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Derek R. Edwards; Jungmee Lee; Jennifer Andrews; Aileen Wong

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Contribution of onset/offset information of modulation to amplitude modulation depth discrimination[a)]

Derek R. Edwards, Jungmee Lee, Jennifer Andrews, and Aileen Wong
Department of Speech, Language, and Hearing Sciences, University of Arizona, 1131 E. 2nd Street, Tucson, Arizona 85721-0071
derek09@email.arizona.edu, jmlee6@email.arizona.edu, andrewsj@email.arizona.edu, annw16@email.arizona.edu

Abstract: A previous study by [J. Lee, G. Long, and C. Jeung, J. Acoust. Soc. Am. **119**, S3332 (2006)] found that information at the onset or offset of modulation could be utilized for improved amplitude modulation (AM) depth discrimination in a continuous carrier condition (carrier presented 250 ms earlier and later than the modulator). In this study, the relative contribution of information at the onset or offset of the modulation was examined with an onset-fringe carrier condition (carrier begins 250 ms earlier than the modulator) and an offset-fringe condition (carrier ends 250 ms later than the modulator). The results suggest that modulation information at the onset might be utilized more than at the offset.

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1. Introduction

Lee and Bacon (1997) studied the duration effect on amplitude modulation (AM) depth discrimination with a gated sinusoidal carrier condition (modulation begins and ends with the carrier). AM depth discrimination was found to be influenced by the number of modulation cycles. There was a critical duration of four cycles of modulation in which a dramatic threshold improvement (more than factor of 2) was observed when the stimulus duration increased from a shorter duration to this critical duration; only a slight or no improvement of threshold was observed when the stimulus duration exceeded this critical duration for modulation rates of 10, 20, 40, and 80 Hz. Lee and Bacon (1997) compared AM detection data (Sheft and Yost, 1990) with their AM depth discrimination data and found that AM detection lacks the critical duration effect observed in AM depth discrimination. In contrast, AM detection thresholds were found to decrease gradually with increasing duration from 25 to 400 ms. It should be noted, however, that Sheft and Yost (1990) used the noise carrier whose total duration was 51.2 ms longer (due to 25.6 ms rise/fall time) than modulation duration, while Lee and Bacon (1997) used a gated sinusoidal carrier. This difference between stimuli led to the study of Lee *et al.* (2006) in which both AM detection and AM depth discrimination were measured with the same stimulus conditions.

Lee *et al.* (2006) measured AM detection and AM depth discrimination with gated and continuous noise carrier conditions as a function of the number of modulation cycles. In the continuous noise carrier condition, the carrier was presented 250 ms earlier and 250 ms later than the modulator. A difference in thresholds between gated and continuous carrier conditions was observed for lower modulation rates of 10, 20, 40, and 80 Hz at less than four modulation cycles.

The critical duration of four cycles of modulation was observed for both AM detection and AM depth discrimination (for both standard depths of 0.1 and 0.4) in the gated carrier

[a)]A portion of this study was presented at the American Auditory Society meeting, 2007.

condition for lower modulation rates (10, 20, 40, and 80 Hz). For these lower modulation rates, there was a significant improvement in **both** AM detection and AM depth discrimination thresholds in the continuous carrier condition at fewer than four cycles of modulation. Thresholds were similar for both gated and continuous carrier conditions for modulation cycles greater than four. These results suggest that a difference in stimulus gating may have caused the absence of a critical duration effect in AM detection observed from the comparison of data from Sheft and Yost (1990) and Lee and Bacon (1997). For the gated carrier condition, shaping the onset/offset of stimuli with rise/fall times might reduce modulation information at the onset/offset, which might result in a dramatic change in threshold for a smaller number of modulation cycles. Therefore, the presence of a critical duration effect appears to be the result of gating differences.

In the continuous carrier condition used in Lee *et al.* (2006), the carrier was presented before and after the modulator. Therefore, it is impossible to determine from their data whether it was the modulation information at onset or offset of the modulator that was being used in the AM detection/discrimination task. The goal of the present study was to determine whether the onset or offset of modulation information is responsible for the observed improvement in AM depth discrimination at fewer than four cycles of modulation for lower modulation rates (10, 20, 40 and 80 Hz) in the continuous carrier condition. Four carrier conditions were compared: Gated (carrier gated on and off with the modulator), Onset/offset-fringe (carrier gated on 250 ms before modulator onset and gated off 250 ms after modulator offset), Offset-fringe (carrier gated on with the modulator and gated off 250 ms after modulator offset), and Onset-fringe (carrier gated on 250 ms before modulator onset and gated off with the modulator). For the purposes of this study, the continuous carrier condition of Lee *et al.* (2006) will be referred to as the onset/offset-fringe condition to make a clear distinction from the continuous carrier condition of Sheft and Yost (1990), where the wideband noise carrier was continuously on.

If it is the onset information of the modulator that contributes to the improved AM depth discrimination at fewer than four cycles of modulation, then the expected findings are: (1) the thresholds of the onset-fringe carrier condition will be lower than those of the offset-fringe carrier condition; (2) the thresholds of the onset-fringe and onset/offset-fringe carrier conditions will be similar or the same; (3) the thresholds of the gated carrier and offset-fringe carrier conditions will be similar or the same.

2. Methods

2.1 Subjects

Three normal hearing subjects participated in this study. Their ages ranged from 21 to 41. The subjects were paid for their participation.

2.2 Stimuli

Sinusoidally amplitude modulated noise was used as the stimulus throughout this experiment. The carrier was broadband noise low-pass filtered at 10,000 Hz.

Equation (1) defines the stimuli where A is the amplitude, m is the standard modulation depth, Δm is the change in the modulation depth, f_m is the modulation rate, and θ is the phase of modulation.

$$s(t) = A\{1 + [(m + \Delta m)\cos(2\pi f_m t + \theta)]\}X[\text{noise}], \quad (1)$$

Modulation frequencies of 10, 20, 40, or 80 Hz with a standard modulation depth of 0.1 were used. The phase of modulation was randomly chosen between trials. The onset and offset of all stimuli were shaped by a cosine-squared function resulting in a rise/fall time of 5 ms. The number of cycles for each modulation frequency was as follows: 2, 4, or 8 for 10 Hz; 2, 4, 8, or 16 for 20 Hz; 2, 4, 8, 16, or 32 for 40 Hz; 2, 4, 8, 16, 32, or 64 for 80 Hz. The overall level for each interval was randomized between 65 and 71 dB sound pressure level to ensure that depth discrimination was not based on a change in overall level due to modulation. The Tucker-Davis Technologies (TDT) system 3 was used to generate the stimuli with a 20 kHz sampling rate. Experiments were controlled by SykoFizX software. Four carrier conditions

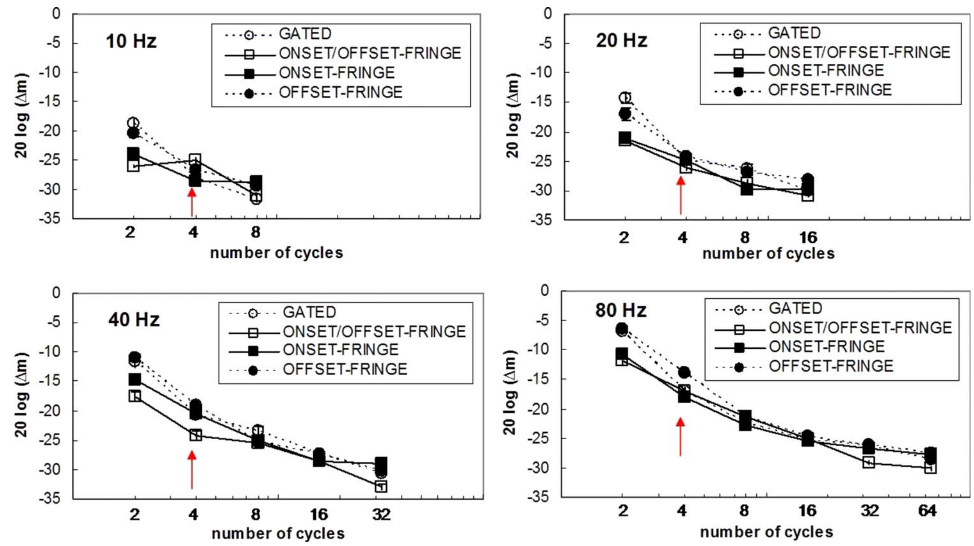

Fig. 1. (Color online) AM depth discrimination thresholds with gated (open circle), onset/offset-fringe carrier (open square), onset-fringe (closed square), and offset-fringe (closed circle) conditions were plotted as a function of the number of modulation cycles for $fm=10$, 20, 40, and 80 Hz. These are the mean thresholds for three subjects. The standard errors are plotted and the size of the standard errors are smaller than the size of symbols.

were compared: Gated (carrier gated on and off with the modulator), onset/offset-fringe (carrier gated on 250 ms before modulator onset and gated off 250 ms after modulator offset), offset-fringe (carrier gated on with the modulator and gated off 250 ms after modulator offset), and onset-fringe (carrier gated on 250 ms before modulator onset and gated off with the modulator).

2.3 Procedure

AM depth discrimination thresholds were determined by a two alternative forced choice paradigm. The psychophysical task was to determine which interval contained the amplitude modulated sound with greater depth of modulation. The "standard" stimulus had a modulation depth of 0.1, and the "signal" stimulus had a modulation depth of $0.1+\Delta m$. The Δm was varied using a 3-down 1-up adaptive procedure (79.4% correct). The step size for the modulation depth change was 2 dB and was reduced to 1 dB after three reversals, and the trials were continued until obtaining seven reversals. The threshold for each run was an average of the final four reversals in the run. For each condition, three threshold estimations were averaged for the final threshold calculation if the standard deviation of the three threshold estimations was smaller than 3 dB. Additional threshold estimations were performed if the standard deviation was equal to or larger than 3 dB until the standard deviation was smaller than 3 dB, but the maximum number of threshold estimations did not exceed five.

Subjects were seated in a sound treated booth and listened to the stimuli through Sennheiser HD 250 linear II earphones. All stimuli were monaurally presented. Subject's responses were obtained with a push button response box with two buttons corresponding to two intervals. Practice trials were given before every run began and lasted until the subjects indicated that they understood the task. Correct answer visual feedback was provided after each response.

3. Results

All data in the figures are the mean of three subjects with standard error. In many cases, the standard error bars are smaller than the symbols. Figure 1 shows AM depth discrimination thresholds as a function of the number of modulation cycles for gated (open circles), onset/offset-fringe carrier (open square), onset-fringe (closed square), and offset-fringe (closed circle) conditions. Each panel represents different modulation rates. For a given modulation rate, a two-way repeated analysis of variance (carrier type *x* number of cycles) indicated the main effect of carrier type is dependent on the number of modulation cycles since there is a significant interaction between the carrier type and the number of cycles ($p < 0.01$) for all modulation rates. Additional multiple comparison analysis (Holm–Sidak method) indicated that thresholds of gated and onset/offset-fringe conditions were not significantly different for four or greater number of cycles for all modulation rates except at 40 Hz for four modulation cycles, but the onset/offset-fringe condition thresholds were significantly better than those of the gated condition for two modulation cycles for all modulation rates ($p < 0.05$). Thresholds tend to increase as the number of modulation cycles decreases ($p < 0.025$) for all modulation rates. This finding is consistent with the results of Lee *et al.* (2006).

Comparison analysis of onset-fringe and offset-fringe conditions indicated that thresholds were not significantly different for four or greater number of cycles for all modulation rates except at 80 Hz for four modulation cycles, but the onset-fringe condition thresholds were significantly better than those of the offset-fringe condition for two modulation cycles for all modulation rates ($p < 0.05$).

Thresholds of offset-fringe and gated conditions were not significantly different for all modulation cycles for all modulation rates except at 20 Hz for two modulation cycles and at 80 Hz for four modulation cycles. Also, thresholds of onset-fringe and onset/offset-fringe conditions were not significantly different for all modulation cycles for all modulation rates except at 40 Hz for two and four modulation cycles.

Overall, at two modulation cycles, thresholds were better for conditions in which modulation information at the onset was well preserved (onset-fringe and onset/offset-fringe carrier) than for conditions in which modulation information at onset was distorted by the gating function (gated carrier and offset-fringe carrier). This supports our hypothesis that the modulation information at onset may contribute to better AM depth discrimination.

4. Discussion

For AM depth discrimination, conditions that included an unmodulated carrier prior to the modulator (onset-fringe and onset/offset-fringe carrier) had lower thresholds at two modulation cycles, resulting in gradual threshold improvement with increasing number of modulation cycles, than other conditions without an unmodulated carrier prior to the modulator (offset-fringe and gated carrier), resulting in an abrupt threshold improvement with increasing modulation cycles from two to four. Similar findings have been reported in studies with AM sounds (Sheft and Yost, 1990; Viemeister, 1979) and with recognition of syllables (Ainsworth and Meyer, 1994)

Sheft and Yost (1990) found that AM detection thresholds were reduced by the addition of 500 ms of carrier prior to the onset of modulation (fringe condition), which is similar to our onset-fringe condition. Their continuous condition (wideband noise carrier continuously on) produced lower thresholds than both gated and fringe conditions. This is different from the data reported here, which showed no significant difference between onset-fringe and onset/offset-fringe carrier conditions. Note, however, that their continuous carrier condition differs from our onset/offset-fringe condition. Our onset/offset-fringe had only 250 ms of noise present before and after the modulation, while their continuous carrier condition had a non-stop continuous carrier throughout the trials.

Viemeister (1979) measured AM detection for a gated and a continuous carrier condition (wideband noise carrier that was continuously on). Thresholds were found to be lower for the continuous carrier condition than for the gated carrier condition at low modulation rates (64 Hz and lower), while thresholds were similar across the two carrier conditions at higher modulation rates. The threshold difference between gated and continuous carrier conditions was larger for shorter stimulus durations. Viemeister speculated that improved thresholds for the continuous carrier condition at lower modulation rates may be due to a slow (100–200 ms) adaptation process occurring in the gated carrier condition. Short-term adaptation might reduce sensitivity to the modulation if the initial neural response to the onset of the stimulus is larger relative to the change in neural response produced by the sinusoidal modulation. This reduced sensitivity effect is larger near carrier onset and will be more apparent for shorter durations; the first cycles of low frequency modulation would be masked.

Ainsworth and Meyer (1994) showed improved recognition of plosive syllables for a condition where noise was presented continuously (subjects were exposed to the noise at least 1 min before the task started), but this improved recognition was not present for a condition where noise was gated with syllables. They suggested that this may be the result of cochlear nerve fiber adaptation to the noise. Adaptation results in an increased dynamic range (increased saturation threshold) of the nerve fiber and could be the cause of improved recognition of syllables in continuous noise conditions (similar to our onset-fringe and onset/offset-fringe carrier conditions).

Therefore, it is possible that the improved AM depth discrimination at the shorter durations (usually corresponding to modulation cycles less than four) for the onset-fringe and onset/offset-fringe carrier condition in our study might be due to auditory nerve fibers' adaptation to the preceding noise. Another possible explanation is that unmodulated noise presented prior to the modulation could help preserve modulation information at the onset since the onset of modulation portion would not be shaped by the rise/fall time.

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