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Amplitude modulation detection by human listeners in reverberant sound fields: Effects of prior listening exposure

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Abstract

Previous work [Zahorik et al., POMA, 15, 050002 (2012)] has reported that for both broadband and narrowband noise carrier signals in a simulated reverberant sound field, human sensitivity to amplitude modulation (AM) is higher than would be predicted based on the acoustical modulation transfer function (MTF) of the listening environment. These results may be suggestive of mechanisms that functionally enhance modulation in reverberant listening, although many details of this enhancement effect are unknown. Given recent findings that demonstrate improvements in speech understanding with prior exposure to reverberant listening environments, it is of interest to determine whether listening exposure to a reverberant room might also influence AM detection in the room, and perhaps contribute to the AM enhancement effect. Here, AM detection thresholds were estimated (using an adaptive 2-alternative forced-choice procedure) in each of two listening conditions: one in which consistent listening exposure to a particular room was provided, and a second that intentionally disrupted listening exposure by varying the room from trial-to-trial. Results suggest that consistent prior listening exposure contributes to enhanced AM sensitivity in rooms. [Work supported by the NIH/NIDCD.]

INTRODUCTION

Human abilities to identify sources of sound and to understand speech depend critically on sensitivity to amplitude modulation (AM) – changes in a sound's amplitude envelope over time. Although it is well-known that various environmental factors, such as room reverberation or background noise, can profoundly influence the AM reaching a listener's ears as characterized by the acoustical modulation transfer function, or MTF (Houtgast and Steeneken, 1985), the influence of room acoustic effects has not been extensively studied under realistic listening conditions.

Previous work (Zahorik *et al.*, 2011; Zahorik *et al.*, 2012) has reported that for both broadband and narrowband noise carrier signals in a simulated reverberant sound field, human sensitivity to amplitude modulation is 4 – 8 dB lower than would be predicted based on the acoustical MTF of the listening environment. These results may be indicative of mechanisms that counteract the harmful effects of reverberation in order to produce enhanced AM sensitivity in reverberant sound fields. Such enhancement is consistent with recent neural data that demonstrate the presence of reverberation-resistant coding of AM in the response properties of single neurons in the inferior colliculus (Delgutte *et al.*, 2012; Kuwada *et al.*, 2012). Because other studies have demonstrated that speech understanding in reverberant soundfields may be modified (Watkins, 2005) or improved (Brandewie and Zahorik, 2010; Srinivasan and Zahorik, 2013) with prior listening exposure to reverberation, and that this effect appears to most strongly influence the processing of the amplitude

envelope of the speech signal (Watkins *et al.*, 2011), it is important to determine whether AM sensitivity could be similarly affected by prior listening exposure to reverberation. This is the goal of the present study.

METHODS

Subjects

Seven listeners (5 male, 2 female, age range 24 – 43 years) participated in the experiment. All had normal hearing, as verified by standard pure-tone audiometric screening at 25 dB HL from 250 – 8000 Hz. Two of the participants were authors of this study.

Soundfield Simulation

Virtual auditory space techniques were used to simulate a sound field in a reverberant room with dimensions of $5.7 \times 4.3 \times 2.6$ m (L $\times$ W $\times$ H). The test room had a broadband reverberation time, T_{60} , of approximately 1.8 s. An anechoic room and a less reverberant room (broadband T_{60} of approximately 1 s), both with the same dimensions as the test room, were also simulated. Non-individualized head-related impulse responses were used for the simulations, which synthesized binaural room impulse responses (BRIRs) using techniques described by Zahorik (2009). The simulated sound source location was directly in front of the listener (0°) at a distance of 1.4 m. A diotic control condition that contained no BRIR processing was also tested.

Acoustic MTF Determination

Acoustic MTFs for the sound field listening condition in the test room were computed from the BRIRs based on a technique described by Schroeder (1981). This technique, which is identical to that used in previous related work (Zahorik *et al.*, 2012), involves first band-pass filtering the BRIR with a bandwidth of that corresponds to the bandwidth of the carrier signal used in the psychophysical experiment; one octave in this case. The MTF is then computed as the energy, at each frequency, of the squared band-pass filtered impulse response normalized by its total energy.

Stimuli and Procedure

The carrier signal was a 1-octave wide band of noise with a center frequency of 4 kHz, and duration of 400 ms (raised cosine gating function with 50 ms rise/fall). Independent noise samples were used for each presentation. Detection thresholds were measured using an adaptive 2-interval, 2-alternative forced choice procedure, with a 2-down, 1-up tracking rule. Listeners reported the interval containing the sinusoidal AM and received feedback as to the correctness of their response. All testing was conducted at a single modulation frequency of 64 Hz. The starting AM depth was -6 dB ($20\log_{10}m$, where m is the modulation proportion). Adaptive track step size was initially 4 dB, and then decreased to 1 dB after 2 reversals. Threshold estimates were based on the median modulation depth over the last 10 reversals in the adaptive track.

Two types of listening contexts were tested: one in which consistent listening exposure to a particular sound field was provided, and a second that intentionally disrupted listening exposure by varying the room from trial-to-trial. Consistent exposure was implemented by holding the soundfield simulation fixed throughout a single adaptive track. Variable exposure was implemented by testing using 4 interleaved adaptive tracks, each with a different soundfield simulation. Diotic and reverberant room ($T_{60} = 1.8$ s) listening were tested in both consistent and variable listening context. The anechoic and a less-reverberant room ($T_{60} = 1$ s) sound field simulations were used for the other two tracks in the variable

listening context. Each subject completed all listening conditions in all contexts (completely within-subjects design).

RESULTS AND DISCUSSION

Figure 1 displays the acoustic MTFs from the simulated reverberant sound field for the 1-octave band centered at 4 kHz. Consistent with past research, the test room exhibits a low-pass characteristic (Houtgast and Steeneken, 1985). At 64 Hz, the room attenuates sinusoidal AM by 13.2 and 12.3 dB in the left and right ears respectively. Based on these acoustical results, one would predict that detection threshold for sinusoidal AM with a 1-octave wide noise band centered at 4 kHz should be elevated by at least 12.3 dB in the reverberant room relative to no room (diotic listening).

Figure 2 displays mean modulation detection thresholds for both diotic and reverberant sound field listening. In each condition, results are shown for both consistent and variable listening contexts. Overall, detection thresholds were elevated for the reverberant sound field relative to diotic listening. This is not surprising, given the MTF characteristics of the room shown in Fig. 1. Perhaps more interesting is the effect of consistent listening context, which was found to produce lower thresholds in the reverberant room relative to variable listening context. This result was found to be statistically significant using a match-pair t -test, $t(6) = 4.58$, $p = .004$. Similar differences were not observed for diotic listening, indicating that the effect is specific to reverberant soundfields.

In order to more easily visualize the modulation enhancement effect, psychophysically determined modulation gain values were computed for individual subjects by subtracting the room threshold from diotic threshold for each listening context. Results of this analysis are shown in Fig. 3, and can easily be compared to the gain predicted based on the acoustic MTF analysis alone. From this analysis, it is clear that modulation enhancement is observed, but only for the case of consistent prior exposure to the same reverberant soundfield. The observed enhancement effect of 3.7 dB is statistically significant, $t(6) = 4.04$, $p = .007$, although of somewhat smaller magnitude than that reported in a previous study (Zahorik *et al.*, 2012). This difference may be attributable to differences in the psychophysical procedures used in the two studies: objective (current study) versus subjective method of adjustment (Zahorik *et al.*, 2012). Finally, it is important to note that the enhancement effect reported here is in the opposite direction of other modulation adaptation effects reported in the literature, where modulation sensitivity is found to decrease with repeated exposure to a particular modulation pattern in the absence of reverberation (Tansley and Suffield, 1983; Wojtczak and Viemeister, 2003). Further study will be needed to more fully characterize the enhancement effect, and to evaluate any potential relationships with modulation adaptation phenomena.

CONCLUSIONS

Enhanced AM sensitivity in a reverberant soundfield has been demonstrated, and appears to require prior consistent listening exposure to the reverberation. Variable listening exposure results in non-enhanced AM sensitivity, which is well-predicted by the acoustic MTF of the room alone.

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FIGURE 1.

Acoustic MTFs for a 1-octave wide band centered at 4 kHz at both left (blue) and right (red) ears in the simulated reverberant sound field (broadband $T_{60} = 1.8$ s) used for testing in this study. Gain at the modulation frequency used for psychophysical testing was -13.2 and -12.3 dB in the left and right ears respectively.

FIGURE 2.

Mean ($n = 7$) modulation detection thresholds for a 1-octave band of noise centered at 4 kHz and sinusoidally amplitude modulated at 64 Hz. Results for both diotic and reverberant soundfield (MTF shown in Fig. 1) listening conditions are shown. In each condition, thresholds were determined when the listening context remained consistent (i.e. same listening condition) throughout the block of trials, and when the context was made to be variable by switching between different rooms/soundfields from trial to trial (see text for details). Bars indicate ± 1 standard error of the mean. Results of matched-pair t -tests (p -values shown) confirm significantly decreased thresholds for consistent exposure to the reverberant room, but not for diotic listening.

FIGURE 3.

Mean ($n = 7$) psychophysical modulation gain of the room, determined by subtracting room modulation threshold from diotic modulation threshold for each subject in both consistent and variable listening contexts. Bars indicate ± 1 standard error of the mean. The predicted modulation gain is determined from the maximum modulation gain in the acoustic MTF at 64 Hz (see Fig. 1, right ear). Modulation enhancement is indicated by psychophysical room modulation gain that is greater than predicted from the acoustic MTF. Statistically significant enhancement (3.7 dB on average) is observed for the consistent context only.