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A Method to Dynamically Control Unwanted Loudness Cues When Measuring Amplitude Modulation Detection in Cochlear Implant Users

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Abstract

Background—Amplitude modulation (AM) detection is a measure of temporal processing that has been correlated with cochlear implant (CI) users' speech understanding. For CI users, AM stimuli have been shown to be louder than steady-state (non-AM) stimuli presented at the same reference current level, suggesting that unwanted loudness cues might contribute to CI users' AM sensitivity as measured in a modulation detection task. In this paper, a new method is introduced to dynamically control unwanted AM loudness cues when adaptively measuring modulation detection thresholds (MDTs) in CI users.

Methods—MDTs were adaptively measured in 9 CI subjects using a three-alternative, forced-choice procedure, with and without dynamic control of unwanted AM loudness cues. To control for AM loudness cues during the MDT task, the level of the steady-state (non-AM) stimuli was increased to match the loudness of the AM stimulus using a non-linear amplitude scaling function, which was obtained by first loudness-balancing non-AM stimuli to AM stimuli at various modulation depths. To further protect against unwanted loudness cues, ±0.75 dB of level roving was also applied to all stimuli during the MDT task.

Results—Absolute MDTs were generally poorer when unwanted AM loudness cues were controlled. However, the effects of modulation frequency and presentation level on modulation sensitivity were fundamentally unchanged by the availability of AM loudness cues.

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Conclusions—The data suggest that the present method controlling for unwanted AM loudness cues might better represent CI users' MDTs, without changing fundamental effects of modulation frequency and presentation level on CI users' modulation sensitivity.

Keywords

cochlear implant; modulation detection; amplitude modulation; stimulation rate; loudness

1. INTRODUCTION

Amplitude modulation (AM) detection is one of the few psychophysical measures shown to predict speech understanding by cochlear implant (CI) users (Cazals et al., 1994; Fu, 2002; Won et al., 2011). For studies with direct stimulation via research interfaces, various stimulation parameters have been shown to affect modulation detection thresholds (MDTs), including stimulation level, modulation frequency, and stimulation rate (Shannon, 1992; Donaldson and Viemeister, 2000: Fu, 2002; Chatterjee and Oba, 2005; Colletti and Shannon, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007; Luo et al., 2008; Garadat et al., 2012). One potential issue with some of these studies is that loudness cues associated with dynamic stimuli were not adequately or consistently controlled. As such, it is difficult to know whether MDTs measured in previous studies were influenced by sensitivity to AM loudness cues or to sensitivity to the temporal envelope (i.e., changes in amplitude over time). Given a fixed reference amplitude, the peak amplitude of an AM stimulus will be higher (and possibly louder) than the peak of a steady-state (non-AM) stimulus. McKay and Henshall (2010) found that CI users perceived AM stimuli to be louder than non-AM stimuli with the same average current level. At equal loudness, mean current levels (across subjects) for non-AM stimuli were found to be between the peak and average current levels of the AM stimuli. Accordingly, the authors argued that it might be necessary to control AM loudness cues when measuring CI users' modulation detection. If AM loudness cues are not adequately controlled, MDTs may reflect listeners' sensitivity to the peak amplitude of the AM signal (similar to an increment detection task), rather than the changes amplitude over time. Recent studies by Chatterjee and Ozerbut (2011), Green et al. (2012), and Fraser and McKay (2012) have attempted to control for these potential loudness cues in various ways, with somewhat inconsistent results.

Chatterjee and Ozerbut (2011) found markedly smaller current level differences between equally-loud AM and non-AM stimuli for modulation depths <16%, compared with McKay and Henshall (2010). The authors also measured MDTs with and without some control of loudness cues. Increasing amounts of level roving applied to all stimuli significantly worsened mean MDTs, but did not change the slope of the temporal modulation transfer function (TMTF). Although a few subjects exhibited sensitivity to loudness cues in AM, most did not. The authors argued that such level roving seemed only to add "noise" to the modulation detection task, but did not fundamentally change the effects of stimulation level and modulation frequency on MDTs.

Fraser and McKay (2012) combined level roving (±0.75 dB, i.e., ±4 clinical units) with level compensation for AM loudness cues; the level roving was added to address potential loudness imbalances (Dai and Micheyl, 2010). Non-AM and AM stimuli (at various modulation depths) were first loudness-balanced at different stimulation rates and levels. Loudness balancing results were similar to those of McKay and Henshall (2010) and Chatterjee and Ozerbut (2011), in that the amount of non-AM level compensation increased with AM modulation depth. Different from McKay and Henshall (2010), Fraser and McKay (2012) found that at equal loudness, non-AM current levels were closer to AM peak levels than to average current levels. The loudness-balanced AM and non-AM stimuli were used for modulation detection using a (non-adaptive) method of constant stimuli. With the level compensation and roving, the effects of modulation frequency and presentation level were similar to those from previous studies that did not control for AM loudness cues (Chatterjee and Oba, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007): MDTs worsened with increasing modulation frequency and decreasing presentation level. In a few conditions and subjects, MDTs also were collected without the level compensation and roving. For these few cases reported, MDTs were better without the level compensation and roving, suggesting that CI users were indeed sensitive to AM loudness cues when detecting AM.

AM loudness cues were not controlled in many previous modulation detection studies (Shannon, 1992; Donaldson and Viemeister, 2000: Fu, 2002; Chatterjee and Oba, 2005; Colletti and Shannon, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007; Luo et al., 2008; Garadat et al., 2012). Other studies seem to offer inconsistent and/or incomplete pictures regarding the effect of AM loudness cues on modulation detection by CI users. Chatterjee and Ozerbut (2011) compared MDTs with and without level roving only. Green et al. (2012) measured MDTs with level roving, but not without. Fraser and McKay (2012) combined level roving and AM loudness compensation, but only compared MDTs without the roving/compensation in a few conditions; also Fraser and McKay used a method of constant stimuli. None had implemented control for AM loudness cues within an adaptive modulation detection procedure, a common method used to measure MDTs in CI listeners. Given that MDTs have been significantly correlated with CI and ABI speech performance (Cazals et al., 1994; Fu, 2002; Colletti and Shannon, 2005), it is important to know how these AM loudness cues might affect CI users’ modulation detection. To provide a more comprehensive picture, in this study, MDTs were adaptively measured with and without a novel method to dynamically control AM loudness cues. During the adaptive MDT task, the level of non-AM stimuli was dynamically adjusted to match the loudness of AM stimuli, followed by global level-roving of all stimuli. Thus, the new adaptive method was different from the method of constant stimuli used by Fraser and McKay (2012), and different from Chatterjee and Ozerbut (2011) and Green et al. (2012) in that AM loudness compensation and level roving were combined within the adaptive modulation detection task. By adjusting the level of the non-AM stimulus to match the loudness of the modulation depth during the adaptive procedure, listeners must primarily attend to the temporal envelope of the AM stimulus.

2. METHODS

2.1 Participants

Nine adult, post-lingually deafened CI users participated in this experiment. All had more than 2 years of experience with their implant device. Relevant subject details are shown in Table 1; subjects S1, S2 and S5 participated in the Galvin and Fu (2009) study. All subjects provided informed consent in accordance with the guidelines of the local Institutional Review Board, and all were financially compensated for their participation.

2.2 Stimuli

All stimuli were 300-ms biphasic pulse trains. The pulse phase duration was 100 μs; the inter-phase gap was 20 μs. The test electrode was generally located in the middle-apical region of the cochlea, similar to Fu (2004). Table 1 lists the test electrodes and stimulation mode for each subject. The stimulation rate was 500 or 2000 pulses per second (pps), spanning the range of rates typically used in clinical processors. The stimulation levels were referenced to 25% or 50% of the dynamic range (DR) of the 500 pps stimulus. The relatively low and high presentation levels were selected because MDTs have been shown to be level-dependent in many previous studies (Donaldson and Viemeister, 2000; Fu, 2002; Chatterjee and Oba, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007). The modulation frequency was 10 Hz or 100 Hz, as MDTs generally worsen with increasing modulation frequency, up to ~300 Hz (Shannon, 1992; Fraser and McKay, 2012; Green et al., 2012).

Sinusoidal AM was applied as a percentage of the carrier pulse train amplitude according to $[f(t)][1+m*\sin(2*\mu *f_m*t)]$, where f(t) is a steady-state pulse train, m is the modulation index, and f_m is the modulation frequency. All stimuli were presented via research interface (Wygonski and Robert, 2001), bypassing CI subjects' clinical speech processors and settings.

2.3 Loudness balancing across stimulation rates

DRs were estimated for the 500 pps and 2000 pps stimuli, presented without modulation (non-AM). Absolute detection thresholds were estimated according to the "counting" method commonly used for clinical fitting. In the counting method, a number of 300-ms pulse trains were presented to the subject. If the subject correctly identified the number of beeps, the current level was reduced. If the subject incorrectly identified the number of beeps, the current level was increased. The initial step size for adjustments was 5 clinical units (CUs) and the final step size was 2 CUs. The current level after six reversals was taken to be the detection threshold. Maximum acceptable loudness (MAL) levels, defined as the "loudest sound that could be tolerated for a short time," were estimated by slowly increasing the current level until reaching MAL. Threshold and MAL levels were averaged across of a minimum of two runs, and the DR was calculated as the difference in current (in microamps) between MAL and threshold.

Stimuli (non-AM) were loudness balanced using an adaptive two-alternative, forced-choice (2AFC), double-staircase procedure (Jesteadt 1980). Reference stimuli were 500 pps, presented at 25% or 50% DR. The current amplitude of the 2000 pps stimulus was adjusted according to subject response (2-down/1-up or 1-down/2-up, depending on the track). During each trial, the subject would hear two intervals, one which contained the 500 pps reference and the other which contained the 2000 pps probe. The subject was asked to pick which interval was louder, ignoring all other sound qualities (e.g., pitch). For each run, the final 8 of 12 reversals in current amplitude were averaged, and the mean of 2–4 runs was considered to be the loudness-balanced level. In almost all cases, 2 runs were averaged to determine the loudness-balanced level. In cases where the loudness-balanced level differed by 1 dB or more (S2: 25% DR; S5: 25% DR, 50% DR; S8: 25% DR, 50% DR), 2 more runs were performed. In this paper, the low and high presentation levels are referred to as the 25 loudness-balanced level (LL) and 50 LL, respectively. Thus, MDTs were measured at equally loud levels across stimulation rates and modulation frequencies.

2.4 Modulation detection

MDTs were measured using an adaptive, 3AFC procedure. The modulation depth was adjusted according to subject response (3-down/1-up), converging on MDT that corresponded to 79.4% correct (Levitt, 1971). One interval (randomly assigned) contained the AM stimulus and the other two intervals contained non-AM stimuli. Subjects were asked to indicate which interval was different (ignoring the difference in loudness). For each run, the final 8 of 12 reversals in AM depth were averaged to obtain the MDT; 3–6 test runs were conducted for each experimental condition.

2.5 Method for dynamically controlling unwanted AM loudness cues

For each stimulation rate, modulation frequency, and presentation level condition, MDTs were measured with and without control for unwanted AM loudness cues. To control for loudness cues within each trial, two current level adjustments were made across stimuli: 1)

Upward adjustment to the level of non-AM stimuli to compensate for the loudness of AM stimuli, and 2) Level roving across all stimuli (to address potential inaccuracies in loudness balancing and to further reduce loudness cues).

To determine how much non-AM level compensation was required for AM loudness, non-AM stimuli were first loudness-balanced to AM stimuli using an adaptive, 2AFC, double-staircase procedure (Jesteadt, 1980), similar to methods used by Chatterjee and Ozerbut (2011) and Fraser and McKay (2012). During loudness-balancing, the AM stimulus served as the reference. To cover the range of stimulation rates, modulation frequencies, and presentation levels to be tested during modulation detection, four AM reference conditions were tested: 1) 500 pps, 10 Hz, 25 LL, 2) 500 pps, 100 Hz, 50 LL, 3) 2000 pps, 100 Hz. 25 LL, and 4) 2000 pps, 10 Hz, 50 LL. Within these four AM reference conditions, AM depths were 5%, 10%, 20%, or 30%. The current amplitude of non-AM stimulus was adjusted according to subject response (2-down/1-up or 1-down/2-up, depending on the track). For each run, the final 8 of 12 reversals in current amplitude were averaged, and the mean of 2–4 runs was considered to be the current level needed to equate the loudness of the non-AM stimulus to that of the AM stimulus. In almost all cases, 2 runs were averaged to determine the loudness-balanced level. In cases where the loudness-balanced level differed by 1 dB or more (S4: 25 LL/10 Hz; S8: 25% DR/10 Hz, 50% DR/100 Hz), 2 more runs were performed.

Exponential fits were applied to the loudness balance data (averaged across conditions). For individual subjects, the amount of level compensation *y* (in dB) was dynamically adjusted during the MDT task according to:

$$y=20 \times \log_{10}\left(\frac{1+m}{1+\alpha m}\right) \quad \text{Eq. (1)}$$

where *m* is the modulation index of the modulated stimulus and α is the exponent (ranging from 0 to 1) of the exponential function fit to each subject's AM vs. non-AM loudness-balance data. Thus, during each trial of the modulation detection task, the level of the non-AM stimulus was upwardly adjusted by *y* dB to match the loudness of the AM stimulus at the target modulation depth according to each subject's loudness-balancing data. After applying this level compensation to the non-AM stimuli, the current level of each stimulus in each trial was independently roved by a random value between − 0.75 and 0.75 dB (±4 clinical units) as in Fraser and McKay (2012). Level roving was applied to all stimuli to further reduce any residual loudness differences between AM and non-AM stimuli that may not have been addressed by the loudness balancing. MDTs were also measured without controlling for loudness cues, as in many previous studies (e.g., Shannon, 1992, Donaldson and Viemeister, 2000; Galvin and Fu, 2005, 2009; Pfingst et al. 2007).

3. RESULTS

3.1 Loudness balancing

At equal loudness, the mean current level difference between 500 pps and 2000 pps non-AM stimuli was 3.29 and 2.73 dB for 25 LL and 50 LL, respectively. Current level differences at equal loudness across rates were quite variable across subjects, ranging from 0.48 dB (S5, 50 LL) to 4.95 dB (S7, 25 LL). A one-way repeated measures analysis of variance (RM ANOVA) showed no significant effect of presentation level (25 LL or 50 LL) on current level differences between equally loud 500 pps and 2000 pps non-AM stimuli [F(1,8)=2.398, p=0.160].

The top panel of Figure 1 shows exponential fits to the non-AM vs. AM loudness balance data for individual subjects. These functions were eventually used to dynamically adjust the level of the non-AM stimuli to match the loudness of the AM stimulus during the modulation detection task. For each subject, the slope of the fits was averaged across the 4 AM reference conditions. The slope (*a*) of the fits (listed in the legend of Fig. 1) was variable across subjects, reflecting differences in sensitivity to AM loudness. Slopes for some subjects (S5 and S9) were close to the peak level of AM, and for others were midway between the reference and peak level of AM (S4 and S9). The data were well fit by the functions, as reflected by the high r^2 values.

3.2 Modulation detection

The bottom panels of Figure 1 show mean MDTs (across subjects) with and without control for AM loudness cues. With the 500 pps stimulation rate, MDTs were consistently poorer when AM loudness cues were controlled. With the 2000 pps stimulation rate, controlling for AM loudness cues had a much smaller effect. A multi-way RM ANOVA showed significant main effects for presentation level [F(1,8)=13.053, p=0.007], modulation frequency [F(1,8)=23.777, p=0.001], and controlling for AM loudness cues[F(1,8)=10.704, p=0.011], but not for stimulation rate [F(1,8)=4.537, p=0.066]. There were significant interactions between modulation frequency and controlling for AM loudness cues [F(1,8)=8.960, p=0.017] and among modulation frequency, stimulation rate, and controlling for AM loudness cues [F(1,8)=10.413, p=0.012].

DISCUSSION

The present method appears to be appropriate for controlling unwanted AM loudness cues when measuring modulation detection by CI users. Different from the simple level roving used by Chatterjee and Ozerbut (2011) and Green et al. (2012) when adaptively measuring MDTs, the present method incorporated an AM loudness adjustment. Different from the method of constant stimuli used by Fraser and McKay, the present method incorporated level roving and AM loudness adjustment within an adaptive procedure, which is most commonly used when measuring MDTs. Controlling for AM loudness cues generally increased absolute MDTs, but did not fundamentally change the effects of modulation frequency and presentation level on modulation sensitivity. With or without controlling for AM loudness cues, MDTs improved as the presentation level increased and as the modulation frequency was reduced, consistent with previous studies (Pfingst et al., 2007; Galvin and Fu, 2009). Controlling for AM loudness cues significantly interacted with the effect of stimulation rate on MDTs, possibly due to small and/or inconsistent differences in MDTs across stimulation rates. This suggests that previous findings (Galvin and Fu, 2005, 2009; Pfingst et al., 2007) regarding the effect of stimulation rate on MDTs might have been influenced by AM loudness cues.

AM stimuli were consistently louder than non-AM stimuli with the same reference amplitude, consistent with previous studies (McKay and Henshall 2010; Chatterjee and Ozerbut 2011; Fraser and McKay 2012). For the present loudness balance data, adjustments to non-AM current levels were closer to the AM peak amplitude than to the AM reference amplitude, consistent with Fraser and McKay (2012), but different from McKay and Henshall (2010), who found non-AM current levels closer to average than to peak current levels of equally loud AM stimuli. This difference might be due to the lower presentation levels and lower modulation frequencies used in the present study than in McKay and Henshall (2010).

There was a wide variability in subjects’ perception of AM loudness, as reflected by the different AM loudness fits in Figure 1. Peak level differences between equally loud non-AM and AM stimuli were as large as −1.57 dB (i.e., nearly 16 clinical units less than the peak AM level), but mostly were close to the peak AM level. Differences across subjects' AM loudness judgments might reflect individual differences in loudness integration. As such, loudness balancing might be necessary for tasks in which loudness cues could influence perception, such as modulation detection and pulse rate discrimination. In such cases, simple level roving (as is sometimes done) might not be adequate because given a fixed reference level and any amount of level roving, AM stimuli would remain louder than non-AM stimuli, on average. Too much level roving might simply make the task too difficult, as suggested by Chatterjee and Ozerbut (2011). By first compensating for the loudness of the AM stimuli, and then roving by a relatively small amount, MDTs may be measured without consistent loudness cues that could influence modulation detection. Whether elevated MDTs were due to controlling loudness cues or due to introducing greater uncertainty in level roving is not possible to know given the present study. Further studies may wish control for loudness cues or rove the level independently to isolate their effects on MDTs. It is likely that the present elevated MDTs at small modulation depths may have been more due to the level roving, as the AM loudness cues at those depths would have been quite small. It may also be preferable in future studies to rove only the level of the non-AM intervals, as MDTs have been shown to be very level dependent (Donaldson and Viemeister, 2000: Chatterjee and Oba, 2005; Colletti Galvin and Fu, 2005, 2009; Pfingst et al., 2007). In the present study, the level of the AM signal was roved from trial to trial, which may have resulted in unwanted changes in modulation sensitivity during the test run.

In summary, this study presented a novel method to dynamically adjust the level of non-AM stimuli to compensate for unwanted AM loudness cues during an adaptive modulation detection task. On average, controlling for AM loudness cues significantly worsened absolute modulation sensitivity, but did not fundamentally change the effects of modulation frequency and presentation level on MDTs. Thus, findings from many previous CI modulation studies (Shannon, 1992; Donaldson and Viemeister, 2000: Fu, 2002; Chatterjee and Oba, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007) would remain fundamentally true, albeit with possibly elevated absolute MDTs. Different from previous studies (Galvin and Fu, 2005, 2009; Pfingst et al., 2007), there was no significant difference in MDTs between the 500 pps and 2000 pps stimulation rates when AM loudness cues were controlled. The present data suggest that controlling for AM loudness cues might better represent CI users' limits to temporal processing, as measured with an adaptive modulation detection task.

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Abbreviations

CI	cochlear implant
MDT	modulation detection threshold
DR	dynamic range
PPS	pulses per second
MAL	maximum acceptable loudness

AM	amplitude modulated
LL	loudness-balanced level
RM ANOVA	repeated measures analysis of variance

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- Unwanted loudness cues may contribute to cochlear implant (CI) users' modulation detection thresholds (MDTs).
- A method to control for amplitude-modulated (AM) loudness cues was used in an adaptive modulation detection task.
- The level of non-AM stimuli was adjusted to match the loudness of AM stimuli, followed by roving the level of all stimuli.
- Absolute MDTs were poorer after controlling for AM loudness cues.
- Effects of presentation level and modulation rate were unchanged by the new method, with an interaction with carrier rate.

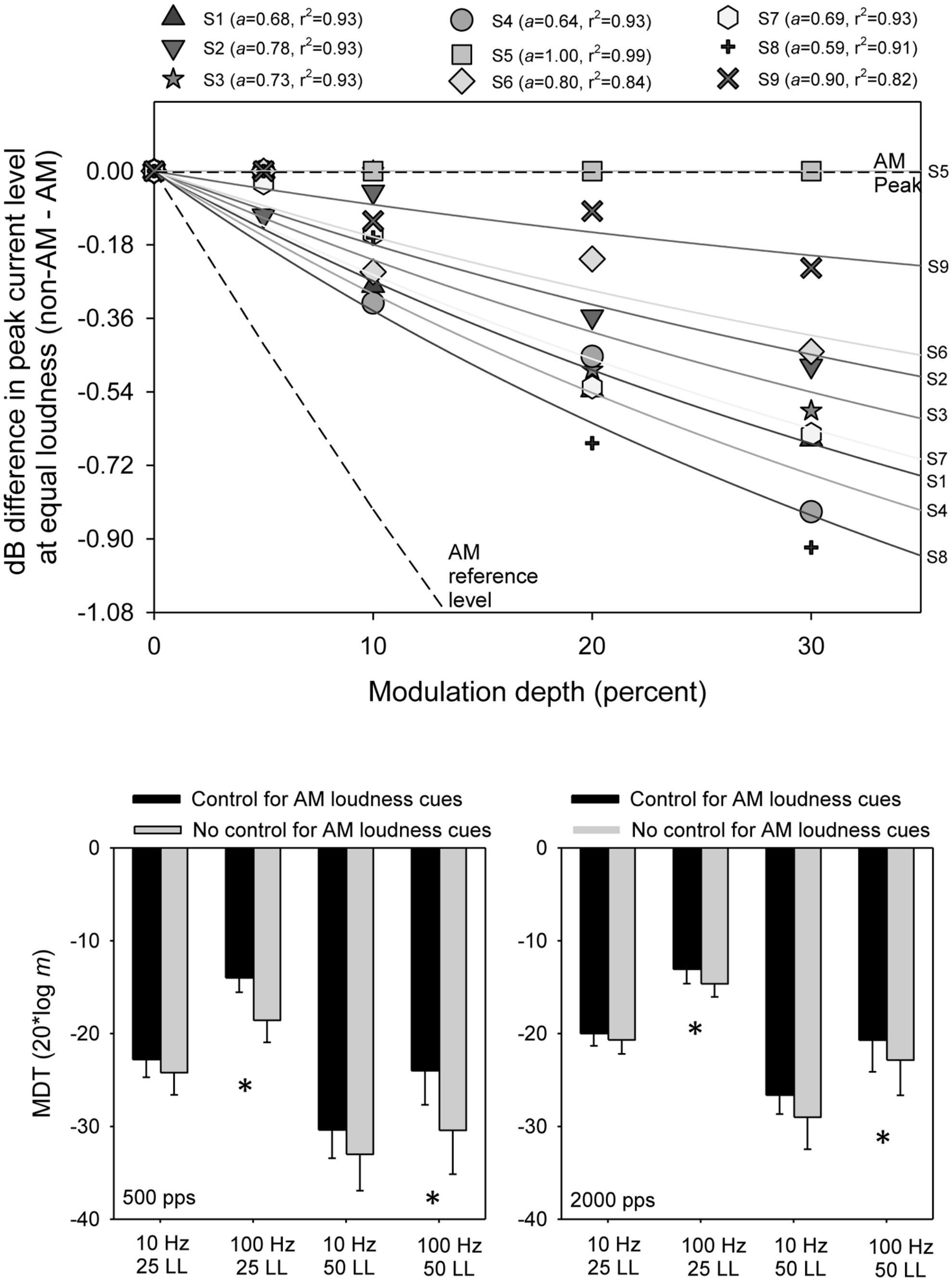

Fig. 1.

Top panel: Non-linear fits to loudness-balance data between AM and non-AM stimuli, as a function of modulation depth. Data were fit according to Eq. 1 (see Methods). The slope (*a*) and goodness of fit (r^2) for the functions are listed next to individual subject symbols in the legend. The top dashed line shows the difference between AM and non-AM loudness in terms of average current level and the bottom dashed line shows the difference in terms of peak level. Each y-axis tic is equivalent to 1 clinical unit in the Nucleus CI device. Bottom left panel: Mean MDTs (across subjects) with the 500 pps stimulation rate, as a function of modulation frequency and stimulation level conditions. The black and gray bars show data with and without control for unwanted AM loudness cues, respectively. The asterisks show significant differences (paired t-tests, $p<0.05$). The error bars show the standard error. Bottom right panel: Same as bottom left panel, but for the 2000 pps stimulation rate.

Table 1

CI subject demographic information.

Subject	Gender	Age at Testing (yrs)	CI experience (yrs)	Duration of deafness (yrs)	Device	Electrode (Mode)
S1	F	77	10	12	N-24	17 (MP1+2)
S2	F	67	7	20	N-24	14 (MP1+2)
S3	M	81	15	1	N-22	14 (BP+1)
S4	F	78	23	14	Freedom	15 (MP1+2)
S5	M	70	21	4	N-22	14 (BP+1)
S6	F	58	17	20	N-22	15 (BP+1)
S7	F	28	5	5	Freedom	14 (MP1+2)
S8	F	66	7	24	Freedom	14 (MP1+2)
S9	M	74	3	2	Freedom	14 (MP1+2)