

Supplemental Material S39. Additional analysis of Syllable 1 (carrying T1-4) in each neutral tone word of experiment 2.

Given that in experiment 1 (lexical tones) there were only four test items (one token for each lexical tone), we performed an additional analysis on syllable 1 of the neutral tone words used to validate the results of experiment 1. Recall that the only early implanted children produced lexical tone pitch contours comparable to those of NH children, while other children, including those with longer CI experience, produced flatter pitch for all tones.

A linear mixed-effects model was performed on the pitch contour parameters (slope and curvature) of Syllable 1 of neutral tone words, with two fixed factors “Group” (NH = 3, CI_Imp 1-2, CI_Imp 2-3, CI_Imp 3-4, and CI_Imp 4-5) and “Tones” (T1, T2, T3, and T4), a covariant “Chronological age” (age in months; to control for the different chronological ages across participants) and a random factor “Participant”. The results showed significant interactions of “Group × Tone” on pitch slope ($F(12, 12019) = 18.71, p < .001$) and curvature ($F(12, 11999) = 5.15, p < .001$; Table S39-1). Tukey-HSD post-hoc tests showed that the CI_Imp 1-2 group produced pitch contours comparable to those of the NH children for all lexical tones, while other CI groups differed from the NH children in T2, T3, and T4 productions, with flatter pitch contours (Table S39-2).

Table S39-1. Results of linear mixed-effects model on pitch shape (slope and curvature) in children’s productions of Syllable 1 (lexical tones) of neutral tone words, with two fixed factors “Group” (NH = 3, CI_Imp 1-2, CI_Imp 2-3, CI_Imp 3-4, and CI_Imp 4-5) and “Tones” (T1, T2, T3, and T4) and a covariate “Chronological Age.”

Parameter	Factors	df 1	df 2	<i>F</i>	<i>p</i>
Pitch slope	Group	4	188	4.17	< .01**
	Tone	3	8903	15.03	< .001***
	Chronological Age	1	227	0.91	.341
	Group × Tone	12	12019	18.71	< .001***
	Group × Chronological Age	4	191	1.18	.321
	Tone × Chronological Age	3	7009	1.76	.152
	Group × Tone × Chronological Age	12	7772	1.68	.064
Pitch curvature	Group	4	1548	4.47	< .01**
	Tone	3	11868	5.66	< .001***
	Chronological Age	1	2053	1.07	.301
	Group × Tone	12	11999	5.15	< .001***
	Group × Chronological Age	4	1571	1.43	.220
	Tone × Chronological Age	3	11760	0.82	.484
	Group × Tone × Chronological Age	12	11730	0.72	.733

Table S39-2. Pairwise comparisons of pitch contours of syllable 1 (TX) of neutral tone words between groups (NH = 3, CI_Imp 1-2, CI_Imp 2-3, CI_Imp 3-4, and CI_Imp 4-5).

Tone	Group difference	Parameter	β	SE	df	t	p
T1	NH = 3 – CI_Imp 1-2	Slope	1.43	1.07	661	1.34	.666
		Curvature	0.70	0.83	8508	0.84	.917
	NH = 3 – CI_Imp 2-3	Slope	1.31	0.57	514	2.32	.142
		Curvature	–0.17	0.43	7740	–0.39	.995
	NH = 3 – CI_Imp 3-4	Slope	1.55	0.66	482	2.36	.130
		Curvature	–0.24	0.49	7545	–0.48	.989
	NH = 3 – CI_Imp 4-5	Slope	1.08	0.86	504	1.26	.716
		Curvature	–0.09	0.65	7607	–0.14	1.000
	CI_Imp 1-2 – CI_Imp 2-3	Slope	–0.12	1.16	643	–0.10	1.000
		Curvature	–0.86	0.90	8434	–0.96	.873
	CI_Imp 1-2 – CI_Imp 3-4	Slope	0.12	1.21	619	0.10	1.000
		Curvature	–0.93	0.93	8330	–1.00	.854
	CI_Imp 1-2 – CI_Imp 4-5	Slope	–0.35	1.33	603	–0.26	.999
		Curvature	–0.79	1.02	8221	–0.77	.939
	CI_Imp 2-3 – CI_Imp 3-4	Slope	0.23	0.80	505	0.29	.998
		Curvature	–0.07	0.60	7703	–0.12	1.000
	CI_Imp 2-3 – CI_Imp 4-5	Slope	–0.23	0.97	515	–0.24	.999
		Curvature	0.08	0.73	7699	0.10	1.000
	CI_Imp 3-4 – CI_Imp 4-5	Slope	–0.46	1.03	501	–0.45	.991
		Curvature	0.15	0.77	7625	0.19	1.000
T2	NH = 3 – CI_Imp 1-2	Slope	0.37	1.04	735	0.35	.997
		Curvature	1.64	0.83	9076	1.98	.277
	NH = 3 – CI_Imp 2-3	Slope	1.26	0.58	579	2.17	< .05*
		Curvature	2.64	0.45	8249	5.90	< .001***
	NH = 3 – CI_Imp 3-4	Slope	2.21	0.70	601	3.15	< .05*
		Curvature	2.12	0.54	8339	3.91	< .001***
	NH = 3 – CI_Imp 4-5	Slope	2.10	0.87	554	2.42	< .05*
		Curvature	2.30	0.66	8012	3.47	< .01**
	CI_Imp 1-2 – CI_Imp 2-3	Slope	2.89	1.14	721	1.78	< .05*
		Curvature	1.00	0.91	9012	1.10	.806
	CI_Imp 1-2 – CI_Imp 3-4	Slope	1.84	1.21	714	1.52	.547
		Curvature	0.48	0.96	8963	0.50	.987
	CI_Imp 1-2 – CI_Imp 4-5	Slope	1.74	1.32	668	1.32	.679
		Curvature	0.66	1.03	8737	0.64	.968
	CI_Imp 2-3 – CI_Imp 3-4	Slope	2.95	0.85	619	2.12	< .05*
		Curvature	–0.52	0.66	8451	–0.79	.933

	CI_Imp 2-3 – CI_Imp 4-5	Slope	0.84	0.99	576	0.85	.914
		Curvature	–0.33	0.76	8171	–0.44	.992
	CI_Imp 3-4 – CI_Imp 4-5	Slope	–0.11	1.07	586	–0.10	1.000
		Curvature	0.19	0.82	8221	0.23	.999
	NH = 3 – CI_Imp 1-2	Slope	–1.67	1.04	594	–1.61	.490
		Curvature	0.82	0.79	8071	1.03	.841
	NH = 3 – CI_Imp 2-3	Slope	–3.61	0.57	514	–6.36	< .001***
		Curvature	–0.58	0.43	7740	–1.36	.657
	NH = 3 – CI_Imp 3-4	Slope	–3.90	0.66	482	–5.94	< .001***
		Curvature	–0.22	0.49	7545	–0.44	.992
	NH = 3 – CI_Imp 4-5	Slope	–4.11	0.86	504	–4.78	< .001***
		Curvature	–0.22	0.65	7607	–0.34	.997
T3	CI_Imp 1-2 – CI_Imp 2-3	Slope	–1.94	1.13	587	–1.91	< .05*
		Curvature	–1.40	0.87	8063	–1.61	.488
	CI_Imp 1-2 – CI_Imp 3-4	Slope	–2.23	1.18	569	–1.89	< .05*
		Curvature	–1.03	0.90	7980	–1.15	.781
	CI_Imp 1-2 – CI_Imp 4-5	Slope	–2.44	1.30	563	–1.87	.334
		Curvature	–1.04	0.99	7928	–1.05	.834
	CI_Imp 2-3 – CI_Imp 3-4	Slope	–0.29	0.80	505	–0.37	.996
		Curvature	0.36	0.60	7703	0.60	.975
	CI_Imp 2-3 – CI_Imp 4-5	Slope	–0.51	0.97	515	–0.52	.985
		Curvature	0.36	0.73	7699	0.49	.988
	CI_Imp 3-4 – CI_Imp 4-5	Slope	–0.21	1.03	501	–0.21	1.000
		Curvature	0.00	0.77	7625	–0.01	1.000
	NH = 3 – CI_Imp 1-2	Slope	–2.06	1.04	595	–1.99	.274
		Curvature	–0.84	0.79	8081	–1.06	.826
	NH = 3 – CI_Imp 2-3	Slope	–2.40	0.57	507	–4.25	< .001***
		Curvature	–0.87	0.43	7679	–2.04	< .05*
	NH = 3 – CI_Imp 3-4	Slope	–2.66	0.66	485	–4.04	< .001***
		Curvature	–0.91	0.49	7573	–1.84	.351
T4	NH = 3 – CI_Imp 4-5	Slope	–2.14	0.86	506	–2.49	< .05*
		Curvature	–0.29	0.65	7623	–0.45	.992
	CI_Imp 1-2 – CI_Imp 2-3	Slope	–0.34	1.13	584	–0.30	.998
		Curvature	–0.03	0.86	8040	–0.03	1.000
	CI_Imp 1-2 – CI_Imp 3-4	Slope	–0.60	1.18	569	–0.51	.987
		Curvature	–0.07	0.90	7980	–0.07	1.000
	CI_Imp 1-2 – CI_Imp 4-5	Slope	–0.08	1.30	563	–0.06	1.000
		Curvature	0.55	0.99	7928	0.56	.981

CI_Imp 2-3 – CI_Imp 3-4	Slope	–0.26	0.80	499	–0.33	.998
	Curvature	–0.04	0.60	7654	–0.07	1.000
CI_Imp 2-3 – CI_Imp 4-5	Slope	0.26	0.97	511	0.27	.999
	Curvature	0.58	0.73	7666	0.79	.934
CI_Imp 3-4 – CI_Imp 4-5	Slope	0.52	1.03	501	0.51	.987
	Curvature	0.62	0.77	7625	0.80	.931

Note. NH = normal hearing; CI = cochlear implant.

We then explored the effect of CI experience on the pitch realization of children’s productions of Syllable 1 of neutral tone words. A linear mixed-effects model was performed on the pitch contour (slope and curvature) for each token, with two fixed factors “Group” (CI_Exp < 1, CI_Exp 1-2, CI_Exp 2-3, CI_Exp 3-4, NH = 3) and “Tones” (T1, T2, T3, and T4), a covariant “Chronological age” and a random factor “Participant”. The results showed significant interactions of “Group × Tone” on pitch slope ($F(12, 11989) = 19.38, p < .001$) and curvature ($F(12, 11998) = 5.17, p < .001$; Table S39-3). Tukey-HSD post-hoc tests revealed that, relative to the NH children, all CI groups generally produced flatter pitch contours for T2, T3, and T4 (Table S39-4).

Table S39-3. Results of linear mixed-effects model on pitch shape (slope and curvature) in children’s productions of Syllable 1 (lexical tones) of neutral tone words, with two fixed factors “Group” (NH = 3, CI_Exp < 1, CI_Exp 1-2, CI_Exp 2-3, and CI_Exp 3-4) and “Tones” (T1, T2, T3, and T4) and a covariate “Chronological Age.”

Parameter	Factors	df 1	df 2	<i>F</i>	<i>p</i>
Pitch slope	Group	4	175	4.25	< 0.01**
	Tone	3	12006	13.06	< 0.001***
	Chronological Age	1	173	0.01	0.942
	Group × Tone	12	11989	19.38	< 0.001***
	Group × Chronological Age	4	174	0.19	0.945
	Tone × Chronological Age	3	12009	0.42	0.741
	Group × Tone × Chronological Age	12	11979	0.90	0.544
Pitch curvature	Group	4	1381	3.11	< 0.05*
	Tone	3	11948	3.46	< 0.05*
	Chronological Age	1	1353	0.34	0.558
	Group × Tone	12	11998	5.17	< 0.001***
	Group × Chronological Age	4	1353	0.13	0.970
	Tone × Chronological Age	3	11949	0.12	0.947
	Group × Tone × Chronological Age	12	11948	0.21	0.998

Note. NH = normal hearing; CI = cochlear implant.

Table S39-4. Pairwise comparisons of pitch contours of syllable 1 (TX) of neutral tone words between groups (NH = 3, CI_Exp < 1, CI_Exp 1-2, CI_Exp 2-3, and CI_Exp 3-4).

Tone	Group difference	Parameter	β	SE	df	<i>t</i>	<i>p</i>
T1	NH = 3 – CI_Exp < 1	Slope	–0.32	0.95	502	–0.34	.997
		Curvature	0.14	0.72	7771	0.20	1.000
	NH = 3 – CI_Exp 1-2	Slope	0.11	0.97	498	0.11	1.000
		Curvature	0.64	0.74	7769	0.87	.909
	NH = 3 – CI_Exp 2-3	Slope	0.29	1.31	576	0.22	1.000
		Curvature	0.36	1.00	8013	0.36	.996
	NH = 3 – CI_Exp 3-4	Slope	–1.41	0.82	478	–1.74	.414
		Curvature	0.39	0.61	7593	0.64	.968
	CI_Exp < 1 – CI_Exp 1-2	Slope	0.43	0.79	542	0.54	.983
		Curvature	0.50	0.61	8078	0.82	.925
	CI_Exp < 1 – CI_Exp 2-3	Slope	0.61	1.18	622	0.51	.986
		Curvature	0.22	0.91	8203	0.24	.999
	CI_Exp < 1 – CI_Exp 3-4	Slope	–1.10	0.58	538	–1.88	.332
		Curvature	0.25	0.45	8000	0.56	.981
	CI_Exp 1-2 – CI_Exp 2-3	Slope	0.18	1.20	613	0.15	1.000
		Curvature	–0.28	0.93	8187	–0.30	.998
	CI_Exp 1-2 – CI_Exp 3-4	Slope	–1.53	0.63	521	–2.43	.109
		Curvature	–0.25	0.48	7965	–0.51	.986
	CI_Exp 2-3 – CI_Exp 3-4	Slope	–1.70	1.08	630	–1.58	.514
		Curvature	0.03	0.83	8189	0.04	1.000
T2	NH = 3 – CI_Exp < 1	Slope	–1.73	1.00	617	–1.92	< .05*
		Curvature	0.84	0.78	8496	1.08	.819
	NH = 3 – CI_Exp 1-2	Slope	–0.85	1.03	595	–0.82	.924
		Curvature	2.52	0.80	8365	2.66	< .05*
	NH = 3 – CI_Exp 2-3	Slope	–0.65	1.26	603	–0.52	.986
		Curvature	2.64	0.98	8502	2.65	< .05*
	NH = 3 – CI_Exp 3-4	Slope	–2.59	0.86	574	–3.00	< .05*
		Curvature	–1.76	0.66	8238	–2.64	< .05*
	CI_Exp < 1 – CI_Exp 1-2	Slope	0.88	0.83	652	1.06	.828
		Curvature	–0.32	0.65	8694	–0.49	.989
	CI_Exp < 1 – CI_Exp 2-3	Slope	1.08	1.10	638	0.98	.865
		Curvature	–0.20	0.86	8728	–0.23	.999
	CI_Exp < 1 – CI_Exp 3-4	Slope	–0.87	0.61	655	–1.42	.617
		Curvature	–2.60	0.48	8725	–5.41	< .001***
	CI_Exp 1-2 – CI_Exp 2-3	Slope	0.20	1.12	618	0.18	1.000

		Curvature	0.12	0.88	8612	0.13	1.000
	CI_Exp 1-2 – CI_Exp 3-4	Slope	–1.75	0.66	595	–2.66	< .05*
		Curvature	–2.28	0.51	8378	–4.49	< .001***
	CI_Exp 2-3 – CI_Exp 3-4	Slope	–1.94	0.97	608	–2.00	< .05*
		Curvature	–2.40	0.76	8597	–3.15	< .05*
	NH = 3 – CI_Exp < 1	Slope	–2.17	0.95	502	–2.24	< .05*
		Curvature	–0.15	0.72	7771	–0.21	1.000
	NH = 3 – CI_Exp 1-2	Slope	2.26	0.97	486	2.33	< .05*
		Curvature	0.92	0.73	7661	1.26	.718
	NH = 3 – CI_Exp 2-3	Slope	2.17	1.34	625	2.17	< .05*
		Curvature	0.25	1.04	8338	0.24	.999
	NH = 3 – CI_Exp 3-4	Slope	4.00	0.82	478	4.90	< .001***
		Curvature	0.54	0.61	7594	0.88	.904
	CI_Exp < 1 – CI_Exp 1-2	Slope	3.43	0.78	523	4.38	< .001***
		Curvature	1.07	0.60	7923	1.80	.377
	CI_Exp < 1 – CI_Exp 2-3	Slope	2.35	1.22	687	1.93	.302
		Curvature	0.41	0.95	8580	0.43	.993
	CI_Exp < 1 – CI_Exp 3-4	Slope	5.17	0.58	538	8.85	< .001***
		Curvature	0.69	0.45	8000	1.56	.526
	CI_Exp 1-2 – CI_Exp 2-3	Slope	–1.09	1.23	665	–0.88	.904
		Curvature	–0.67	0.96	8497	–0.70	.958
	CI_Exp 1-2 – CI_Exp 3-4	Slope	1.74	0.62	491	2.81	.041
		Curvature	–0.38	0.47	7710	–0.81	.929
	CI_Exp 2-3 – CI_Exp 3-4	Slope	2.83	1.12	709	2.53	.085
		Curvature	0.29	0.87	8636	0.33	.997
	NH = 3 – CI_Exp < 1	Slope	–2.60	0.95	502	–2.63	< .05*
		Curvature	–0.08	0.72	7771	–0.12	1.000
	NH = 3 – CI_Exp 1-2	Slope	–2.21	0.97	486	–2.22	< .05*
		Curvature	–0.29	0.73	7661	–0.40	.995
	NH = 3 – CI_Exp 2-3	Slope	2.04	1.31	576	–2.03	< .05*
		Curvature	–0.90	1.00	8013	–0.90	.898
	NH = 3 – CI_Exp 3-4	Slope	2.09	0.82	480	2.56	< .05*
		Curvature	0.57	0.62	7611	0.92	.890
	CI_Exp < 1 – CI_Exp 1-2	Slope	0.39	0.78	523	0.50	.987
		Curvature	–0.21	0.60	7923	–0.35	.997
	CI_Exp < 1 – CI_Exp 2-3	Slope	0.56	1.18	622	0.47	.990
		Curvature	–0.21	0.60	7923	–0.35	.997

	Curvature	−0.81	0.91	8203	−0.90	.899
CI_Exp < 1 – CI_Exp 3-4	Slope	2.69	0.59	542	4.60	< .001***
	Curvature	0.65	0.45	8032	1.45	.594
CI_Exp 1-2 – CI_Exp 2-3	Slope	0.17	1.20	603	0.14	1.000
	Curvature	−0.61	0.92	8123	−0.66	.965
CI_Exp 1-2 – CI_Exp 3-4	Slope	2.30	0.62	495	3.71	< .01**
	Curvature	0.86	0.47	7740	1.83	.355
CI_Exp 2-3 – CI_Exp 3-4	Slope	2.13	1.08	632	1.97	.280
	Curvature	1.46	0.83	8198	1.76	.395

Note. NH = normal hearing; CI = cochlear implant.