Age-related temporal processing deficits in word segments in adult cochlear-implant users

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Appendix A

Experiment 2: Processing of silence duration cues in word segments as a function of presentation level in CI listeners

In this additional analysis, we re-analyzed the data using sensation levels. This is to support that results from our main analysis using presentation levels were less likely due to systematic audibility/loudness differences across age groups.

Methods

***Statistical analysis*.** To determine the sensation level, we first set the hearing threshold individually as the lowest presentation level (i.e., the sound level that they could just hear the sample word dish) that each participant was tested. Then, we converted presentation levels to sensation levels individually by subtracting their hearing threshold from each presentation level. Table S1 displays the distribution of hearing threshold for each age group. The possible range of sensation level is 0 to 60 dB. We excluded 60 dB from statistical analysis because, as can be inferred from Table S1, no OCI participant was tested at this level. We adopted similar approaches to those detailed in the main analysis for Experiment 2 to examine the effects of age group (YCI, MCI, or OCI) and sensation level (0 to 50 dB) on the crossover point and slope. Specifically, in the linear mixed-effects model, age group and sensation level were included as the fixed effects, and by-participant intercept was included as a random effect to account for baseline performance difference. Both fixed-effect factors were treated as categorical variables. Descriptive statistics, if reported, represent mean ± standard deviation (*SD*).

[Insert Table S1.]

Results

[Insert Figure S1.]

Figure S1A displays the percentage of dish responses as a function of silence duration. While the three age groups (YCI, MCI, and OCI) were able to discriminate the words dish and ditch, the MCI and OCI groups had longer crossover durations and shallower slopes (i.e., shallower curves for the percentage of dish responses as a function of silence duration) than the YCI listeners at higher sensation levels but not at lower levels. These patterns were similar to results from the main analysis with presentation levels (Fig. 3A).

Figure S1B shows the mean crossover point of the performance functions for the three groups across sensation levels 0 to 50 dB. The main effect of sensation level was significant [$F(5, 255.5) = 11.707$, $p < 0.001$]. Post-hoc analysis showed that the crossover point was significantly later at 50 dB compared to 40 dB or below ($p < 0.01$ in all cases). Also, the crossover point was significantly later at 0 or 40 dB compared to 20 and 30 dB ($p < 0.01$ in all cases). These results suggest that participants needed longer silence durations to change their percept from dish to ditch when the stimuli were presented at lower or higher sensation levels than intermediate levels. While the trend of results with the crossover point metric was similar to those from the main analysis with presentation levels (Fig. 3B), the main analysis revealed significant effects regarding age group.

Figure S1C shows the mean slope of the performance functions for the three groups across sensation levels 0 to 50 dB. The main effect of age group was not statistically significant [$F(2, 50.5) = 2.089$, $p = 0.134$]. The main effect of sensation level was significant [$F(5, 241.3) =$

19.931, $p < 0.001$]. The interaction between age group and sensation level was significant [$F(10, 241.4) = 2.366$, $p = 0.011$]. Post-hoc analysis on the interaction revealed that the slope was significantly shallower for the OCI group than that for the YCI group at 40 dB (OCI: 1.64 %/ms ± 1.09 vs. YCI: 3.78 %/ms ± 1.93; $p = 0.003$) or 50 dB (OCI: 0.73 %/ms ± 1.21 vs. YCI: 2.53 %/ms ± 1.42; $p = 0.008$). No other comparisons between the age groups (YCI vs. MCI or MCI vs. OCI) were statistically significant ($p > 0.08$ in all cases). This suggests that OCI listeners found it more difficult to discriminate dish and ditch than YCI listeners at sensation levels 40 to 50 dB. The patterns of results with the slope metric were similar to those from the main analysis with presentation levels (Fig. 3C).

In sum, results using sensation levels (Fig. 1S) were generally consistent with those with presentation levels (Fig. 3).

Experiment 3: Processing of silence duration cues in sine-vocoded word segments as a function of presentation level in NH listeners

Similar to Experiment 2, we additionally re-analyzed the data using sensation levels. This again is to support that results from our main analysis using presentation levels were less likely due to systematic audibility/loudness differences across age groups.

Methods

Statistical analysis. Similar to Experiment 2, we set hearing threshold individually as the lowest presentation level (i.e., the sound level that they could just hear the sample word dish) that each participant was tested. Then we converted presentation levels to sensation levels individually by subtracting their hearing threshold from each presentation level. Table S2 displays the distribution of hearing threshold for each age group. The possible range of sensation level is 0 to 60 dB. We excluded 60 dB from statistical analysis because, as can be inferred from Table S2, the number of participants was extremely unbalanced between the two groups at this level (YNH: n = 13; ONH: n = 3). We adopted similar approaches to those detailed in the main analysis for Experiment 3 to examine the effects of age group (YNH or ONH), number of channels (2 channels, 4 channels, 8 channels, or unprocessed) and sensation level (0 to 50 dB) on the crossover point and slope. Specifically, in the linear mixed-effects model, age group, number of channels and sensation level were included as the fixed effects, and by-participant intercept was included as a random effect to account for baseline performance difference. All the fixed-effect factors were treated as categorical variables. Descriptive statistics, if reported, represent mean ± standard deviation (*SD*).

[Insert Table S2.]

Results

Figure S2A displays the percentage of dish responses as a function of silence duration. While both groups (YNH and ONH) were able to discriminate the words dish and ditch, the ONH group had longer crossover durations and shallower slopes (i.e., shallower curve for the percentage of dish responses as a function of silence duration) than the YNH participants across sensation levels and channels. These patterns were similar to results from the main analysis with presentation levels (Fig. 5A).

[Insert Figure S2.]

Figure S2B shows the mean crossover point of the performance functions for the two groups as a function of sensation level for unprocessed and vocoded stimuli. All main effects were significant: age group [$F(1, 25) = 4.608$, $p = 0.042$], channel [$F(3, 595) = 5.649$, $p < 0.001$], and sensation level [$F(5, 595) = 107.011$, $p < 0.001$]. The interaction between channel and age group was significant [$F(3, 595) = 5.763$, $p < 0.001$]. Post-hoc analysis revealed that the crossover point was significantly later in the ONH group than the YNH group for unprocessed stimuli (ONH: 49.4 ms ± 18.46 vs. YNH: 37.32 ms ± 18.66; $p = 0.013$). No significant age group difference was observed for 8-channel (ONH: 43.88 ms ± 25.22 vs. YNH: 35.86 ms ± 21.44; $p = 0.062$), 4-channel (ONH: 51.35 ms ± 22.32 vs. YNH: 42.21 ms ± 21.77; $p = 0.087$), or 2-channel stimuli (ONH: 43.62 ms ± 32.81 vs. YNH: 44.9 ms ± 25.52; $p = 0.798$). These results indicate that ONH listeners, relative to YNH listeners, generally need longer silence durations to change their percept from dish to ditch, but such age-related differences may disappear for stimuli with fewer vocoded channels.

The interaction between channel and sensation level was significant [$F(15, 595) = 1.84$, $p = 0.027$]. Post-hoc analysis revealed that for the unprocessed stimuli, the crossover point was significantly earlier with increasing sensation levels up to 30 dB ($p < 0.05$ in all cases), but the crossover point at 20 dB was not significant different from that at 10 dB ($p = 0.188$) or at 30 dB ($p = 0.103$). For the 8-channel stimuli, the crossover points were earliest for sensation level at 50 dB, followed by those at 30 dB, then for that at 20 dB, and latest for those at 10 dB or below ($p < 0.05$ in all cases). The crossover points were earliest for sensation level at 40 dB, followed by those at 20 dB, and latest for those at 10 dB or below ($p < 0.001$ in all cases). The crossover point at 40 dB was not significant different from that at 50 dB ($p = 0.565$) or at 30 dB ($p = 0.057$). For the 4-channel stimuli, the crossover points were earliest for sensation levels at 40 dB and above, followed by that at 30 dB, then for that at 20 dB, and latest for those at 10 dB or below ($p < 0.05$ in all cases). For 2-channel stimuli, the crossover points became significantly earlier with increasing sensation levels up to 30 dB ($p < 0.05$ in all cases), but the crossover point at 20 dB was not significant different from that at 10 dB ($p = 0.092$) or at 30 dB ($p = 0.073$). These results indicate that participants generally need shorter silence durations to change their percept from dish to ditch with increasing sensation levels, but the level benefit is dependent on the spectral resolution of the stimuli. Together, the patterns of results with the crossover point metric were similar to those from the main analysis with presentation levels (Fig. 5B), particularly regarding the effect of age group.

Figure S2C shows the mean slope of the performance functions for the two groups as a function of sensation level for unprocessed and vocoded stimuli. All main effects were significant: age group [$F(1, 25) = 5.266$, $p = 0.03$], channel [$F(3, 590) = 59.125$, $p < 0.001$], and sensation level [$F(5, 590) = 62.903$, $p < 0.001$]. The interaction between channel and age group was significant [$F(3, 590) = 3.491$, $p = 0.016$]. Post-hoc analysis revealed that the slopes were significantly shallower for the ONH group than those for the YNH group when listening to 8-channel (ONH: 1.98 %/ms ± 1.91 vs. YNH: 3.13 %/ms ± 2.56; $p = 0.007$) and 2-channel (ONH: 0.09 %/ms ± 1.08 vs. YNH: 1.58 %/ms ± 1.89; $p = 0.032$) stimuli, but not when listening to unprocessed (ONH: 2.64 %/ms ± 2.3 vs. YNH: 3.29 %/ms ± 2.49; $p = 0.229$) or 4-channel (ONH: 2.05 %/ms ± 2.46 vs. YNH: 2.56 %/ms ± 2.36; $p = 0.352$) stimuli.

The interaction between age group and sensation level was significant [$F(5, 590) = 2.601$, $p = 0.024$]. Post-hoc analysis revealed that the slope was significantly shallower for the ONH group than that for the YNH group at 40 dB (ONH: 2.67 %/ms ± 2.45 vs. YNH: 4.11 %/ms ± 2.2; $p = 0.009$) or 50 dB (ONH: 2.53 %/ms ± 2.37 vs. YNH: 4.04 %/ms ± 2.26; $p = 0.006$). No other comparisons between the age groups were statistically significant ($p > 0.059$ in all cases). These results suggest that ONH listeners found it more difficult to discriminate dish and ditch than YNH listeners at sensation levels 40 to 50 dB.

The interaction between channel and sensation level was significant [$F(15, 590) = 5.103$, $p < 0.001$]. Post-hoc analysis revealed that for the unprocessed stimuli, the slopes became significantly steeper with increasing sensation levels up to 30 dB ($p < 0.05$ in all cases). The slopes were not significant difference across 30 to 50 dB ($p > 0.12$ in all cases). For the 8-channel stimuli, the slopes were steepest for sensation levels at 40 dB and above, followed by those at 20 and 30 dB, and least steep for those at 10 dB or below ($p < 0.05$ in all cases). For the 4-channel stimuli, the slopes were steepest for sensation levels at 30 dB and above, followed by that at 20 dB, and least steep for those at 10 dB or below ($p < 0.05$ in all cases). For 2-channel stimuli, the slopes were not significantly different between sensation levels ($p > 0.17$ in all cases). These results suggest that while it generally became easier to discriminate dish and ditch with increasing sensation level, the level benefit is dependent on the spectral resolution of the stimuli. Together, the patterns of results with the slope metric were similar to those from the main analysis with presentation levels, particularly regarding the effects of age group except that the effect of age group was found to be dependent on sound level here when using sensation levels (Fig. 2SC) but not in the main analysis with presentation levels (Fig. 5C).

In general, results using sensation levels (Fig. 2S) and presentation levels (Fig. 5) were relatively consistent.

Appendix B

In Figure S3, we plotted the percentage of trials that participants reported dish responses for the dish-ditch continuum as a function of presentation level (45 to 85 dB), comparing the two ears across thirteen bilateral CI users. Descriptively, we observed between-ear differences in identifying words dish and ditch for the majority of participants. This was one of the reasons that prompted us to treat data from the two ears in those bilateral CI users as independent.

[Insert Figure S3.]

Table S1. Proportion of participants/ears tested at each presentation level and the distribution of hearing threshold (i.e., the lowest presentation level tested) for each age group in Experiment 2. Number(s) in parentheses represent the proportion of participants/ears (relative to the total number of participants/ears who completed the task at that level for that age group) that were fitted by a logistic function in a backward direction (first number) and that failed to be fitted by the logistic function (second number). Zeros were included into the parentheses for illustration purposes.

Age group	Presentation level (dB)						
	25	35	45	55	65	75	85
YCI	9.09	90.91 (10;10)	100	100	100	100	100
MCI	14.29	57.14 (16.67;0)	95.24	100 (4.76;0)	100 (9.52;0)	100 (4.76;0)	100 (4.76;19.05)
OCI	0	86.36 (10.53;0)	100	100	100	100 (4.55;4.55)	100 (22.73;0)
YCI: Threshold	9.09	81.82	9.09	0	0	0	0
MCI: Threshold	14.29	42.86	38.10	4.75	0	0	0
OCI: Threshold	0	86.36	13.64	0	0	0	0

Note. YCI, younger cochlear-implant users; MCI, middle-aged cochlear-implant users; OCI, older cochlear-implant users.

Table S2. Proportion of participants tested at each presentation level and the distribution of hearing threshold (i.e., the lowest presentation level tested) for each age group in Experiment 3. Number(s) in parentheses represent the proportion of participants/ears (relative to the total number of participants/ears who completed the task at that level for that age group) that were fitted by a logistic function in a backward direction (first number) and that failed to be fitted by the logistic function (second number). Zeros were included into the parentheses for illustration purposes.

Age group	Number of channels	Presentation level (dB SPL) 25	35	45	55	65	75	85
ONH	Unprocessed	27.27 (100;0)	100 (45.45;0)	100 (18.18;0)	100	100	100	100
	8 channels	27.27 (33.33;0)	100 (54.55;0)	100 (9.09;0)	100	100	100	100
	4 channels	27.27 (100;0)	100 (63.64;9.09)	100 (36.36;18.18)	100	100 (9.09;0)	100	100
	2 channels	27.27 (66.67;0)	100 (36.36;18.18)	100 (27.27;18.18)	100 (45.45;18.18)	100 (45.45;18.18)	100 (18.18;18.18)	100 (27.27;18.18)
YNH	Unprocessed	81.25 (7.69;0)	100 (6.25;0)	100	100	100	100	100
	8 channels	81.25 (15.38;0)	100 (6.25;0)	100	100	100	100	100
	4 channels	81.25 (23.08;0)	100 (12.5;0)	100 (6.25;0)	100	100 (6.25;0)	100	100
	2 channels	81.25 (23.08;0)	100 (12.5;6.25)	100 (18.75;0)	100	100 (12.5;0)	100 (6.25;0)	100 (0; 6.25)
ONH: Threshold		27.27	72.73	0	0	0	0	0
YNH: Threshold		81.25	18.75	0	0	0	0	0

Note. YNH, younger normal-hearing listeners; ONH, older normal-hearing listeners.

Figure Captions

Figure S1. Results for YCI (blue/squares), MCI (green/circles), and OCI (red/triangles) groups as a function of sensation level (0 to 50 dB) in Experiment 2. *Panel A*: Mean percentage of trials that participants reported dish responses for the dish-ditch continuum. The continuum consisted of 7 stimuli with the silence duration parametrically varied from 0 to 60 ms. Error bars denote ±1 standard deviation. *Panels B* and *C*: Mean crossover point and slope of the psychometric functions. Error bars denote 95% confidence interval. YCI, younger cochlear-implant users; MCI, middle-aged cochlear-implant users; OCI, older cochlear-implant users.

Figure S2. Results for YNH (blue/squares) and ONH (red/triangles) groups as a function of sensation level (0 to 50 dB) in Experiment 3. *Panel A*: Mean percentage of trials that participants reported dish responses for the dish-ditch continuum. The rows (from top to bottom) show data for unprocessed and vocoded stimuli (8, 4, and 2 channels). The continuum consisted of 7 stimuli with the silence duration parametrically varied from 0 to 60 ms. Error bars denote ±1 standard deviation. *Panels B* and *C*: Mean crossover point and slope of the psychometric functions. As a comparison, we displayed results for YCI (transparent blue/squares) and OCI (transparent red/triangles) groups from Experiment 2. The columns (from left to right) show data for unprocessed and vocoded stimuli (8, 4, and 2 channels). Error bars denote 95% confidence interval. YNH, younger normal-hearing listeners; ONH, older normal-hearing listeners; YCI, younger cochlear-implant users; OCI, older cochlear-implant users.

Figure S3. Percentage of trials that participants reported dish responses for the dish-ditch continuum as a function of presentation level (45 to 85 dB), comparing data from the two ears of thirteen bilateral CI users with two ears tested separately. The continuum consisted of 7 stimuli with the silence duration parametrically varied from 0 to 60 ms. For CCI, the ear annotation might be swapped due to missing information.