target component frequency of 100 Hz. This is consistent with the relatively broad tuning of the modulation filters inferred from experiments on modulation masking. The pattern of the results was very similar to that found earlier for normally hearing listeners, although performance overall was slightly poorer than for normally hearing listeners (Sek and Moore, 2003).

Experiment 2 examined the ability to hear a change in the relative phase of the components in a three-component modulator with harmonically spaced components. The frequency of the central component, $f_c$, was either 50 or 100 Hz. Performance was good (70–80% correct) when the component spacing was $\leq 0.5f_c$, but worsened markedly for frequency spacings greater than that. This is broadly the pattern of results predicted from the concept of the MFB. Performance was only slightly impaired by randomizing the overall modulation depth from one stimulus to the next. This suggests that listeners did not use the overall effective internal depth of the modulation as a cue. Again, the pattern of the results was very similar to that found earlier for normally hearing listeners, although performance overall was slightly poorer than for normally hearing listeners (Sek and Moore, 2003).

It may be concluded that the ability to process complex suprathreshold patterns of AM is affected only slightly by cochlear hearing loss.

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