Discrimination of the phase of amplitude modulation applied to different carriers: Effects of modulation rate and modulation depth for young and older subjects

Brian C. J. Moore[a)]

Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England

Aleksander P. Sęk

Institute of Acoustics, Faculty of Physics, Adam Mickiewicz University, Poznań, Poland

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[a)] Author to whom correspondence should be addressed. Electronic mail: bcjm@cam.ac.uk

Abstract

The discrimination of amplitude modulation (AM) from frequency modulation (FM) of a 1000-Hz carrier, with equally detectable AM and FM, is better for a 2-Hz than for a 10-Hz modulation rate. This might reflect greater sensitivity to temporal fine structure for low than for high rates. Alternatively, AM-FM discrimination may depend on comparing fluctuations in excitation level on the two sides of the excitation pattern, which are in phase for AM and out of phase for FM. Discrimination of the relative phase of fluctuations might worsen with increasing rate, which could account for the effect of rate on AM-FM discrimination. To test this, discrimination of the phase of AM applied to two sinusoidal carriers was assessed, with a band of noise between the two carriers to prevent use of within-channel cues. Young and older subjects with normal hearing were tested. Performance was almost constant for AM rates from 2 to 10 Hz, but worsened at 20 Hz. Performance was near chance for AM depths near the detection threshold. The results suggest that the superior AM-FM discrimination at 2 Hz cannot be explained in terms of comparison of the phase of fluctuations on the two sides of the excitation pattern.

I. INTRODUCTION

Frequency modulation (FM) of a sinusoidal carrier may be detected using two mechanisms: (1) The FM is converted into amplitude modulation (AM) via the filtering that occurs in the cochlea and the AM is then detected as a fluctuation in excitation level over time (Zwicker, 1956); (2) The FM leads to changes over time in the temporal fine structure (TFS) of the waveform evoked on the basilar membrane and the corresponding pattern of action potentials in the auditory nerve (Rose *et al.*, 1967) and cochlear nucleus (Paraouty *et al.*, 2018), and detection of FM depends on tracking these changes over time. These mechanisms are referred to here as “FM-to-AM” and “FM-to-TFS”. It has been shown that the ability to discriminate AM from FM of a low or medium frequency sinusoidal carrier, when the AM and FM are equally detectable, is better for low modulation rates (e.g. 2 Hz) than for higher modulation rates (e.g. 10 Hz) (Demany and Semal, 1986; Edwards and Viemeister, 1994; Moore and Sek, 1995; Moore *et al.*, 2018; Moore *et al.*, 2019). It has been proposed that this reflects greater sensitivity to fluctuations in TFS for low than for high rates (Moore *et al.*, 2018; Moore *et al.*, 2019). For a 2-Hz rate, but less so for a 10-Hz rate, a stimulus with supra-threshold FM leads to detectable fluctuations in TFS (related to changes in instantaneous frequency, IF) over time, and these can be used to distinguish AM from FM. Here, we tested an alternative explanation, based on the idea that AM-FM discrimination may depend on comparing the relative phase of the fluctuations in excitation level on the two sides of the excitation pattern; the fluctuations are in phase for AM and 180° out of phase for FM (Zwicker, 1956; Moore and Sek, 1994). This is referred to as the “AM-phase hypothesis”. AM phase discrimination might worsen with increasing rate, and this could account for the effect of modulation rate on AM-FM discrimination. This idea was tested here by assessing the ability to discriminate the phase of AM applied to two different sinusoidal carriers, including a condition with a band of noise centered between the two carriers to prevent the use of within-channel cues.

Moore *et al*. (2018; 2019) showed that AM-FM discrimination using a 1000-Hz sinusoidal carrier was better for a 2-Hz rate than for a 10-Hz rate for all 12 young normally hearing (YNH) subjects that they tested. However, of 13 older subjects with normal audiometric thresholds at the carrier frequency of 1000 Hz (designated YNH), six showed very small or no effects of modulation rate, and most older hearing-impaired (OHI) subjects showed little effect of modulation rate, mainly because of poorer performance for the 2-Hz rate. Moore *et al*. proposed that the lack of effect for some subjects was caused by a decrease in sensitivity to TFS with greater age (Ross *et al.*, 2007; Grose and Mamo, 2010; Moore *et al.*, 2012; Moore, 2014; Füllgrabe *et al.*, 2015) and with hearing loss (Hopkins and Moore, 2007; 2011).

An alternative explanation is based on the AM-phase hypothesis, that discrimination of FM from AM depends on comparison of the phase of fluctuations on the lower and upper sides of the excitation. To account for the pattern of results observed by Moore *et al*. (2018; 2019) using this hypothesis, it would need to be the case that the ability to detect differences in AM phase in different frequency regions is consistently better for a 2-Hz modulation rate than for a 10-Hz rate for YNH subjects, but that for some ONH subjects and for OHI subjects there is a worsening of AM phase discrimination that is greater for a 2-Hz rate than for a 10-Hz rate. To test whether these conditions held true, the present study examined the effect of modulation rate on AM phase discrimination for young and for older subjects, all with normal or near-normal audiometric thresholds at the carrier frequency of 1000 Hz.

The extent to which the phase of AM on the two sides of the excitation pattern can be compared has been assessed indirectly in modeling studies. Paraouty *et al*. (2016) measured the effects of hearing loss and age on the ability to detect 5-Hz FM in the presence of interfering AM of the same rate, and to detect 5-Hz AM in the presence of interfering FM of the same rate. They attempted to account for the results using a model based on optimal use of the outputs of auditory filters centered below and above the 500-Hz carrier frequency. The interference effects could be predicted adequately only for the hearing-impaired subjects. Paraouty *et al*. (2016) concluded that this indirectly supported the idea that normal-hearing subjects use the FM-to-TFS mechanism in addition to FM-to-AM. Walleart *et al*. (2018) compared the effect of the number of modulation cycles on FM detection with and without interfering AM for normal-hearing and hearing-impaired subjects, using a 500-Hz sinusoidal carrier and FM rates of 2 and 20 Hz. They showed that for the normal-hearing subjects, a model of temporal-envelope processing based on a modulation filter bank and a template-matching decision strategy (Dau *et al.*, 1997) accounted better for FM detection at the 20-Hz rate than at the 2-Hz rate. They concluded that that different mechanisms underlie AM and FM detection at low rates. King *et al.* (2019) measured the effect of interfering AM on FM detection for normal-hearing listeners as a function of FM rate, carrier frequency, duration, AM rate, AM depth, and phase difference between the FM and interfering AM. The data were compared to predictions of a model incorporating an AM filter bank (Dau *et al.*, 1997). They found that the model could account for FM detection for rates above 8 Hz, but the interfering effect of AM was predicted to be much smaller than the observed effect unless the envelope phase at the outputs of the modulation filters was discarded. However, in this case the interference effect was overestimated. Overall, these studies suggest that models based on the assumption that listeners can compare the phase of AM on the two sides of the excitation pattern cannot fully account for the interfering effects of AM on FM detection.

Previous data on the discrimination of the phase of AM applied to different carriers are sparse. Green *et al*. (1990) measured the AM depth required to discriminate in-phase AM from anti-phase AM for carriers separated by 2/3 or 4/3 octave and found slightly poorer performance for a 4-Hz rate than for a 10-Hz rate (their figure 6). However, they tested only three normal-hearing students (presumably young), and they did not report any results for AM rates below 4 Hz. Thus their results cannot be used to assess whether the effects of modulation rate and age on AM-FM discrimination found by Moore *et al*. (2018; 2019) can be explained in terms of the AM-phase hypothesis.

A potential problem in using stimuli like those of Green *et al*. (1990) to test the AM-phase hypothesis is that the outputs of auditory filters centered between the two carriers may provide a cue related to changes in IF, i.e., a TFS cue. For example, if the AM is applied to carriers with frequencies of 700 and 1300 Hz, the output of an auditory filter centered at 1000 Hz will have an almost constant IF when the AM is in phase for the two carriers, but will have an IF that varies when the AM is out of phase; the IF will be higher when the upper carrier has a short-term amplitude above than that of the lower carrier, and vice versa. The use of this cue can be avoided by presenting a narrowband noise masker centered at a frequency between the two AM carrier frequencies. In the present study, conditions both without and with such an added noise were used.

II. METHOD

A. Subjects

Two groups of subjects were tested. There were eight YNH subjects (three female), aged 20 to 31 years (mean = 25 yr, standard deviation, SD = 4 yr), all of whom had audiometric thresholds ≤20 dB Hearing Level (HL) for frequencies from 125 to 8000 Hz. Their mean audiometric threshold at the test center frequency of 1000 Hz was 1.3 dB HL. There were 14 ONH subjects (six female). Some of the ONH subjects had previously taken part in experiments on AM and FM detection and AM-FM discrimination (Moore *et al.*, 2018; 2019). The ONH subjects were aged 39 to 75 yr (mean = 60 yr, SD = 11.5 dB). All had audiometric thresholds ≤25 dB HL at 1000 Hz and below, but some had hearing loss at higher frequencies; audiometric thresholds were above 25 dB HL for one subject at 3000 Hz, three subjects at 4000 Hz and five subjects at 6000 Hz. Their mean audiometric threshold at 1000 Hz was 9.6 dB HL. The test ear for the YNH subjects was chosen randomly. The test ear for the ONH subjects was selected as the ear with the lower audiometric threshold at 1000 Hz. Subjects were paid to participate.

B. Stimuli and procedure

All stimuli were generated digitally using a sample rate of 48000 Hz and 24-bit resolution. They were converted to analog form using an external sound card and delivered via Sennheiser (Wedemark, Germany) HD580 headphones. All testing took place in double-walled sound-attenuating booths.

Initially, absolute thresholds at 1000 Hz were estimated using a two-interval two-alternative forced-choice (2AFC) 2-down 1-up adaptive procedure tracking 71% correct, with observation intervals marked by boxes on a screen. The signal duration was 1000 ms, including 20-ms raised-cosine ramps. The intervals were separated by 300 ms. At least two runs were obtained for each subject, and the final threshold was averaged across runs. The mean absolute thresholds at 1000 Hz were 2.5 dB SPL for the YNH group and 11.2 dB SPL for the ONH group. Based on a non-matched samples *t*-test, the mean threshold for the ONH group was significantly higher than that for the YNH group ($t = 2.9$, $p < 0.01$). The carriers used in the main experiment were centered on either side of 1000 Hz and each had a level 30 dB above the measured absolute threshold at 1000 Hz, giving a sensation level (SL) of about 30 dB. For the ONH group, this relatively low SL limited the spread of excitation of the stimuli to the frequency region where absolute thresholds were near-normal (below 2000 Hz).

In the experiments on AM detection and AM phase discrimination, the modulator was "quasi-trapezoidal" (Shailer and Moore, 1993; Moore and Sek, 1995), as was the case for our studies of AM-FM discrimination (Moore *et al.*, 2018; 2019). This meant that the time spent at the extremes of amplitude was longer than for sinusoidal modulation. This was done in our previous studies to promote the use of TFS information, since the mechanism that "decodes" TFS information is assumed to operate most effectively when the TFS is stable over many tens of ms (Sek and Moore, 1995; Moore and Sek, 1995; 1996). For all AM rates, f_m, the transition between amplitude extremes lasted 10 ms and had the shape of a half-cosine function. The time spent at each amplitude extreme was 240, 90, 40, and 15 ms for f_m= 2, 5, 10, and 20 Hz, respectively. The signal duration was 1000 ms, including 20-ms raised-cosine ramps.

Prior to starting the main experiment, thresholds for detecting AM were measured for two of the modulation rates used in the main experiment, 2 and 10 Hz, using a carrier with a frequency of 1000 Hz presented at 30 dB SL. A 2AFC 2-down 1-up adaptive procedure tracking 71% correct was used to estimate the AM depth needed for a detectability index, d′ of 0.78 (Hacker and Ratcliff, 1979). One randomly selected interval contained an unmodulated stimulus and the other contained a modulated stimulus. Each stimulus had a duration of 1000 ms, including 20-ms rise/fall ramps. The silent gap between the intervals was 300 ms. The task was to indicate the interval that contained the modulated stimulus. Feedback was provided after each trial. The step size started at 4 dB (in terms of $20\log_{10}(m)$, where m is the modulation index) and was decreased to 2 dB after two reversals. Six reversals were obtained using the 2-dB step size and the threshold was taken as the mean value of

$20\log_{10}(m)$ at these six reversals. At least two, and usually three or more estimates were obtained for each AM rate, and the final threshold was taken as the mean for all estimates for a given rate.

For f_m = 2 and 10 Hz only, psychometric functions for the detection of AM were also measured, again using a 2AFC task. The stimulus timing, carrier frequency and level were the same as for the AM-detection task described above. Feedback was given after each trial. Five AM depths were chosen to span the range from poor to very good detectability. A run started with the largest modulation depth, and the modulation depth was progressively decreased over the next four trials. Then the whole sequence was repeated until 30 trials had been completed. Thus, an easy "reminder" stimulus was presented every five trials. The results for the first five trials were discarded and the number correct for each modulation depth was determined for the remaining 25 trials. At least 10 blocks were run for each condition, giving a total of at least 50 trials for each modulation depth. The percent correct score for each modulation depth was converted to d′, and a straight line, constrained to pass through the origin, was fitted to the d′ values as a function of the square of the modulation index (Moore and Sek, 1995). The fitted line was used to estimate the modulation depth that would be required to give d′ = 1.

In the main experiment, AM of the same rate (2, 5, 10 or 20 Hz) and depth was applied to two sinusoidal carriers, one with a frequency of 762 Hz and one with a frequency of 1296 Hz. These frequencies correspond to values 2 Cams below and 2 Cams above 1000 Hz, respectively, on the ERB_N-number scale (Glasberg and Moore, 1990; Moore, 2012). The carrier frequencies were chosen as a compromise. We wanted them to be reasonably close to 1000 Hz, since AM-FM discrimination based on AM phase would depend on comparison of the phase of excitation-pattern fluctuations for center frequencies just below and above the carrier frequency. However, we also wanted to avoid strong peripheral interactions between the two carriers. Also, we wanted to use a noise centered between the two carriers, to prevent the use of within-channel cues, specifically, changes in IF at the outputs of auditory filters centered between the two carriers. The spacing of the carrier frequencies was chosen so that this noise would not substantially affect the detection of envelope fluctuations on the two carriers. Each carrier was presented at a level that was 30 dB above the measured absolute threshold at 1000 Hz. Performance was measured in the presence and absence of a narrowband noise centered at 1000 Hz. The noise was digitally synthesized and had a bandwidth of 0.5 Cams (66 Hz). Its level was 30 dB above the measured absolute threshold at 1000 Hz.

A 2AFC task was used. The stimulus timing was the same as for the AM-detection task. In one randomly chosen interval, the AM was in phase across the two carriers. In the other interval the AM was 180° out of phase across the two carriers. The starting phase of the AM in each interval was randomly chosen. The task was to indicate the interval with out-of-phase AM. Feedback was given after each trial to help the subject to "know what to listen for". For each modulation rate, five AM depths were used. They were chosen to span the range from where the AM was barely detectable to where it was highly detectable. The exact AM depths used varied across subjects depending on the AM detection thresholds measured before the main experiment, but they typically ranged from about – 23 dB to –6 dB (in terms of $20\log_{10}(m)$). The five AM depths were presented in a sequence going from large to small and the sequence was repeated every five trials. The results for the first five trials were discarded and the number correct for each AM depth was determined for the remaining 25 trials. At least 10 blocks were run for each condition, giving a total of at least 50 trials for each AM depth. Percent correct scores for each AM depth and each AM rate were converted to values of the detectability index, d′.

III. RESULTS

For the main experiment, although there was individual variability in overall performance, the variation of d′ scores with AM depth and AM rate was similar across subjects within each group. To display mean results for each group, the d′ values were averaged across subjects for each of the five AM depths used. Since slightly different AM depths were used for each subject, the AM depths (in dB) were also averaged across subjects for each of the five AM depths (lowest, next lowest, etc.). The SD of the AM depths across subjects for a given ordinal value (e.g. the lowest AM depth) was about 2 dB for group YNH and 4 dB for group ONH. Figure 1 shows the mean results for group YNH. For the two lowest AM depths, AM phase discrimination was generally very poor, with d′ values below 0.5, even though the AM was above the AM detection threshold for the second-lowest AM depth. Discrimination improved with increasing AM depth, with d′ values close to 2 for the largest AM depth used for the three lowest AM rates. Performance was somewhat poorer for f_m = 20 Hz. As expected, performance was worse when the added noise was present, although the effect was not large. For comparison, the open diamonds show the mean scores for discrimination of FM from AM by YNH subjects obtained by Moore *et al.* (2018). AM-FM discrimination was markedly better than AM phase discrimination for the 2-Hz rate for all AM depths used, and slightly better for the 10-Hz rate for the higher AM depths.

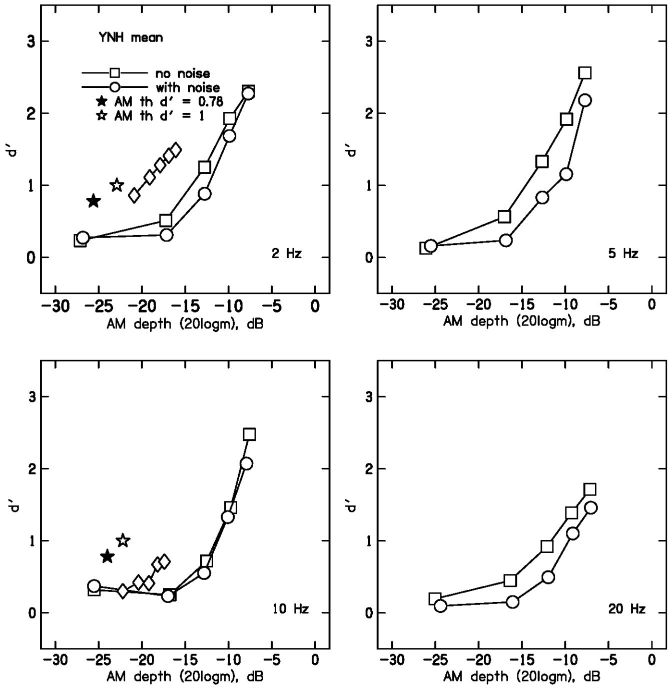

FIG. 1. Mean results for group YNH. Each panel shows results for one modulation rate. The filled stars indicate the AM depths required for AM detection with d′ = 0.78, as estimated in the initial experiment. The open stars indicate the AM depths required for AM detection with d′ = 1.0, as estimated from the psychometric functions for AM detection. Open squares and open circles show d′ values for AM phase discrimination without and with a narrowband noise centered at 1000 Hz, respectively, as a function of AM depth. For comparison, open diamonds show scores for AM-FM discrimination for the YNH group tested by Moore et al. (Moore et al., 2018).

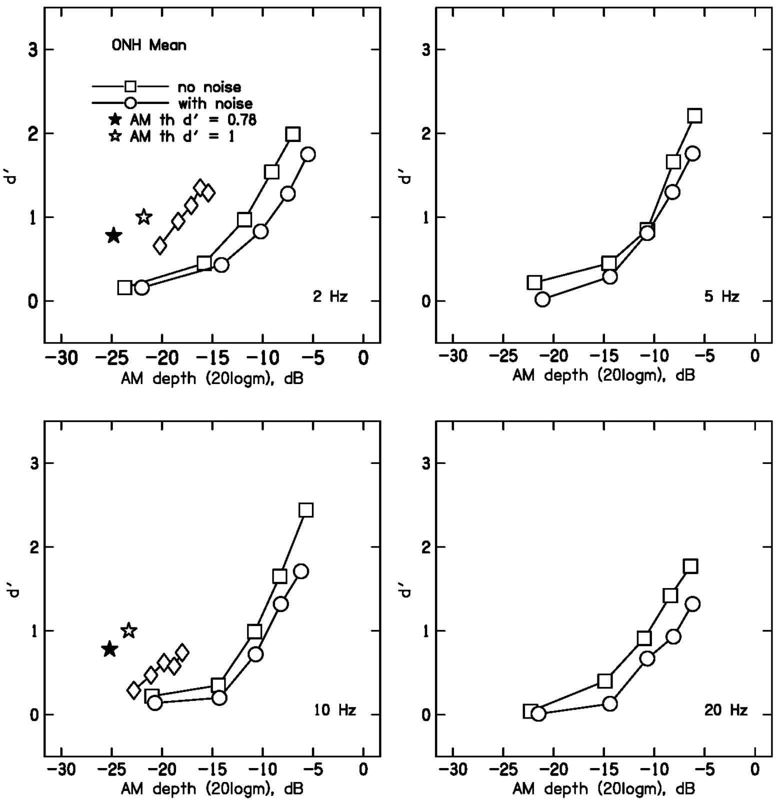

FIG. 2. As Fig. 1, but for group ONH.

For the two lowest AM depths used, performance was close to what would be expected by chance (Miller, 1996; Jesteadt, 2005). Hence, further analyses were based on the d′ values for the three higher AM depths only. Also, since we were primarily interested in performance when within-channel cues were not useable, the analysis was restricted to the condition when narrowband noise was present. An analysis of variance was conducted on the d′ values for the three highest AM depths with modulation rate and modulation depth as within-subjects factors and group as a between-subjects factor. The effect of group was not significant: $F(1, 20) = 1.34$, $p > 0.05$. Grand mean d′ values were 1.36 for group YNH and 1.19 for group ONH. There was a significant effect of AM rate: $F(3, 60) = 9.45$, $p < 0.001$. Post hoc comparisons based on Fisher's protected least-significant-differences (LSD) test showed that d′ did not differ significantly for f_m = 2, 5 and 10 Hz, but d′ for f_m = 20 Hz was significantly lower than for all other AM rates ($p < 0.02$). There was no significant interaction between AM rate and group: $F(3, 60) = 0.81$, $p > 0.05$. As expected, there was a significant effect of AM depth: $F(2, 40) = 168.7$, $p < 0.001$, performance improving with increasing AM depth. There was a significant interaction between group and AM depth: $F(2, 40) = 6.29$, $p = 0.004$. LSD tests showed that the ONH group had significantly lower d′ than the YNH group for the highest AM depth ($p = 0.05$: mean d′ = 2.01 for group YNH and 1.64 for group ONH) but that d′ did not differ across the two groups for the two lower AM depths. There was a marginally significant three-way interaction, [$F(6, 6) = 2.21$, $p = 0.047$], but it accounted for only a very small proportion of the variance in the data and will not be considered further. In summary, performance did not vary significantly for f_m from 2 to 10 Hz, but d′ was lower for f_m = 20 Hz than for the other rates. Overall performance was similar for the two groups, but the ONH group performed slightly more poorly than the YNH group for the highest AM depth.

Within the ONH group there was a reasonably wide range of ages (39 to 75 yr) and a small range of absolute thresholds at 1000 Hz, measured using the 2AFC task (0 to 26 dB SPL). To assess whether performance was related to age or absolute threshold, an overall measure of performance was calculated for each subject in group ONH. Firstly, the d′ values were averaged across the three highest AM depths for each modulation rate. As for the previous analysis, values for the two lowest AM depths were excluded because they were often within the range that would be obtained by chance (Miller, 1996; Jesteadt, 2005). Then, the d′ values were averaged across modulation rates. The correlation between these grand mean d′ values and age was –0.39. Thus, there was a weak trend for AM phase discrimination to worsen with increasing age. However, the correlation was not significant ($p > 0.05$). The correlation between the grand mean d′ values and the absolute threshold at 1000 Hz was 0.74, which was significant ($p = 0.0025$, two tailed). Thus, AM phase discrimination *improved* with increasing absolute threshold, even though the absolute thresholds covered only a small range.

IV. DISCUSSION

It has been assumed so far that AM phase discrimination depends directly on comparison of the patterns of AM fluctuation of the two carriers. However, it is necessary to consider possible alternative cues that might have been used. One possibility is that the interaction of the two carriers produced a combination tone of the type $2f_1 - f_2$, where f_1 and f_2 are the frequencies of the two carriers. The amplitude of this combination tone might have fluctuated differently when the AM was in phase on the two carriers than when it was 180° out of phase, providing a potential cue. However, the ratio f_1/f_2 for the two carriers used here was 1.7, and this relatively large ratio leads to a very weak $2f_1 - f_2$ combination tone (Zwicker, 1981; Humes, 1983). Given the low SL of the two carriers, the combination tone would almost certainly have been inaudible. Another possibility is that suppressive interactions between the two carriers played a role. Suppression of one frequency component by another tends to be stronger when the suppressor has a higher level than the component that is being suppressed (Duifhuis, 1980; Houtgast, 1974; Humes, 1983; Javel *et al.*, 1983). Hence, when the AM of the two carriers was 180° out of phase, the strength of suppression might have varied more over time than when the AM was in phase, providing a cue that might have been usable without comparison across frequency channels. However, for the relatively widely separated carrier frequencies and low SLs used in our experiments, suppression effects would have been very weak or absent (Duifhuis, 1980; Houtgast, 1974; Humes, 1983; Javel *et al.*, 1983). Hence, it seems unlikely that suppression influenced the AM phase discrimination results presented here. Overall, it is likely that the results reflect the ability to compare the patterns of AM fluctuation of the two carriers.

AM phase sensitivity did not differ significantly for AM rates of 2 and 10 Hz. In the presence of noise to prevent the use of within-channel cues, the mean d′ values across groups for the three highest AM depths were 1.40 at 2 Hz and 1.24 at 10 Hz. This contrasts with the results of Moore *et al*. (2018) for AM-FM discrimination, which showed markedly better performance at 2 than at 10 Hz, for both YNH and ONH subjects (see the open diamonds in Figs. 1 and 2), although some ONH subjects showed little or no difference. For example, when the AM and the FM both had a just-detectable depth (d′ = 1), the mean d′ values for AM-FM discrimination for the YNH group were 0.91 at 2 Hz and 0.3 at 10 Hz. When the AM and the FM were more highly detectable (d′ = 2), the mean d′ values for AM-FM discrimination were 1.53 at 2 Hz and 0.43 at 10 Hz. The lack of effect of modulation rate on AM phase discrimination found here for AM rates up to 10 Hz together with the large effect of modulation rate for AM-FM discrimination found earlier, suggests that the AM-phase hypothesis cannot account for the better AM-FM discrimination at 2 than at 10 Hz. AM phase discrimination did worsen slightly but significantly for the 20-Hz AM rate. This may reflect a transition between AM rates that are low enough for the individual cycles of the modulation to be "followed" and rates that are high enough that only an overall "roughness" is perceived (Terhardt, 1974).

For the two lowest AM depths, AM phase discrimination in the presence of noise was very poor, with d′ less than 0.3. This happened despite the fact that the second-lowest AM depth was typically about 7 dB above the AM detection threshold corresponding to d′ = 0.78 (filled stars in Figs. 1 and 2) and about 5 dB above the AM detection threshold corresponding to d′ = 1 (open stars in Figs. 1 and 2). This finding contrasts with results for AM-FM discrimination using a modulation rate of 2 Hz (Moore *et al.*, 2018; 2019), which showed that AM-FM discrimination was well above chance when the AM alone and FM alone were themselves only just detectable (d′ = 1; see the diamonds in the top-left panels of Figs. 1 and 2). In other words AM can be discriminated from FM at a 2-Hz rate for modulation depths where AM-phase discrimination is close to chance. This again suggests that the AM-phase hypothesis cannot account for AM-FM discrimination at a 2-Hz rate.

There was no significant effect of age group on d′ values for the three highest AM depths for the condition when noise was present. Furthermore, there was no significant interaction between age group and AM rate. This indicates that the AM phase hypothesis cannot account for the effect of age on AM-FM discrimination reported previously (Moore *et al.*, 2018; 2019). These studies showed that some but not all ONH subjects showed worse AM-FM discrimination than YNH subjects for the 2-Hz rate but not for the 10-Hz rate.

Some of the ONH subjects had participated in our previous experiment measuring AM-FM discrimination (Moore *et al.*, 2018; 2019). This allowed a direct comparison of performance for AM-FM discrimination and AM phase discrimination. Example results for subject ONH1 are shown in Fig. 3. The open squares and circles show d′ values for AM phase discrimination without and with a narrowband noise centered at 1000 Hz, respectively, as a function of AM depth. The filled squares show d′ values for AM-FM discrimination, plotted as a function of AM depth; the FM in this case was equated in detectability to the AM for each AM depth. The d′ values for the AM and FM were 1, 1.5, 2, 2.5 and 3. For AM-FM discrimination at the 2-Hz rate, d′ values were above 1 for all modulation depths used, reaching about 2.5 for the highest modulation depth, which was about –14 dB. In contrast, AM phase discrimination was at chance for the two lowest AM depths, which were –13 dB with noise and –11 dB without noise. AM-FM discrimination at the 10-Hz rate was markedly worse than for the 2-Hz rate, d′ for the former reaching 0.78 for the highest modulation depth. AM-FM discrimination at 10 Hz was still better than AM phase discrimination at similar modulation depths, but not by very much.

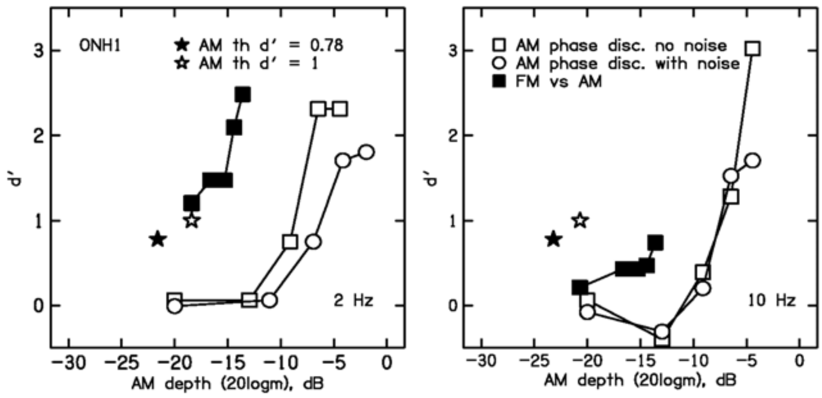

FIG. 3. Comparison of results for AM phase discrimination (open squares: without noise; open circles: with noise) and AM-FM discrimination (filled squares) for subject ONH1, for modulation rates of 2 Hz (left) and 10 Hz (right). Otherwise as Fig. 1.

Figure 4 shows results for ONH2. For the 2-Hz rate, d′ values for AM-FM discrimination were 2.5 or higher for all modulation depths used, reaching 3 for the three highest modulation depths, which were –16.6, −15.6, and –14.8 dB. In contrast, AM phase discrimination was at chance for modulation depths up to –10.5 dB. AM-FM discrimination at the 10-Hz rate was again markedly worse than for the 2-Hz rate, d′ not exceeding 0.43 for any modulation depth. For this subject, AM-FM discrimination at 10 Hz was similar to AM phase discrimination at similar modulation depths; both were close to chance.

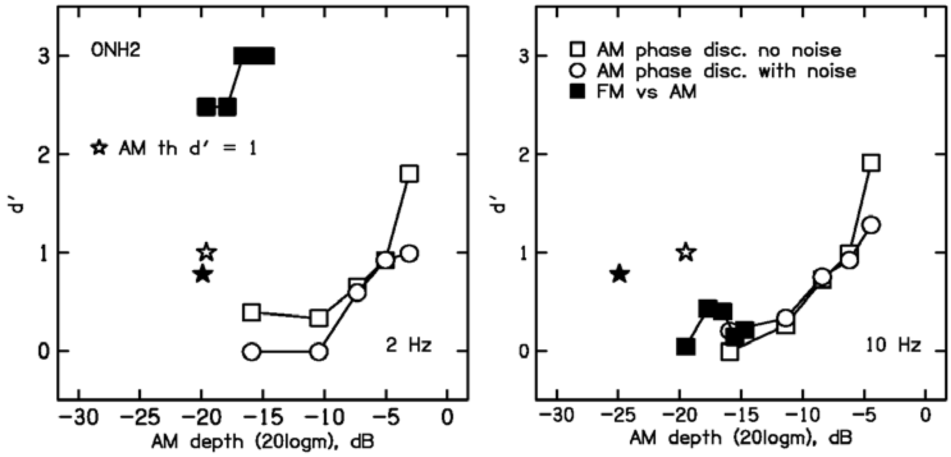

FIG. 4. As Fig. 3, but for subject ONH2.

Subjects ONH1 and ONH2 both showed markedly better AM-FM discrimination for the 2-Hz rate than for the 10-Hz rate, as was found for all YNH subjects. As described in the introduction, some ONH subjects did not show a clear difference in AM-FM discrimination for the two rates. An example of the results for such a subject, ONH4, is shown in Fig. 5. ONH4 showed relatively poor AM-FM discrimination for both rates and for all AM depths used, the maximum d′ value being 0.80 at 2 Hz and 0.74 at 10 Hz. For this subject, AM-FM discrimination was only slightly better than AM phase discrimination, for both modulation rates.

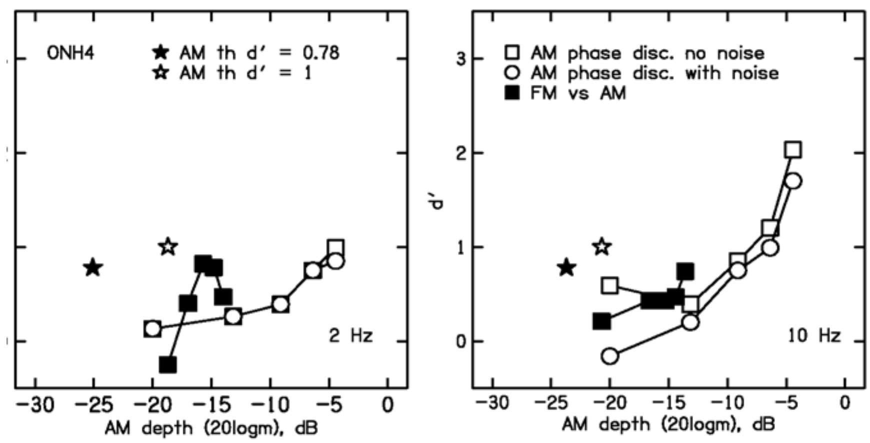

FIG. 5. As Fig. 3, but for subject ONH4.

Overall, these results suggest that the better AM-FM discrimination at 2 than at 10 Hz, which occurs consistently for YNH subjects and often for ONH subjects, cannot be explained in terms of better sensitivity to AM phase at 2 than at 10 Hz. In other words, the AM-phase hypothesis does not account for the pattern of results obtained for AM-FM discrimination. Rather, the results are consistent with the proposal that the superior AM-FM discrimination at 2 Hz is a consequence of a better ability to use TFS information at that rate, resulting from "sluggishness" of the mechanism that decodes TFS information (Sek and Moore, 1995; Moore and Sek, 1995; Moore and Sek, 1996). ONH subjects who do not show better AM-FM discrimination at 2 than at 10 Hz, such as ONH4, probably have reduced sensitivity to TFS information. For such subjects, AM-FM discrimination is only slightly better than AM phase discrimination.

If AM-FM discrimination at a 10-Hz rate did not depend at all on the use of TFS information, but rather depended exclusively on AM phase discrimination, performance would be expected to be similar for AM-FM discrimination and AM phase discrimination. In fact, for most of the ONH subjects who were tested both in our earlier experiments (Moore *et al.*, 2018; 2019) and here, AM-FM discrimination was slightly better than AM phase discrimination at the 10-Hz rate. There are at least two possible explanations for this. Firstly, there may be some ability to use TFS information even for the 10-Hz rate. Recall that the stimuli used in our earlier studies and here had quasi-trapezoidal modulation; the stimuli spent more time at the extremes of frequency or amplitude than is the case for sinusoidal modulation. This may have promoted the use of TFS information to discriminate AM from FM, even for the 10-Hz rate. Secondly, AM-FM discrimination worsens with increasing frequency separation of the two carriers (Green *et al.*, 1990). In the present AM phase discrimination experiment the carrier frequencies were 762 Hz and 1296 Hz, corresponding to 2 Cams below and 2 Cams above 1000 Hz, respectively, on the ERB_N-number scale. In a task of discriminating AM from FM imposed on a 1000-Hz carrier, subjects might compare the phase of excitation level fluctuations for more closely spaced center frequencies than the ones used here. As noted earlier, very closely spaced carriers were avoided here so as to limit the use of within-channel cues, and to allow the use of a narrowband noise masker between the two carriers without the masker strongly influencing the processing of the two carriers.

The correlational analysis conducted on the data for the ONH group suggested that individual variability in AM-FM discrimination was more related to the absolute threshold at 1000 Hz than to age. However, greater hearing loss was associated with *better* AM phase discrimination. This probably occurred because cochlear hearing loss is usually associated with loudness recruitment, which, for AM stimuli, has the effect of magnifying the perceived amount of modulation (Moore *et al.*, 1996), and which may be associated with better AM detection for stimuli at low SLs (Bacon and Gleitman, 1992; Ernst and Moore, 2012; Schlittenlacher and Moore, 2016). Since AM phase discrimination improved with increasing AM depth, it seems plausible that the loudness recruitment associated with hearing loss had a beneficial effect on AM phase discrimination. In contrast to AM-phase discrimination, hearing loss adversely affects AM-FM discrimination for a 2-Hz modulation rate (Moore *et al.*, 2019), again suggesting that AM-FM discrimination for a 2-Hz modulation rate is not based on AM phase discrimination.

V. SUMMARY AND CONCLUSIONS

Using quasi-trapezoidal modulation, it has previously been shown that, for YNH subjects, discrimination of AM from FM, when the AM and FM are equally detectable, is better for a 2-Hz modulation rate than for a 10-Hz modulation rate (Moore *et al.*, 2018; 2019). AM-FM discrimination for a 2-Hz rate is poorer than for YNH subjects for some but not all ONH subjects, and for most subjects with hearing loss. The experiments described here were intended to assess whether this pattern of results could be accounted for by the AM-phase hypothesis, that AM-FM discrimination depends on a comparison of the phase of excitation pattern fluctuations on the two sides of the excitation pattern. The ability to discriminate the phase of AM applied to two sinusoidal carriers was assessed. A band of noise was centered between the two carriers to prevent use of within-channel cues. Both YNH and ONH subjects were tested.

Several aspects of the results suggest that the AM-phase hypothesis cannot account for the pattern of results for AM-FM discrimination:

(1) AM phase discrimination was not significantly better for f_m = 2 Hz than for f_m = 10 Hz. The effects of AM rate on AM phase discrimination were much smaller than the effects of modulation rate on AM-FM discrimination.

(2) Previous work showed that AM-FM discrimination for a 2-Hz modulation rate was well above chance for AM depths at which the modulation was only just detectable, for both YNH and ONH groups (Moore *et al.*, 2018; 2019). In contrast, AM phase discrimination for both groups tested here was close to chance for AM depths that were close to or somewhat above the AM detection threshold.

(3) There was no significant effect of age group on AM phase discrimination and no significant interaction of age group and AM rate. In contrast, AM-FM discrimination is worse for some but not all ONH subjects than for YNH subjects for a 2-Hz rate but not a 10-Hz rate.

(4) Within the ONH group, there was a significant correlation between absolute threshold and an overall measure of AM phase discrimination, even though all absolute thresholds were normal or near-normal. AM phase discrimination improved with increasing absolute threshold, probably because loudness recruitment had the effect of magnifying the internal representation of AM depth. In contrast, previous work showed that AM-FM discrimination for a 2-Hz rate was worse for older subjects with hearing loss than for YNH or ONH subjects (Moore *et al.*, 2019).

Given that the AM-phase hypothesis cannot account for the pattern of results obtained for AM-FM discrimination, it seems likely that the better AM-FM discrimination of YNH subjects for a 2-Hz rate than for a 10-Hz rate results from a greater sensitivity to TFS for a 2-Hz rate; the fluctuations in IF for the FM stimulus, which are coded in the patterns of TFS in the auditory nerve, allow FM to be distinguished from AM even when the FM and AM are only just detectable. Sensitivity to TFS decreases with increasing age for some but not all subjects, and decreases with hearing loss for most subjects, and this can account for the effects of age and hearing loss on FM-AM discrimination at a 2-Hz rate.

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