Modulation detection interference in cochlear implant listeners under forward masking conditions

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Little is known about cochlear implant (CI) users' ability to process amplitude modulation (AM) under conditions of forward masking (forward-modulation detection/discrimination interference, or F-MDI). In this study, F-MDI was investigated in adult CI listeners using direct electrical stimulation via research interface. The target was sinusoidally amplitude modulated at 50 Hz, and presented to a fixed electrode in the middle of the array. The forward masker was either amplitude modulated at the same rate (AM) or unmodulated and presented at the peak amplitude of its AM counterpart (steady-state peak, SSP). Results showed that the AM masker produced higher modulation thresholds in the target than the SSP masker. The difference (F-MDI) was estimated to be 4.6 dB on average, and did not change with masker-target delays up to 100 ms or with masker-target spatial electrode distances up to eight electrodes. Results with a coherent remote cue presented with the masker showed that confusion effects did not play a role in the observed F-MDI. Traditional recovery from forward masking using the same maskers and a 20-ms probe, measured in four of the subjects, confirmed the expected result: higher thresholds with the SSP masker than the AM masker. Collectively, the results indicate that significant F-MDI occurs in CI users.

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I. INTRODUCTION

The terms “modulation masking” and “modulation detection/discrimination interference” (MDI) refer to an elevation in amplitude-modulation detection/discrimination thresholds in the presence of competing modulations, phenomena which have been shown to play an important role in speech recognition in noisy backgrounds (Stone *et al.*, 2012; Dau *et al.*, 1997; Yost and Sheft, 1994). When the interference occurs between masker and target in the same frequency channel, it is referred to as modulation masking, and when the masker and target excite different frequency channels, the interference is referred to as MDI. In cochlear implants (CIs), it is often difficult to separate within- from across-channel interference. Here, we use the term “MDI” collectively to mean both within- and across-channel sources of temporal envelope interactions. MDI is thought to arise at brainstem or higher levels of processing, and the within-channel component has been successfully modeled by the action of a bank of modulation-tuned filters on the cochlear output (Dau *et al.*, 1997). While the majority of experiments on MDI in normal hearing listeners have been conducted using simultaneous masking paradigms, there is also some evidence for such interference persisting after the masker has been turned off [henceforth referred to as “forward modulation detection/discrimination interference (MDI)” or “F-MDI” (Wojtczak and Viemeister, 2005; Wojtczak *et al.*, 2011)]. In listeners with CIs, temporal envelope cues are particularly important for speech recognition, and interference

with these cues is likely to have significant impact on their hearing, particularly on speech recognition, which requires the listener to hear and process sound elements arriving at the ear in rapid succession. MDI has been shown in CI listeners for both amplitude modulation (AM) detection and rate discrimination (Richardson *et al.*, 1998; Chatterjee, 2003; Chatterjee and Oba, 2004; Kreft *et al.*, 2013) in simultaneous masking paradigms, but whether F-MDI occurs in CI users or not remains unknown. In this study, we measured F-MDI effects in CI listeners using direct electrical stimulation. The masker had a syllabic duration and was either sinusoidally amplitude modulated at 50 Hz (AM) or unmodulated and fixed at the peak amplitude of its modulated counterpart (steady-state peak, SSP). Consistent with our previous studies, we measured F-MDI as the difference in amplitude modulation detection thresholds (AMDTs) with the AM and the SSP maskers. This provides a conservative estimate of MDI, as the SSP masker has more energy than the AM masker. Thus, any measure of interference by the AM masker that exceeds the interference by the SSP masker can be thought to be largely due to non-energetic masking effects. To retain relevance to speech syllabic features, the target was also 300 ms long and presented at different delays after masker offset. Masker-target electrode distance was a factor of interest. We considered the possibility that confusion effects (e.g., Neff, 1985) might contribute to our estimate of MDI at early masker-target delays: thus, when the masker and target were perceptually similar, the listener might be unable to tell the difference between the AM masker and the target in the “signal” interval, elevating AM thresholds with the AM masker. Similarly, the listener might

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be unable to discriminate between the SSP masker and the target in the “no-signal” interval, lowering AM thresholds with the SSP masker. As a result, MDI might spuriously be increased in these circumstances. Generally, confusion effects are not expected for target stimuli as long as those used here. We hypothesized that if such effects did occur, we should see larger amounts of MDI when the masker-target delay was shortest, and when masker and target were presented on the same electrode. If confusion effects occurred, we hypothesized they would dominate during the early portion of the target, thus, effectively changing the number of glimpses of the target available to the listener. In addition, we also included a condition in which a remote, coherent-AM “cue” was presented concurrently with the on-channel masker, but not with the target, to help the listener to perceptually separate out the target from the masker. We hypothesized that the “cue” might capture the AM masker in an auditory grouping type of phenomenon. On the other hand, if the additional “cue” simply increased the amount of peripheral excitation (and added to the masker loudness), the masking would likely increase for both modulated and unmodulated targets, and no further relative difference would be observed. To limit the influence of loudness cues in target AM detection, its carrier level was randomly roved from interval to interval.

Finally, traditional recovery from forward masking was measured using the same maskers in a subset of the subjects. The purpose of this experiment was to perform a “sanity check” to make sure that forward-masked detection thresholds for a brief probe presented at the same delays were higher for the SSP masker than for the AM masker (as would be predicted if energetic masking dominated the recovery process). If F-MDI was observed, it was important to exclude the possibility that the salience of the target was somehow reduced by the preceding AM masker more than by the preceding SSP masker, which might in turn reduce AM sensitivity in the target following an AM forward masker more than a SSP forward masker.

II. METHODS

A. Participants

Ten Cochlear Corporation (Sydney, Australia) device users (11 ears) participated in this study. All participants were

adults. Table I includes relevant information about the participants. Bilaterally implanted subjects were tested on the earliest implanted side. Subject N5 was tested with both sides. In her case, data were first collected with the earlier implanted ear (right ear). Data collection was completed over the period of one year; a record of thresholds and maximum acceptable loudness (MAL) was maintained during that time. We did not find changes in sensitivity over the period of the project. Table I denotes age at initial testing. Four of these participants also completed the traditional forward masking task, which involved the detection of a brief probe on the target electrode presented at various delays following the presentation of a forward masker.

B. Stimuli

Stimuli were trains of charge-balanced, biphasic current pulses presented at 500 pulses/s and either sinusoidally amplitude modulated at 50 Hz or unmodulated. The pulse phase duration was 100 μ s/phase and the interphase gap was 40 μ s for each pulse. Stimulation was fixed in monopolar mode. Stimuli were generated and presented to the listeners using a custom research interface HEINRI (the House Ear Institute Nucleus Research Interface; Shannon *et al.*, 1990; Robert, 2002) via direct stimulation. In these CochlearTM devices, electrodes are numbered 1–22 from base to apex.

1. Maskers

Maskers were presented on electrodes (Els) 2, 6, 10, 14, and 18 (18 is the most apical). Masker carrier stimuli were loudness-balanced to the one on El 10 at 40% dynamic range (DR) level. This loudness-balanced level is referred to as the reference level.

Two main masker types were studied for this experiment: (1) A sinusoidally AM masker with AM rate fixed at 50 Hz, with the carrier at the reference level. (2) An unmodulated masker with an amplitude corresponding to the peak amplitude of the modulated masker (SSP). Masker Els that were modulated had AM depths fixed at 30% above unmasked 50-Hz AMDT levels. The two masker types are schematically shown in the top left-hand corner of Fig. 1.

TABLE I. Pertinent information about the participants. “*” denotes bilaterally implanted, “***” denotes bilaterally implanted with different manufacturer’s device implanted in the opposite ear, “R.E.” denotes right ear, and “L.E.” denotes left ear.

Subject	Onset of deafness	Stimulation mode	Ear	Device	Gender	Age at implantation (years)	Age at initial testing (years)
N3*	Prelingual	MP1	R.E.	CI24R (CA)	M	18	26
N4	Early/prelingual	MP1	L.E.	CI24R(CS)	F	41	51
N5_R.E.	Postlingual	MP1	R.E.	CI512	F	50	53
N5_L.E.	Postlingual	MP1	L.E.	CI422	F	54	56
N7	Postlingual	MP1	R.E.	CI24R(CS)	F	51	60
N11*	Early/prelingual	MP1	R.E.	CI24R(CA)	M	42	51
N14	Postlingual	MP1	R.E.	CI24RE(CA)	F	60	68
N15	Postlingual	MP1	L.E.	CI422	M	59	62
N17	Postlingual	MP1	R.E.	CI422	F	72	74
N19**	Postlingual	MP1	R.E.	CI24R(CS)	M	49	65
N20	Postlingual	MP1	R.E.	CI512	F	70	73

2. Target

EI 10 was selected as the target electrode. The target was also 300 ms long and otherwise identical to the sinusoidally amplitude modulated masker on EI 10, with the exception that the AM depth of the target was adaptively varied until AMDT for the target was reached. The delay from masker offset to target onset varied from 2 to 100 ms (2, 4, 10, 20, 50, and 100 ms) in four of the ten cases (N3, N5_RE, N7, and N11). In the remaining cases (N4, N5_LE, N14, N15, N17, N19, and N20) only three delays were tested (2, 10, and 50 ms). The masker and the target are schematically shown in the top left-hand corner of Fig. 1.

3. Remote cues

The effects of a remote (off-channel) “cue” were also investigated by introducing a second pulse train on a distant electrode concurrently with the masker on EI 10. The cue electrode was either EI 2 or EI 18 at the same level as above, coherently amplitude modulated (or SSP) with the masker. Six of the ten subjects (N4, N5, N3, N7, N11, and N14) participated in this experiment.

4. Recovery from forward masking

To measure recovery from forward masking, brief probes were presented on EI 10 following the same maskers on EI 10 (AM or SSP). In this case the target stimuli were 20-ms-long trains of unmodulated pulses, otherwise identical to the maskers. Subjects N5, N11, N15, and N19 participated in this experiment.

C. Procedure

1. Threshold and DR measurements

Detection threshold was measured using a two-down, one-up, two-interval, two-alternative, forced-choice (2I-2AFC) adaptive procedure. To obtain the maximum acceptable level (MAL), the subject increased the current level of the stimulus in incremental steps until the loudness reached a highest tolerable level. There were several repetitions for these procedures and the means were calculated to obtain the final threshold and MAL. The DR was calculated as the difference in μA between the two.

2. Loudness balancing

The 40% DR level was calculated for EI 10. Stimuli on EI 2, EI 6, EI 14, and EI 18 were then loudness balanced to EI 10 at that level. An adaptive procedure in a 2I-2AFC, double staircase paradigm was used for loudness balancing the experimental electrodes to the reference electrode (Jesteadt, 1980). In each trial, the two signals were presented to the listener in random order, and the listener indicated which sounded louder. The listener was instructed to ignore the pitch or any other quality differences and to concentrate on the loudness. The descending (two-down, one-up) and ascending (two-up, one-down) staircases were interleaved with trials presented randomly from each. The means of the last four reversal points obtained for the descending and

ascending tracks were averaged at the end of the run. At least two repetitions were conducted for each condition. The final loudness-balanced level was calculated from the mean of all repetitions.

3. Unmasked AMDTs on the masker EIs

Unmasked AMDT was measured for each masker EI in a three-interval, three-alternative forced choice (3I-3AFC) adaptive procedure with a two-down, one-up staircase. The adapted variable was AM depth. The carrier signal was at the reference level (i.e., loudness balanced to the EI 10 reference at the 40% DR level). Of the three intervals, two contained the unmodulated carrier and the third (randomly) contained the modulated carrier. The listener indicated which of the three intervals contained the modulated signal. The adaptive track was required to have a minimum of 8 reversals and a maximum of 10 reversals within 55 trials (i.e., the track was aborted if 8 reversals were not achieved within 55 trials, and the track was stopped if 10 reversals were achieved at less than 55 trials). The initial four reversals were discarded and the mean of the last four to six reversals was calculated to obtain the AMDT. At least two repetitions were conducted for each electrode. The final modulation detection threshold was calculated as the mean of all repetitions of each condition.

4. Masker AM depths and SSP masker levels

After obtaining the unmasked AMDTs for each electrode, the masker modulation detection depth was increased by 30% above the AMDT to ensure that the masker modulation was sufficiently salient. The SSP masker stimulus was an unmodulated stimulus with an amplitude corresponding to the peak amplitude of the corresponding AM masker. Precaution was taken to make sure that this higher current level remained below the MAL level.

5. Masked and unmasked AMDTs on the target electrode

Masked AMDTs on the target electrode were measured using a 2I-2AFC adaptive procedure; the adaptive track had a minimum of 8 reversals and a maximum of 10 reversals within 55 trials. The masker and target carrier were present in both intervals, but the target was amplitude modulated in only one of the intervals (random order). The listener's task was to identify the interval that contained the modulated target. “Yes” or “no” feedback was provided for the correct or incorrect responses, respectively. In the adaptive track, the step size (AM depth in %) was halved after the first four reversals. These initial first four reversals were discarded and the mean of the remaining reversals was calculated to obtain the final target AMDT. AMDTs were obtained at masker-target intervals ranging from 2 to 100 ms. For four of the subjects (N3, N5, N7, and N11) the delays were 2, 4, 10, 20, 50, and 100 ms. For the remaining five subjects/six ears (N4, N5_LE, N14, N17, N19) the set of delays was reduced to 2, 10, and 50 ms because of time constraints. To avoid the use of loudness or intensity cues in the task, a level rove

FIG. 1. (Color online) The top left-hand panel shows schematics of the masker and target stimuli in the signal and no-signal interval, and for the AM and SSP masker. ΔT indicates the delay between masker and target. The remaining panels show results obtained in each subject as AMDTs in dB plotted against masker-target delay (ms) for each masker EI (left to right, electrodes 2–18). The target was always presented on electrode 10. Within each panel, AMDTs obtained with the AM masker are shown in circles and solid lines, and AMDTs obtained with the SSP masker are shown in triangles and intermittent lines. The dotted horizontal line indicates the unmasked AMDTs obtained on the target (electrode 10). The ordinate spans a 30 dB range in each plot.

(typically ± 0.63 dB, corresponding to nine clinical units) was applied to the target carrier level (EI 10). The set of conditions (two types of maskers, AM or SSP, presented on one of the five electrodes, and the three to five masker-target delays) were presented in fully randomized order. At least two repetitions were conducted for each condition. The final AMDT was calculated from the mean of all repetitions.

Unmasked AMDTs were also obtained on the target using the same procedure, with the exception that the masker was absent in both intervals. In subjects N7 and N11, unmasked target AMDTs were measured six and two months, respectively, after the masked AMDTs were completed, owing to time constraints in their schedules. The unmasked AMDTs served only as a reference, and were not used in analyses.

6. Recovery from forward masking

Recovery from forward masking was measured in four of the ten subjects (N5, N11, N15, and N19) using the same SSP and AM maskers described above. Measurements were made only in the on-channel condition in which the masker and the probe were both presented on EI 10. Probe detection thresholds were measured using a 2I-2AFC adaptive procedure in the unmasked and the two masking (AM, SSP) conditions. Probe delays were identical to masker-target delays above (2–100 ms). Here as well, different masker-probe conditions and the different delays were presented randomly. The adaptive track was defined similarly to those described for AMDT measurement. The step size in the adaptive track (in dB units) was halved after the first four reversals. The initial four reversals were discarded and the means of the last four to six were calculated to obtain the final detection threshold. At least two repetitions were conducted for each electrode. The final threshold was calculated from the mean of all repetitions.

D. Statistical analyses

Statistical analyses were conducted in R v. 3.1 (R Core Team, 2014) using the *lme4* package (Bates et al., 2014) to conduct the linear mixed effects (LMEs) analyses, along with *lmerTest* (Kuznetsova et al., 2015) and *ggplot2* (Wickham, 2009) to plot the results. Outliers were defined as data that fell above the upper fence (third quartile + 1.5 * interquartile range) or below the lower fence (first quartile – 1.5 * interquartile range).

III. RESULTS

A. AMDTs with modulated and SSP maskers

First, the data were analyzed, including all data, i.e., including subjects who completed the tasks with the full set of six delays and those who completed the tasks with only the reduced set of delays. Figure 1 shows AMDTs [expressed in dB ($20 \log m$, where m is the threshold modulation index)] obtained in each subject (shown in individual panels), for each masker EI (columns within panels) and for the two types of maskers (AM, circles and SSP, triangles). The target was always presented on EI 10. The dashed horizontal line in each panel shows the mean unmasked AMDT for the target

electrode. Note that in subject N3, the mean unmasked AMDTs were consistently higher than the masked AMDTs. It is unclear why this was the case. We speculate that the presence of the forward maskers (AM or SSP) primed the listeners in some way and altered the nature of the task for this subject. The unmasked AMDTs were not used in analyses.

Figure 2 shows boxplots based on the same data as in Fig. 1, with data pooled across subjects and plotted for each electrode and each delay. The six columns show data obtained at each of the six masker-target delays. The five rows show data obtained with the masker at each of the five locations (recall the target was always at the central location in Fig. 2, EI 10). A LME model with fixed effects of masker type (masker), electrode (electrode), masker-target delay (delay), and random subject-based intercepts and slopes was used to fit the data. Results showed significant effects of masker [$t(431.3) = -10.997$, $p < 0.0001$] but no effects of delay or electrode and no significant interactions. However, a marginal interaction between masker type and delay was observed [$t(431.3) = 1.89$, $p = 0.06$]. Visual inspection of the model residuals suggested no violations of normality around a mean of zero. The predicted values were plotted against the observed data, and linear regression analysis showed an adjusted R squared value of 0.88 ($p < 0.00001$), suggesting a good correspondence between the LME model predictions and the data.

B. Forward MDI

Figure 3 shows boxplots of the MDI (dB difference between AMDTs obtained with AM and SSP maskers) plotted against masker EI (within each panel) and for each of the six masker-target delays (across panels). A number of possible outliers are visible in Fig. 3. After outlier analysis, a total of ten outliers (4.44% of the data, comprising points falling above 16 dB and those falling below –8 dB) were excluded from analyses. A LME model analysis of the MDI with fixed effects of masker EI and delay and subject-based random intercepts and slopes showed no significant effects of either masker EI or delay. The intercept is of interest, as it indicates the overall MDI across subjects estimated by the model. A significant intercept of 4.46 dB [$t(11.22) = 4.22$, $p = 0.0014$] was found. These results confirm the previous finding that there was no significant interaction between masker type and the other variables, and also that the effect of masker type is significant, i.e., the MDI has a positive, nonzero value. Consistent with the previous analysis, a marginal effect of masker-target delay was observed in these analyses, with MDI decreasing with increasing delay [$t(34.98) = -1.78$, $p = 0.08$].

C. Effects of the remote cue on F-MDI

Figure 4 shows boxplots of AMDTs obtained with AM and SSP maskers on EI 10, pooled across delays and subjects, for the two different locations of the remote cue (EIs 2 and 18), and for the corresponding condition without any cues present. Visual inspection of the data indicates that, as expected, the presence of the remote cue reduced AMDTs with the AM masker but not the SSP masker, suggesting a

FIG. 2. (Color online) Boxplots of the same data in Fig. 1, showing AMDTs in dB obtained in all subjects for the two masker types, each masker-target delay (columns), and each masker EI (rows).

grouping effect due to coherent AM on the masker and the remote cue. Initial analyses showed no significant differences in the AMDT data based on the electrode location of the remote cue (EI 18 or EI 2). Therefore, data from both

locations of the remote cues were pooled, and the effect of cue presence/absence was tested in a LME analysis. Outlier analyses showed no outliers in the dataset. Fixed effects in the LME were masker, electrode, delay, and cue

FIG. 3. (Color online) Boxplots of MDI (dB) obtained in all subjects, plotted against masker EI and for each masker-target delay (columns).

FIG. 4. (Color online) Boxplots of AMDTs (dB) obtained in all subjects, for each masker type, masker-target delay (rows), and the different cue conditions (columns).

(present or absent). The model was found to be significantly improved when subject-based random slopes of the effect of the cue were included with subject-based random intercepts. Consistent with F-MDI observed previously, results showed a significant effect of masker [$t(180.2) = -2.219$, $p = 0.028$]. A marginal effect of delay [$t(180.4)$, $p = 0.054$] and a significant interaction between masker and cue [$t(180.2) = 2.665$, $p = 0.008$] were also observed. Figure 5 shows the F-MDI (dB difference between AM and SSP maskers) obtained with and without the remote cues plotted against the different delays. Data were analyzed after the exclusion of outliers. LME analysis with delay and cue (present or absent) as fixed effects, and including subject-based random intercepts and slopes varying with both delay and cue, showed significant effects of cue [$t(9.88) = -3.855$, $p = 0.003$], but no effect of delay and no interactions.

D. Analyses with reduced set of masker-target delays

The analyses above were conducted with the full set of data, in which some subjects provided data in all six delay conditions, but others were only able to complete the tasks with three delays. We next repeated the analyses only including the data from subjects who completed all six delays (N3, N5, N7, N11). LME analysis with the same model [fixed effects were masker type (AM or SSP), masker EI, and delay, and subject-based intercepts and slopes were included on

delay and electrode]. Results confirmed a significant effect of masker type [i.e., AM maskers produced higher thresholds than SSP maskers; $t(232.01) = -4.91$, $p < 0.0001$], no other effects, and no interactions. Next, the same analysis was repeated for a dataset including all subjects (11 ears), but only considering the 3 delays that we had data for in all cases (2, 10, and 50 ms). Again, LME analysis with fixed effects of masker type, electrode, and delay with the same random intercepts and slopes showed a significant effect of masker type [$t(308) = -11.405$, $p < 0.0001$], but no effects of electrode or delay and no interactions. These results confirm the basic findings obtained with the full data set.

E. Recovery from forward masking

Figure 6 shows recovery functions for the four subjects. Detection thresholds for the probe (in microamps) in the presence of the AM and SSP maskers are plotted against the masker-probe delay, and the unmasked threshold is indicated by the dashed line in each panel. As the primary purpose of this portion of the study was to ensure that recovery from forward masking demonstrates greater masking with the more energetic (SSP) masker than with the AM masker, a LME analysis was conducted on the threshold with masker type (AM or SSP) as the fixed effect and subject-based random intercepts.

FIG. 5. (Color online) Boxplots of MDI (dB) obtained in all subjects, plotted against masker-target delay and for the cue-absent and -present conditions. Data obtained with the two cue-electrode locations were pooled together for the cue-present condition.

Results showed a significant effect of masker type [$t(43) = -4.35, p < 0.001$], confirming the visual observation that the thresholds obtained with the SSP maskers generally fell above the thresholds obtained with the AM maskers.

F. AMDTs with short targets

The effects of confusion might be more evident with shorter target stimuli than the ones used in this study. With short target stimuli, the confusion effect might result in

elevated AMDTs at short delays. In a limited study, we repeated the measurements with 40-ms-long target stimuli and identical maskers. Four of the subjects (N4, N5, N7, and N11) participated. Owing to time constraints, forward-masked AMDTs with the shorter target were only obtained with the AM masker (and not the SSP masker) with subject N7. The results are shown in Fig. 7. Subject N11 showed no MDI and only evidence for energetic masking, as with the 300-ms-long targets (Fig. 1). The other three subjects showed elevated AMDTs (relative to the longer targets)

FIG. 6. (Color online) Detection thresholds for the probe (microamperes) plotted against masker-probe delay (ms) for each of the four subjects (left to right panels) and for the two masker types (AM and SSP maskers). The dashed line shows the unmasked detection threshold for the probe in each case.

FIG. 7. (Color online) AMDTs obtained in four of the subjects with the shorter, 40-ms-long target stimuli (smaller symbols, solid lines) following the AM (circles) or SSP (triangles), and compared against AMDTs obtained in the same subjects with the 300-ms-long target stimuli (larger symbols, replotted from Fig. 1). As in Fig. 1, the ordinate spans a 30-dB range in each plot.

overall with both AM and SSP maskers as expected for shorter target durations, but no obvious differences in the pattern of results from those obtained with the longer target durations. Only subject N11 showed the elevated AMDTs at short delays expected from confusion effects. These limited data provide further support for the idea that confusion effects were not a factor in this study.

IV. DISCUSSION

A. Summary of findings

The results of this set of experiments show that F-MDI occurs in listeners with CIs. The intersubject variability and range of F-MDI observed here is comparable to previous findings with concurrent maskers and targets (Chatterjee, 2003; Chatterjee and Oba, 2004). No effects of masker-target electrode distance were observed, and nor was the effect of masker-target delay significant. Given the relatively long duration of the target (300 ms), the fact that MDI persists for as long as 100 ms after the masker is notable. In addition, we presented evidence that recovery from forward masking followed the expected course, with higher probe detection thresholds observed with the SSP masker than with the AM masker. In contrast, the F-MDI data showed the opposite effect, with the AM masker producing higher thresholds than the higher-energy SSP masker. A beneficial effect of a masker-grouping cue was observed, suggesting that CI users are able to group and segregate signals with different spectral patterns, at least when they are sequentially presented. This is consistent with recent work suggesting that stream segregation can occur in CI users based on place cues (Tejani *et al.*, 2017). A limited additional study of MDI with four of the subjects using short target stimuli indicated that confusion effects did not contribute to the observed MDI.

B. Mechanisms

Wojtczak and Viemeister (2005) reported on AM detection under forward-masked conditions in normally hearing (NH) listeners using a 50-ms target modulation at 40 Hz and a 150-ms-long masker modulation at the same or different rates, both imposed upon a broadband noise carrier, with different delays between the target and the masker modulations. They found elevated AMDTs for the target modulation in the presence of the masker modulation that decayed with increasing target delay, but remained at an elevated level of 1–2 dB even at very long target delays. The introduction of a cue that was coherently modulated with the masker and either presented ipsilaterally or contralaterally did not improve thresholds except at the shortest target delay. They also showed modulation tuning effects consistent with expectations based on the modulation filterbank hypothesis. In a more recent, related study using similar stimuli, Wojtczak *et al.* (2011) found that inferior colliculus (IC) neurons in the awake rabbit showed systematic increases in the contrast in response to the target as the masker-target delay increased in a way that paralleled findings in human listeners. A key point made by Wojtczak *et al.* (2011) was that IC neurons' responses were quite different in the case of forward masking in modulation domain vs forward masking of unmodulated sounds, suggesting that fundamentally different mechanisms were at play.

The findings of the present study differ from those of Wojtczak and Viemeister (2005) in two ways: First, our results did not show a significant dependence on masker-target delay, and second, our results showed a strong effect of the cue, effectively abolishing the interference due to the AM masker. Various factors that might account for these discrepancies include the obvious differences in subject population, experimental design, and stimuli. In the present study, the longer duration of the target might have contributed to the difference in the results: Any greater forward masking of the target AM at short delays might have been more dominant in the initial

portion of the 300-ms-long target only, allowing subjects to perform the task by attending to the more-salient latter portion of the target. Our results with the shorter target stimuli, albeit limited, indicate otherwise. It is more difficult to account for the discrepancy between the findings of Wojtczak and Viemeister (2005) and the present study in the effect of the cue. One possible explanation is that the duration of the masker in the present study was twice that in their study. If grouping effects take longer to be established in the context of these experiments, then it may be that stronger perceptual grouping between the masker and the cue occurred in the present study. However, this is merely speculative at this stage. Another difference is that the modulation depth of the masker used in the present study was less than 100%, primarily to ensure that the net loudness of the stimuli remained acceptable to the participants. However, it remains unclear how exactly these stimulus differences would account for the divergent findings, and further investigation is clearly warranted.

The AM masker in the present study had lower amplitude than the SSP masker at all points except at the peaks of the AM cycles. The higher target AMDTs obtained with the AM masker than with the SSP masker therefore cannot be accounted for by energetic masking. In previous studies of MDI, we used concurrent maskers and targets (Chatterjee, 2003; Chatterjee and Oba, 2004). With concurrent stimuli, it is more difficult to separate out the effects of peripheral interactions from more central mechanisms. In the present study, the use of forward maskers helped eliminate most of the sources of masker-target interactions that might occur at a peripheral level, retaining only the reduced salience of the target as a result of energetic forward masking. Thus, this measure of MDI is one step “cleaner” than the measures of concurrent MDI we have reported on before.

The presence of a coherent AM cue abolished the F-MDI, suggesting that grouping effects can benefit CI users in these conditions and also reinforcing the idea that the F-MDI effect is not peripheral in origin. In fact, any energetic masking effects should have been enhanced by the presence of the cue, which would have increased the overall excitation during the masker. In contrast, the results showed that it was, in fact, easier for listeners to detect the target AM in the presence of the cue. We note that when the masker and the cue were used singly as maskers in the first experiment, they elevated AMDTs of the target. However, in combination, they reduced target AMDTs in contrast to the increase in AMDTs we would expect from additivity of masking.

One purpose of using the cue was to explore the possibility that any observed F-MDI might arise because of confusion effects, which would make it difficult for listeners to separate the AM target from the AM masker, thus, elevating AMDTs in the presence of the AM masker. As discussed in the Introduction, if such confusion effects in fact occurred, then they should be most prominent at short masker-target delays and decline at longer masker-target delays. In contrast, the results showed no effect of masker-target delay on the effect of the cue. Further, our data with short target stimuli did not support a dominant effect of confusion in our

experiment. Therefore, we infer that confusion effects did not play a role in the present study.

As the stimuli used in the present study were presented in monopolar mode, spread of excitation was likely broad, possibly accounting in part for the lack of an effect of the spatial distance between the masker and the target. It is, however, still remarkable that the fact that no differences were observed in the effects even at the largest spatial distances between the masker and target electrodes (eight electrodes).

In the literature on normal hearing, some studies have investigated the effects of synchronous vs asynchronous gating of the carrier or the modulation. Results generally show that carrier asynchrony reduces the observed MDI, whereas modulation asynchrony does not (Hall and Grose, 1991; Moore and Shailer, 1992; Mendoza *et al.*, 1995; Oxenham and Dau, 2001). Gockel *et al.* (2002) also found reduced MDI with synchronous gating of target and interferer, but interestingly, their results were different for frequency-modulated stimuli. Collectively, these results support the notion of a “carrier-specific” mechanism and a “modulation-specific” mechanism underlying MDI phenomena (Moore and Shailer, 1992). In this scenario, the asynchrony between interferer and target reduce the perceptual grouping of the carriers and therefore reduce MDI. Although the present experiments did not directly compare carrier- vs modulation-specific mechanisms in CI users, the F-MDI measured here is somewhat smaller in magnitude than that reported in previous studies (Chatterjee, 2003; Chatterjee and Oba, 2004). Perhaps the absence of the carrier-specific mechanism in forward masking reduces the overall MDI in CI users, as would be expected in normal hearing listeners.

C. Implications for speech perception with CIs

Speech comprises sequences of sounds with different spectra presented in rapid succession. The processing of the temporal envelopes of these speech elements has been shown to be important for hearing with CIs. CI users’ sensitivity to AMs, measured on single electrodes via direct electrical stimulation, has been shown to be predictive of their performance in a variety of speech perception tasks (Cazals *et al.*, 1994; Fu 2002; Chatterjee and Peng, 2008; Luo *et al.*, 2008). F-MDI of the sort reported here would reduce the salience of a speech sound succeeding an earlier fluctuating element of speech. Previous work by us and others has shown that MDI occurs when concurrent fluctuating maskers compete with an AM target. Studies in NH listeners have shown the strong impact of MDI/modulation masking on speech perception in noise (Stone *et al.*, 2012). The present results indicate that CI users are likely to experience difficulties from MDI under forward masking conditions as well. This may have considerable negative impact because of CI users’ dependence on temporal-envelope information for speech perception.

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