Effects of the use of personal music players on amplitude modulation detection and frequency discrimination

Vinay[a)]
Department of Electronics and Telecommunications, Acoustics Research Center, Norwegian University of Science and Technology, O.S. Bragstads plass 2B, Norway-7491 Trondheim, Norway

Brian C. J. Moore
Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England

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Measures of auditory performance were compared for an experimental group who listened regularly to music via personal music players (PMP) and a control group who did not. Absolute thresholds were similar for the two groups for frequencies up to 2 kHz, but the experimental group had slightly but significantly higher thresholds at higher frequencies. Thresholds for the frequency discrimination of pure tones were measured for a sensation level (SL) of 20 dB and center frequencies of 0.25, 0.5, 1, 2, 3, 4, 5, 6, and 8 kHz. Thresholds were significantly higher (worse) for the experimental than for the control group for frequencies from 3 to 8 kHz, but not for lower frequencies. Thresholds for detecting sinusoidal amplitude modulation (AM) were measured for SLs of 10 and 20 dB, using four carrier frequencies 0.5, 3, 4, and 6 kHz, and three modulation frequencies 4, 16, and 50 Hz. Thresholds were significantly lower (better) for the experimental than for the control group for the 4- and 6-kHz carriers, but not for the other carriers. It is concluded that listening to music via PMP can have subtle effects on frequency discrimination and AM detection.
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I. INTRODUCTION

Exposure to excessive levels of sound is a major preventable cause of acquired sensorineural hearing loss. Such exposure can lead to irreversible loss of cochlear hair cells (Liberman and Kiang, 1978; Borg *et al*., 1995; Rabinowitz, 2010) and may also lead to neural damage, even when absolute thresholds return to normal after the sound exposure (Kujawa and Liberman, 2009). In the past, noise-induced hearing loss was mainly suffered by adults who worked in noisy occupations or used firearms. However, there is concern that many children and young adults are developing noise-induced hearing loss as a result of overexposure to amplified music (Harrison, 2008), especially through the use of personal music players (PMP), such as cassette, compact disk (CD), and MP3 players. Apart from hearing loss as measured using the audiogram, sustained exposure to high sound levels may cause symptoms such as perceived distortion of sounds, tinnitus, and hyperacusis (Davis *et al*., 1950; Katzenell and Segal, 2001; Fligor and Cox, 2004). This paper addresses the question of whether regular use of PMP affects two basic auditory functions: Frequency discrimination and amplitude modulation (AM) detection.

PMP are often capable of producing high sound levels with minimal distortion. Fligor and Cox (2004) measured the sound levels generated by the headphones of commercially available portable CD players using a KEMAR manikin (Burkhard and Sachs, 1975). Several different styles of headphones were used. Free-field-equivalent sound pressure levels measured at maximum volume control settings ranged from 91 to 121 dBA. For a few headphone–CD player combinations, peak sound pressure levels (SPLs) exceeded 130 dB SPL. Hellström and Axelsson (1988) reported comparable sound levels for portable cassette players. In principle, these levels are high enough to cause music-induced hearing loss when the PMP are used at high volume-control settings for long periods.

Several questions arise in connection with the use of PMP: (1) Do users listen at high enough volumes and for long enough durations to lead to a potential for hearing loss? (2) Do users actually experience hearing loss? (3) Are aspects of auditory perception other than audiometric thresholds affected by the use of PMP?

Question (1) has been addressed in several studies. Kuras and Findlay (1974) assessed most comfortable listening levels (MCLs) and uncomfortable levels (UCLs) for speech and rock music delivered via headphones, using 25 people who regularly listened to rock music, with ages in the range 18–25 yr. The MCLs for music (88–93 dB SPL) were high enough to have the potential for causing hearing loss with long exposure. Bradley *et al*. (1987) assessed listening habits with amplified music, especially in relation to portable cassette players, using a questionnaire administered to 1443 schoolchildren, aged 11–18 yr. Among the 37% of respondents who owned PMP, the median usage was 2.5 h/week during term times and 5.5 h/week during vacations. Preferred listening levels (typically about 77 dBA) were probably not

[a)]Author to whom correspondence should be addressed. Electronic mail: vinay.nagaraj@iet.ntnu.no

high enough to lead to hearing loss. Williams (2005) estimated equivalent diffuse-field levels for a sample of 55 participants who used a PMP in noisy backgrounds as part of their daily activity. The average 8-h equivalent continuous noise exposure level was 79.8 dBA. The average was significantly higher for men (80.6 dBA) than for women (75.3 dBA). Williams concluded that "The noise exposure results obtained did not indicate that there was a significant increase in the risk" from PMP use alone.

Torre (2008) obtained questionnaire data about PMP listening habits from 1016 university students. Over 90% of those who completed the survey reported using PMP, and of those, over 50% reported listening between 1 and 3 h/day and almost 90% reported listening at either a medium or loud volume, as also found by Vogel *et al*. (2008). Men were significantly more likely than women to report listening to their PMP for a long duration and were more likely to report listening at a very loud volume. Torre (2008) also recorded sound levels in the ear canal of 32 participants who blindly set the level of a PMP to "low, medium or comfortable, loud, and very loud." The mean levels corresponding to these categories were 62.0, 71.6, 87.7, and 97.8 dB SPL, respectively. The level corresponding to "very loud" was significantly higher for men than for women. Torre concluded that "the volume settings for reported durations may not be hazardous for hearing" but cautioned that "Long-term use of personal music systems, however, in combination with other noise exposures (i.e., recreational, occupational), and their effect on hearing remains a question for additional research."

Worthington *et al*. (2009) measured preferred listening levels for self-selected music presented via PMP either in quiet or in background noise using two methods: (1) With a probe microphone in the ear canal; (2) using the DB-100 ear simulator mounted in KEMAR. Of 30 participants, 7 were found to be listening at levels above 85 dBA, although only one of the participants was found to be listening at hazardous levels, given the duration of exposure.

Overall, the data on the listening levels and exposure duration for regular listeners to PMP are mixed in terms of whether the levels and exposure durations are potentially damaging; they seem to be close to the boundary between safe and damaging values.

Evidence for a relationship between the use of PMP and hearing damage [question (2) above] is also mixed (Fligor and Cox, 2004; Mostafapour *et al*., 1998). It is often assumed that temporary hearing loss caused by exposure to intense sounds is indicative of the potential for long-term damage. Lee *et al*. (1985) measured the extent of temporary threshold shift (TTS) for 16 participants after 3 h of listening via headphones to portable cassette players at the highest listening level that they habitually used. Nine participants had a TTS of 5 dB or less; these listened at an average level of 92 dBA. Six participants had a TTS of 10 dB at one or more frequencies; these listened at an average level of 99 dBA. One participant had a threshold shift of more than 25 dB for both ears at 4 kHz; this participant listened at 103 dBA. After 24 h, the TTS had disappeared for all participants.

Fearn and Hanson (1984) compared audiometric thresholds for two groups of subjects who did not attend pop music live performances. One group regularly listened to music via headphones and one group did not. There was no significant difference in audiometric thresholds between the two groups. The authors concluded that "we can find no evidence of headphone usage being associated with hearing damage." Similarly, Kim *et al*. (2009) found no significant association between absolute thresholds and amount of daily use of PMP. However, absolute thresholds at 4 kHz were significantly higher for participants who had used PMP for more than 5 yr than for participants who did not use PMP.

Kumar *et al*. (2009) compared high-frequency audiometric thresholds (from 3 to 12 kHz) of participants who used PMP to those of age-matched controls who did not use PMP. They also measured sound levels close to the eardrum when the PMP of the experimental group were adjusted to the preferred listening level. There were no significant differences in the audiometric thresholds of the experimental and control groups. However, there was a positive correlation between audiometric thresholds and preferred listening levels, suggesting that people who listen at high levels tend to have poorer hearing.

The potential for damage to hearing produced by listening to PMP has also been assessed using objective measures. Montoya *et al*. (2008) reported that people who had used PMP for several years and for several hours each week exhibited a reduction in transient and distortion-product evoked otoacoustic emission (DPOAE) incidence and amplitude and an increase in DPOAE thresholds. Kumar *et al*. (2009) reported significant correlations between measures of DPOAEs and preferred listening levels to PMP. These results suggest that people who regularly use PMP and who prefer high listening levels may have reduced functioning of cochlear outer hair cells.

The great majority of studies assessing the effects of sound exposure on hearing, including the effects of PMP, have used the audiometric (absolute) threshold as the primary assessment tool. This paper is concerned mainly with question (3) raised above: Are aspects of auditory perception other than audiometric thresholds affected by the use of PMP? There is some evidence that exposure to high-level music can have subtle effects on auditory function that may not be revealed in the audiogram, but may appear in discrimination tasks. For example, Stone *et al*. (2008) measured the ability of participants to discriminate Gaussian narrowband noise, which had pronounced envelope fluctuations, from low-noise noise which had a matched power spectrum but much reduced envelope fluctuations. The noise bands were centered at 2, 3, or 4 kHz. They compared results for an experimental group who went to rock concerts or played in a rock band and for a control group who did not. The experimental group was tested following a sufficient time lapse after the most recent exposure to allow any TTS to disappear. The two groups did not differ significantly in their audiometric thresholds. However, for the experimental group, performance consistently worsened for sensation levels (SLs) of 20 dB or less, while for the control group it did not. Stone *et al*. suggested that the relatively poor ability of the experimental group to discriminate low-level sounds on the basis of their envelope statistics reflected a subtle loss of inner hair cell function.

In this study, we assess whether regular listening to PMP affects two basic auditory functions: Frequency discrimination and AM detection. As in the study of Stone *et al*. (2008), the stimuli were presented at low SLs. This was done so that the stimuli would excite only a restricted region along the basilar membrane, making it more likely that subtle localized effects of cochlear damage could be detected. Frequency discrimination was studied as this may depend upon both place and temporal mechanisms, and might be sensitive to subtle changes in auditory processing; certainly, frequency discrimination is adversely affected by cochlear hearing loss (Tyler *et al*., 1983). AM detection was studied since it is known that cochlear hearing loss can sometimes be associated with better-than-normal AM detection at low SLs, possibly as a side effect of outer hair cell damage and the associated loudness recruitment (Jerger, 1962); this is considered in more detail in Sec. IV.

II. METHOD

A. Participants

Fourteen male participants were tested. It was decided only to test men, since, as reviewed above, men tend to listen to PMP at higher levels than women, and hence are more likely to show effects related to high listening levels. The purpose of the study was explained to all participants and their consent was obtained. The study was approved by the Regional Committee for Medical and Health Research Ethics (REK) in Norway. All participants had bilateral normal hearing sensitivity with audiometric thresholds better than 20 dB hearing level (HL) for frequencies from 250 to 8000 Hz, as measured using a Madsen OB922 audiometer. None of the participants had non-auditory neural conditions and none had any history of discharge, pain, or tinnitus in their ears. None of the participants had any neurological problems. Tympanometry was conducted on all participants using a Grason-Stadler GSI 33 immittance meter to rule out middle-ear pathology.

The participants were divided into two groups. The experimental group of eight participants had a history of listening to music through PMP for at least 2 h/day for at least 2 yr. Most reported that they usually set the volume control on their PMP close to the maximum, but not at the maximum. Note that they were not encouraged to use the PMP; they simply used them as part of their normal lifestyle. The control group of six participants did not listen to music through PMP. Of the 14 participants, 12 reported that they attended live music concerts (a variety of types), typically once a month or once every 2 months. The two groups were matched in terms of the reported frequency of attending live concerts. Other than attending live music, no participant reported exposure to recreational or occupational noise. The mean ages of the participants were 27.6 yr (standard deviation, SD = 5.1) for the experimental group and 33.6 yr (SD = 9.3) for the control group. Testing was carried out separately for each ear of each participant.

B. Signal generation and general procedure

All testing was conducted in a sound-treated room. All stimuli were digitally generated (16-bit resolution, 25-kHz sampling rate) using a personal computer equipped with a D-Audio soundcard. The output of the sound card was fed via the OB922 audiometer to Sennheiser HDA200 headphones. These are "closed" type headphones which give good isolation between the two ears but do not have a "flat" frequency response at the eardrum. The frequency response of the headphones at the eardrum was estimated using a KEMAR manikin. Sound levels given below are "corrected" using this measured response, and correspond to estimated SPLs at the eardrum. An adaptive two-alternative forced-choice method was used for all measurements. The two intervals were indicated by boxes on the computer screen (labeled 1 and 2), each of which was lit up in blue during the appropriate interval. The participant responded by clicking on the appropriate box with a computer mouse, or by pressing button 1 or 2 on the computer numeric keypad. Feedback was provided by flashing the box in green for a correct answer and red for an incorrect answer. For each of the measures described below, a practice run was given before testing proper started, and the final threshold estimate was based on the average for two runs.

C. Measurement of absolute thresholds

Absolute thresholds were measured for pure-tone signals with frequencies of 0.25, 0.5, 1, 2, 3, 4, 5, 6, and 8 kHz. The signal level was started above the threshold level as estimated from the audiogram. The signal could occur either in interval one or interval two, at random. The signal lasted 200 ms, including 20-ms raised-cosine rise-fall times, and the intervals were separated by 500 ms. A two-down, one-up procedure was used. Six turnpoints were obtained. The step size was initially 6 dB. It was changed to 4 dB after one turnpoint and to 2 dB after the second turnpoint. The threshold was taken as the mean signal level at the last four turnpoints.

The measured absolute thresholds were used to set the SLs when measuring frequency discrimination and AM detection.

D. Measurement of frequency discrimination

Frequency discrimination was measured using a fixed SL of 20 dB for frequencies of 0.25, 0.5, 1, 2, 3, 4, 5, 6, and 8 kHz. The procedure was similar to that used by Moore and Vinay (2009), which was in turn based on the procedure described by Moore and Sek (2009). The task was designed to be easy to learn and not to require naming of the direction of a pitch change, which is difficult for some participants (Semal and Demany, 2006). In one interval of a trial (selected randomly), there were four successive 500-ms bursts (including 20-ms raised-cosine ramps) of a tone A, with a fixed frequency. The bursts were separated by 100 ms. In the other interval, tones A and B alternated, with the same 100-ms inter-burst interval, giving the pattern ABAB. Tone B had a frequency that was higher than that of tone A by ΔF Hz. The task of the participant was to choose the interval in which the sound changed across the four tone bursts within an interval. To make it difficult for participants to use loudness cues to detect the frequency changes, the level of each and every tone was varied randomly from one presentation to the next, over a level range of 12 dB (uniform distribution) around the nominal level.

A run was started with a relatively large value of ΔF. Following two correct responses in a row, the value of ΔF was decreased, while following one incorrect response it was increased. The procedure continued until eight turnpoints had occurred. The value of ΔF was changed by a factor of 1.953 (1.25^3) until one turnpoint had occurred, then by a factor of 1.5625 (1.25^2) until the second turnpoint had occurred, and then by a factor of 1.25. The threshold was estimated as the geometric mean of the values of ΔF at the last six turnpoints. The final estimate was taken as the geometric mean value for two runs. The order of testing the different frequencies was randomized for each participant.

E. Measurement of AM detection

Thresholds for detecting sinusoidal AM were measured for carrier frequencies of 0.5, 3, 4, and 6 kHz and modulation frequencies of 4, 16, and 50 Hz. The SL was 10 or 20 dB. The levels were chosen to be in the range where cochlear hearing loss often leads to improved AM detection (Moore, 2007). One interval contained an unmodulated carrier and the other interval contained a carrier that was amplitude modulated with modulation index m. The subject had to indicate the interval containing the modulation. The total power was equated across the two intervals. The duration of each carrier was 1000 ms, including 20-ms raised-cosine rise-fall times. The value of m was adjusted using a two-down one-up adaptive procedure. The initial value was chosen to make the modulation clearly audible. The value of m was adjusted by a factor of 1.25^3 until two turnpoints had occurred, by a factor of 1.25^2 until two more turnpoints had occurred, and by a factor of 1.25 until eight further turnpoints had occurred. The threshold was taken as the geometric mean of the values of m at the last eight turnpoints. In what follows, thresholds are expressed as $20\log_{10}(m)$. The order of testing the different conditions was randomized for each participant.

III. RESULTS

For all of the measures, the results were very similar for the left and right ears. Hence, data were averaged for the left and right ears.

A. Absolute threshold

The mean absolute thresholds for each group are shown in the upper panel of Fig. 1. Error bars show ± 1 SD. The absolute thresholds for the two groups were similar for frequencies up to 2 kHz, but the absolute thresholds for the experimental group were slightly (3–5 dB) higher than for the control group at higher frequencies. A mixed-model analysis of variance (ANOVA) was conducted, with group membership (experimental or control) as a between-subjects factor and frequency and ear as within-subjects factors. Throughout this paper, the Greenhouse–Geisser correction to the degrees of freedom was used when the condition of sphericity was not satisfied. The effect of ear was not significant. The effect of frequency was significant: $F(3.23, 80.7) = 4.88$, $p < 0.01$.

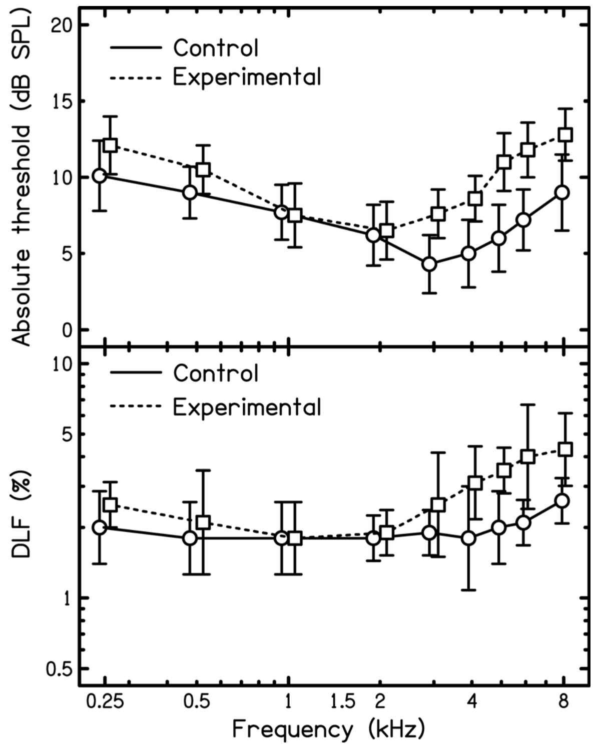

FIG. 1. The top panel shows mean absolute thresholds for the left and right ears of the control group (solid line and circles) and experimental group (dashed line and squares), plotted as a function of frequency. The bottom panel shows mean DLFs expressed as a percentage. Data points are slightly offset from their true values on the abscissa, to avoid overlap. Error bars show ± 1 SD across participants.

The effect of group was significant: $F(1, 25) = 23.7$, $p < 0.001$. The interaction between group and frequency was significant: $F(3.23, 80.7) = 11.78$, $p < 0.001$. *Post hoc* tests, based on Fisher's protected least-significant difference (LSD) test, showed that thresholds were significantly ($p < 0.05$) higher for the experimental group than for the control group for all frequencies from 3 to 8 kHz, but not for lower frequencies. These results suggest that use of PMP can adversely affect absolute thresholds at high frequencies.

B. Frequency discrimination

The difference limens for frequency (DLFs) were expressed as a percentage of the center frequency. The mean DLFs for each group are shown in the lower panel of Fig. 1. Error bars show ± 1 SD (computed in the log-frequency domain). DLFs were similar for the left and right ears for each group. The DLFs for the two groups were similar for frequencies up to 2 kHz, but the DLFs for the experimental group were slightly higher than for the control group at higher frequencies, by a factor of 1.5–2.

A mixed-model ANOVA was conducted, with group membership (experimental or control) as a between-subjects factor and frequency and ear as within-subjects factors. The effect of ear was not significant. The effect of frequency was significant: $F(4.17, 104.2) = 7.47$, $p < 0.001$. The effect of group was significant: $F(1, 25) = 101.3$, $p < 0.001$. The interaction between group and frequency was significant: $F(4.17, 104.2) = 42.5$, $p < 0.001$. LSD tests showed that thresholds were significantly ($p < 0.01$) higher for the experimental group than for the control group for all frequencies from 3 to 8 kHz, but not for lower frequencies.

C. AM detection

Means and SDs of the AM detection thresholds for the control and experimental groups are shown in the left and right panels of Fig. 2, respectively, plotted as a function of modulation frequency for SLs of 10 dB (top) and 20 dB (bottom). Each symbol denotes one carrier frequency, as indicated in the key. Thresholds tended to decrease with increasing modulation frequency. The thresholds were similar for the two groups, except for the 6-kHz carrier frequency, for which thresholds were lower (better) for the experimental group than for the control group.

A mixed-model ANOVA was conducted, with group membership (experimental or control) as a between-subjects factor and carrier frequency, modulation frequency, SL, and ear as within-subjects factors. The effect of ear was not significant. There was a significant effect of group: $F(1, 25) = 142.6$, $p < 0.001$. The mean threshold was 1.9 dB lower (better) for the experimental group than for the control group. The effect of SL was significant [$F(1, 25) = 7.0$, $p < 0.05$], the mean threshold being slightly higher at the lower SL, but the interaction of SL and group was not significant. The effect of modulation frequency was significant [$F(1.94, 49.1) = 9.6$, $p < 0.001$], but the interaction of modulation frequency with group was not significant. The effect of carrier frequency was significant [$F(2.7, 67.9) = 15.07$, $p < 0.001$], as was the interaction of group and carrier frequency: $F(2.7, 67.9) = 70.4$, $p < 0.001$. LSD tests showed that AM detection thresholds were significantly lower for the experimental group than for the control group for the 6-kHz carrier ($p < 0.001$) and for the 4-kHz carrier ($p < 0.01$). AM detection thresholds did not differ significantly across groups for the other carrier frequencies. No other interactions were significant.

D. Relationship among the measures

To assess whether performance on the different tasks was related, the following overall measures of performance were calculated for each participant:

(1) The mean absolute threshold at 4, 5, 6, and 8 kHz (Average Abs).
(2) The mean DLF at 4, 5, 6, and 8 kHz (Average DLF).
(3) The AM detection threshold at 6 kHz averaged across modulation frequency and SL (Average AM thr).

The measures were restricted to frequencies for which clear differences between the two groups were found. Figure 3 shows scatter plots of the relationships between these three quantities.

The correlation between Average Abs and Average DLF was 0.654 ($p < 0.001$, two-tailed); higher absolute thresholds were associated with larger DLFs. The correlation between Average Abs and Average AM thr was -0.512 ($p = 0.005$,

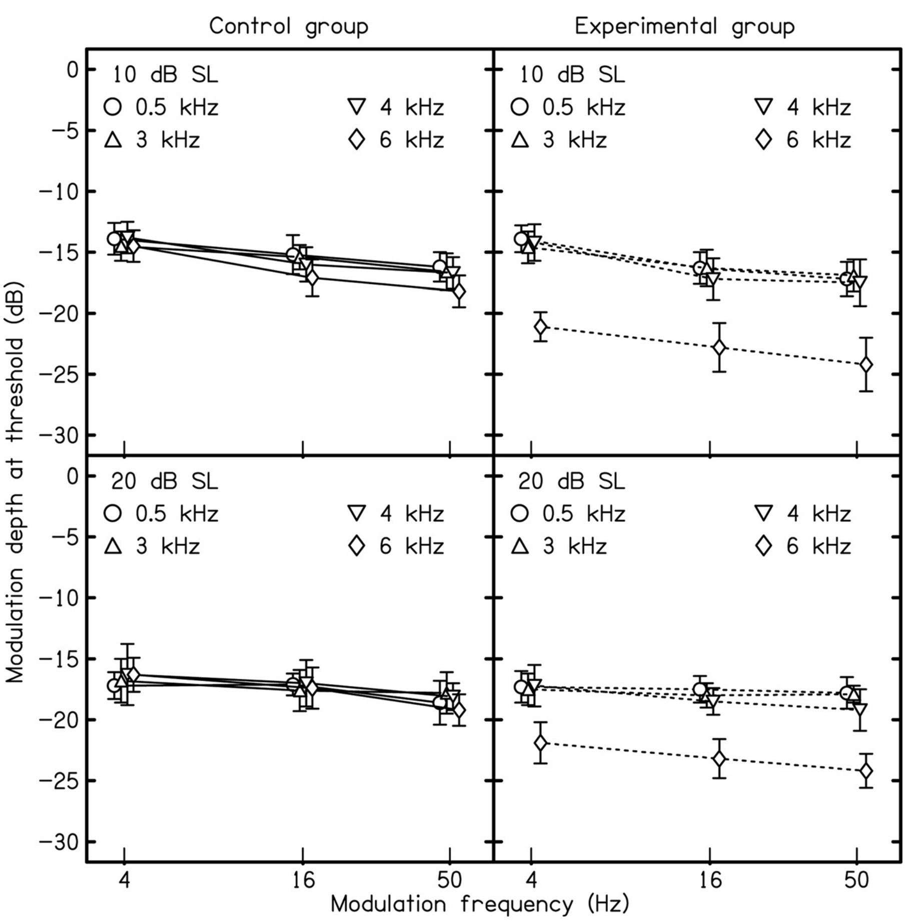

FIG. 2. Mean and SDs of the AM-detection thresholds, expressed as $20\log_{10}(m)$, for the control group (left) and experimental group (right), plotted as a function of modulation frequency for SLs of 10 dB (top) and 20 dB (bottom). Each symbol denotes one carrier frequency, as indicated in the key. Data points are slightly offset from their true values on the abscissa, to reduce overlap.

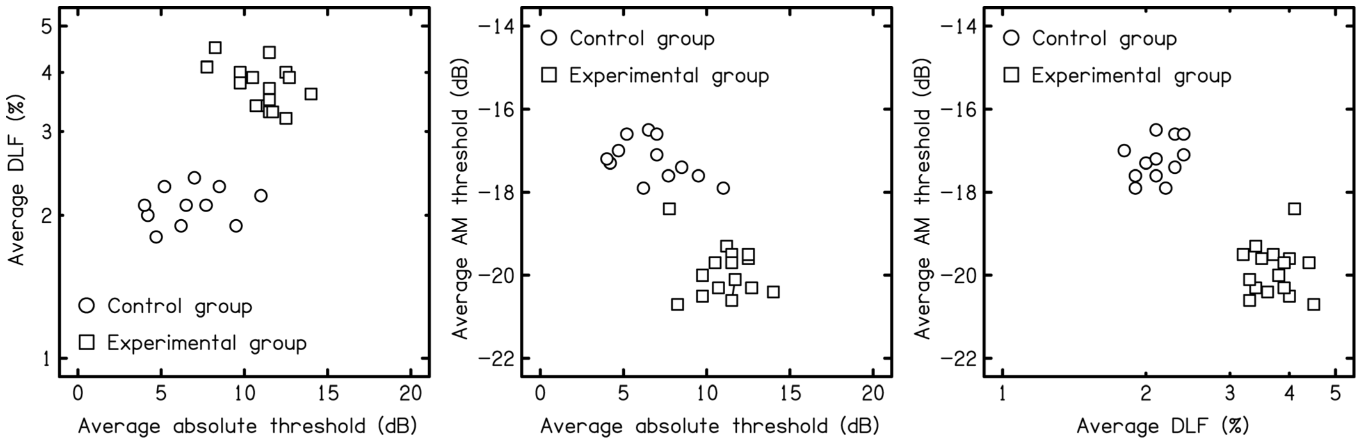

FIG. 3. Scatter plots showing the relationship between Average Abs, Average DLF, and Average AM thr (see text for details). Results for the control and experimental groups are shown by circles and squares, respectively.

two-tailed); higher absolute thresholds were associated with lower AM detection thresholds. Finally, the correlation between Average DLF and Average AM thr was −0.406 ($p = 0.032$, two-tailed); larger DLFs were associated with lower AM detection thresholds. These correlations suggest that there may be some common factor underlying the deficits in performance for the three measures. However, the correlations were not high, especially that between Average DLF and Average AM thr. Furthermore, there were no clear associations for the data of each group considered separately; the significant correlations described above arose mainly because of differences between groups rather than individual differences within each group.

IV. DISCUSSION

As described in Sec. I, previous data addressing the issue of whether regular listening to PMP is associated with elevated absolute thresholds are equivocal; some studies showed such an association, while some did not. Our data showed significant differences in absolute thresholds between the experimental and control groups for frequencies from 3 to 8 kHz. However, the differences were only 3–5 dB. The fact that the differences were significant is almost certainly related to our use of a forced-choice task to measure absolute thresholds. This gives more precise threshold estimates than the traditional audiometric methods used in earlier studies; for standard audiometry, the threshold at each frequency is estimated using 5-dB steps (Carhart and Jerger, 1959), giving a rather coarse quantization. The fact that the threshold elevations associated with PMP use occurred only at higher frequencies is consistent with much previous work showing that noise-induced hearing loss has its greatest effects at high frequencies (Borg *et al.*, 1995). The most likely cause of the hearing loss observed here is reduced functioning of the outer hair cells, which tends to occur following prolonged exposure to sounds of moderately high intensity (Borg *et al.*, 1995), as was the case for our experimental group. Loss of function of inner hair cells is associated more with impact sounds, or very high intensity sounds (Borg *et al.*, 1995), and the damage needs to be substantial before it has effects on the absolute threshold (Schuknecht and Gacek, 1993). An interpretation in terms of outer hair cell damage is consistent with the findings of Montoya *et al.* (2008) and Kumar *et al.* (2009), described earlier, that DPOAEs were affected by listening to PMP.

The measures of frequency discrimination also showed a subtle impairment of auditory function at high frequencies. DLFs were larger for the experimental than for the control group for frequencies of 3 kHz and above. Frequency discrimination is thought to depend partly on "place" information derived from shifts in the excitation pattern (Zwicker, 1956), which may be used over the whole audible frequency range, and partly on information derived from phase locking in the auditory nerve (temporal fine structure), which becomes less precise at very high frequencies (Moore, 1973, 2003; Goldstein and Srulovicz, 1977; Heinz *et al.*, 2001). The DLFs found here for the control group vary less with frequency than has been reported in some earlier studies (Moore, 1973; Wier *et al.*, 1977), perhaps as a consequence of the procedure used here, which did not require the participants to identify the direction of the frequency changes, and which included roving of the level of each tone. Nevertheless, the DLFs did increase somewhat for frequencies above 4 kHz, consistent with reduced precision of phase locking at high frequencies. The impairments in frequency discrimination found here for the experimental group might be a consequence of a reduction in frequency selectivity associated with outer hair cell dysfunction or from a reduced sensitivity to temporal fine structure, which has been shown to occur even with mild hearing losses (Hopkins and Moore, 2007; Moore, 2008; Lorenzi *et al.*, 2009).

The results for AM detection showed that performance was better for the experimental group than for the control group for the carrier frequencies of 4 and 6 kHz. This may again reflect mild outer hair cell dysfunction in the experimental group, which can lead to steeper input–output functions on the basilar membrane (Ruggero and Rich, 1991; Oxenham and Plack, 1997), and may be associated with loudness recruitment (Moore *et al.*, 1985; Moore and Glasberg, 1997, 2004). The effect of this is to magnify perceived amplitude fluctuations in sounds (Moore *et al.*, 1996). Indeed an increased sensitivity to AM at low SLs has been used as a diagnostic test for cochlear hearing loss (Jerger, 1962). However, this test is not commonly used nowadays, as it does not seem to be reliable (Buus *et al.*, 1982a,b; Moore, 1995), perhaps because the "beneficial" effects of loss of compression on the internal representation of AM are sometimes offset by deleterious effects of inner hair cell and/or neural dysfunction. The difference between the experimental and the control groups for the 4- and 6-kHz carrier frequencies was almost independent of modulation frequency, which is consistent with the data of Moore *et al.* (1996) showing that the perceived magnification of AM depth produced by loudness recruitment was independent of modulation frequency (up to the highest frequency tested, which was 32 Hz).

Our results for AM detection appear to conflict with the results of Stone *et al.* (2008), which showed impaired processing of AM for a group exposed to very intense sounds from live rock music. The discrepancy may be explicable in terms of the type of underlying damage. As mentioned earlier, reduced functioning of the outer hair cells tends to occur following prolonged exposure to sounds of moderately high intensity (Borg *et al.*, 1995), as was the case for our experimental group. In contrast, loss of function of inner hair cells is associated more with impact sounds, or very high intensity sounds (Borg *et al.*, 1995), as was the case for the experimental group of Stone *et al.* Outer hair cell dysfunction may lead to improved AM detection, while inner hair cell dysfunction may lead to impaired AM detection or processing.

The enhanced detection of AM for the experimental group was found mainly for the 6-kHz carrier and to a lesser extent for the 4-kHz carrier, but not for the 3-kHz carrier. This contrasts to some extent with the findings for absolute threshold and frequency discrimination, which revealed differences between the experimental and control groups for all frequencies from 3 to 8 kHz. However, the difference in absolute threshold between the experimental and control groups was maximal (about 5 dB) at 5 and 6 kHz, so the restricted range over which AM detection was affected may reflect the magnitude of the underlying damage. These effects probably arise from impaired functioning of outer hair cells. Since the study involved only a small number of participants, all of whom were male, the study should be repeated with a larger number of participants, both male and female.

V. SUMMARY AND CONCLUSIONS

Auditory performance was compared for an experimental group who listened regularly to music at high levels via PMP and a control group who did not. Absolute thresholds measured in dB SPL using a forced-choice task were similar for the two groups for frequencies up to 2 kHz, but the experimental group had slightly but significantly higher thresholds at higher frequencies. Thresholds for the frequency discrimination of pure tones were measured for an SL of 20 dB and center frequencies of 0.25, 0.5, 1, 2, 3, 4, 5, 6, and 8 kHz. Thresholds were significantly higher (worse) for the experimental than for the control group at 3 kHz and above, but not at lower frequencies. Thresholds for detecting sinusoidal AM were significantly lower (better) for the experimental than for the control group for the 4- and 6-kHz carriers at both SLs; otherwise, AM detection thresholds were similar for the two groups. It is concluded that listening to music via PMP can have subtle effects on frequency discrimination and AM detection even when absolute thresholds are within the normal range.

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