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Research Note

Processing of Phonological Variation in Children With Hearing Loss: Compensation for English Place Assimilation in Connected Speech

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Purpose: In this study, the authors explored phonological processing in connected speech in children with hearing loss. Specifically, the authors investigated these children's sensitivity to English place assimilation, by which alveolar consonants like *t* and *n* can adapt to following sounds (e.g., the word *te**n*** can be realized as *te**m*** in the phrase *te**n** **p**ounds*).

Method: Twenty-seven 4- to 8-year-old children with moderate to profound hearing impairments, using hearing aids (n = 10) or cochlear implants (n = 17), and 19 children with normal hearing participated. They were asked to choose between pictures of familiar (e.g., pen) and unfamiliar objects (e.g., astrolabe) after hearing *t*- and *n*-final words in sentences. Standard pronunciations (*Can you find the pe**n** **d**ear*?) and assimilated forms in correct (*… pe**m** **p**lease?*) and incorrect contexts (*… pe**m** dear?*) were presented.

Results: As expected, the children with normal hearing chose the familiar object more often for standard forms and correct assimilations than for incorrect assimilations. Thus, they are sensitive to word-final place changes and compensate for assimilation. However, the children with hearing impairment demonstrated reduced sensitivity to word-final place changes, and no compensation for assimilation. Restricted analyses revealed that children with hearing aids who showed good perceptual skills compensated for assimilation in plosives only.

Key Words: language, hearing loss, phonology, speech perception, deafness

Advances in cochlear implantation, digital hearing aids, and early diagnosis and aiding after universal newborn hearing screening have made oral language acquisition an obtainable goal for many children with hearing loss. In a longitudinal study by Yoshinaga-Itano, Baca, and Sedey (2010), for instance, a quarter of the early-aided hearing-impaired children reached age-appropriate language skills on standardized tests at 5 years of age. However, we know little about their phonological processing and acquisition because most researchers focus on global performance measures such as key word recognition, overall speech intelligibility, or standardized language scores (for recent reviews see Eisenberg 2007; Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007; Peterson, Pisoni, & Miyamoto, 2010).

A number of researchers have investigated how children with hearing loss perceive specific sounds in syllables and words. Tyler et al. (1997) established an acquisition hierarchy for different phonetic features in English-learning children with cochlear implants (CIs), with place of articulation differences being among the latest features acquired (but see Kishon-Rabin et al., 2002, for a different acquisition order in Hebrew). Eisenberg, Martinez, Holowecky, and Pogorelsky (2002) investigated pediatric CI users' word recognition in isolation and in sentences and report similar word frequency and neighborhood density effect as in children with normal hearing. However, lexical processing is slowed even for highly familiar words in children with CIs (Grieco-Calub, Saffran, & Litovsky, 2009), and they have reduced phonological short-term memory and phonological awareness (Spencer & Tomblin, 2009).

To our knowledge, no study has directly investigated how children with hearing loss process language-specific phonological variation in connected speech. Word form

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realizations in sentences are more variable than in isolation because phonological processes can induce sound changes at word junctures (Newton & Wells, 2002). For instance, in English, the place of articulation of alveolar consonants like *t* and *n* can be assimilated to that of following labials like *p* and *m,* such that the word *te**n*** can be pronounced as *te**m***, and a phrase like *te**n** pounds* can be pronounced as *te**m** pounds*. Children with normal hearing as young as age 2–2½ years (Skoruppa, Mani, & Peperkamp, 2013; Skoruppa, Mani, Plunkett, Cabrol, & Peperkamp, 2013) compensate for native language assimilations during lexical access, but we expect assimilation to be problematic for children with hearing loss. In particular, their reduced perception of fine phonetic detail may not be reliable enough to allow them to detect this type of phonological regularity in the ambient language input.

Thus, in the present study, we investigated whether English children with hearing loss can compensate for place assimilation, using the same methodology for younger children with normal hearing used in Skoruppa, Mani, and Peperkamp (2013). Specifically, we tested whether they interpret forms with labial *m* or *p* (e.g., *pe**m***) as assimilated instances of a familiar word (here, *pe**n***) rather than as new names for an unfamiliar object (e.g., an astrolabe) in a forced-choice picture-pointing task.

Because perception of the place of articulation feature develops relatively late in English-speaking children with hearing loss (Tyler et al., 1997), we concentrated on older children who had been using their devices for at least 3 years. We also highlighted word-final changes in place of articulation (e.g., *pen–pem*) prior to testing assimilation, as in Skoruppa, Mani, & Peperkamp (2013). In order to validate this pointing task with older children, we also tested a group of children with normal hearing.

Methods

Participants

Twenty-seven 4- to 8-year-old children from the South of England with nonprogressive moderate to profound bilateral sensorineural hearing impairment participated as part of a larger study. Their hearing loss was present from birth, or its onset occurred during the first year of life (although they were diagnosed later in some cases). They had been fitted with hearing aids (HAs, *n* = 10, moderate to severe-profound impairment) or CIs (*n* = 17, profound impairment) by age 3;1 (years;months). The children had been using these devices for at least 3 years when they entered the study. The only spoken language they were exposed to regularly was English, and this was also their main communication mode, although parents reported occasional use of sign language or sign-supported English. According to parental report, all children had normal intelligence. As part of the larger study, standardized tests of vocabulary (British Picture Vocabulary Scale, Third Edition [BPVS–III], Dunn, Dunn, Styles, & Sewell, 2009), expressive phonology (Diagnostic Evaluation of Articulation and Phonology [DEAP] phonology subtest, Dodd, Hua, Crosbie, Holm, & Ozanne, 2002) and verbal working memory (Working Memory Test Battery for Children [WMTB–C] digit span subtest, Pickering & Gathercole, 2001) were carried out. Overall, the children's vocabulary was quite good, with about half the children in each group reaching age-appropriate levels (CI: 8/17, HA: 5/10). The consonant production skills of the children with HAs were, however, less well developed (CI: 7/16 and HA: 0/10 being age-appropriate). Individual test scores and detailed characteristics of the children can be found in Tables 1 (CI) and 2 (HA).

Table 1. Individual characteristics of the children with cochlear implants.

Sex	Age	Hear. Age	Diagnosis	Implantation	BPVS age	BPVS SS	DEAP PCC	Digit Span
M	8;7	5;7	2nd year	bilateral, sequential	**10;9**	**128**	88	4
F	6;9	5;7	1 month	bilateral, sequential	**5;6**	**87**	94	4
F	6;11	4;1	2nd year	bilateral, sequential	4;9	70	80	4
M	6;4	5;4	4 weeks	bilateral, sequential	**5;3**	**86**	**98**	*3*
M	5;7	3;11	6 weeks	unilateral	**5;4**	**96**	93	4
F	5;6	3;8	9 months	bilateral, sequential	< 3;9	73	**96**	4
F	6;2	4;11	9 months	bilateral, sequential	4;8	77	**96**	4
M	6;2	5;0	2 months	bilateral, sequential	**5;6**	**92**	**91**	4
F	5;5	3;5	5 weeks	bilateral, sequential	< 3;9	77	88	5
F	5;7	3;9	birth	bilateral	**6;5**	**110**	**94**	5
M	4;10	3;6	birth	bilateral, simultaneous	**4;10**	**103**	**96**	3
M	8;2	5;9	birth	bilateral, sequential	5;0	< 70	82	5
M	5;11	4;11	birth	bilateral, sequential	< 3;9	73	79	3
M	8;3	5;11	birth	bilateral, sequential	4;6	< 70	77	4
F	5;1	3;3	birth	bilateral, sequential	**6;2**	**115**	**92**	4
F	7;9	5;5	birth	unilateral	5;4	77	n/a[a]	3
F	7;9	5;5	birth	unilateral	4;7	< 72	89	2

Note. Hear. age = time in years since implantation; BPVS = British Picture Vocabulary Scale; SS = standard scores; DEAP PCC = percentage consonant correct in the Diagnostic Evaluation of Articulation and Phonology, Phonology subtest; M = male; F = female. For BPVS and DEAP, age-appropriate values are marked in bold.

[a] Due to experimenter error, this child's productions were not recorded correctly.

Table 2. Individual characteristics of the children with hearing aids.

Sex	Age	Severity	PTA	Diagnosis	BPVS age	BPVS SS	DEAP PCC	Digit span
M	7;1	moderate-severe	68	2 weeks	4;6	< 70	81	3
F	8;9	moderate-severe	65	1 year	**8;11**	**103**	93	4
M	8;10	moderate	50	2nd year	6;3	77	96	4
F	8;6	severe-profound	91	2nd year	5;4	< 70	70	4
M	7;0	severe	78	3 months	**6;2**	**94**	96	4
F	8;3	severe	75	birth	**8;11**	**116**	82	6
F	8;8	severe-profound	n/a[a]	2nd year	4;7	< 70	86	4
M	6;10	moderate-severe	65	3rd year	5;2	80	89	4
M	7;10	severe	73	6 weeks	**8;7**	**110**	91	5
M	7;7	severe	78	birth	**7;2**	**98**	80	4

Note. PTA = unaided pure-tone average in the better ear in dB hearing loss.

[a] The parents of this child were unable to provide this information.

Nineteen monolingual English children with typical development in the same age range (9 girls, 10 boys) served as a control group. Most of them were siblings or classmates of the children with hearing impairment. They passed a hearing screening (thresholds in both ears ≤ 20 dB HL at 250, 500, 1000, 2000, 4000, and 8000 Hz), a speech screening (only age-appropriate errors in the DEAP screening) and a vocabulary test (standard scores ≥ 85 on the BPVS). Twenty additional children participated but were excluded because they failed the hearing ($n = 6$), speech ($n = 7$), or vocabulary ($n = 2$) screening, or did not complete testing ($n = 5$).

Stimuli

Thirty imageable monosyllabic nouns with a mean age of acquisition of 2;10 (maximum = 3;9, according to norms by Cortese & Khanna, 2008) were selected (see Appendix, Table A1). Half of them ended with the plosive *t* (e.g., *boat*), the other half with the nasal *n* (e.g., *pen*). Six nouns ending in other sounds (e.g., *car, ball, duck*) were selected for training and catch trials (see Appendix, Tables A2 and A3). As in Skoruppa, Mani, Plunkett, et al. (2013), the nouns were used in the following three sentence conditions (examples can be found in Table 3):

1. Standard: The correctly produced target word is followed by alveolar *n* or *d,* thus place assimilation is impossible.
2. Assimilation: The assimilated form of the noun is followed by labial *m* or *p,* thus place assimilation is possible.
3. Mispronunciation: The assimilated form of the noun is followed by alveolar *n* or *d,* thus place assimilation is impossible.

Note that the content words used at the end of the sentences (*please, dear, now, my*) are reversed for plosives and nasals, in order to avoid children using them to determine their response. The training and catch nouns were recorded in the Standard and Mispronunciation conditions only. For the first two training items, the mispronunciations involved nonminimal changes (e.g., *car–wug*); for the other four they involved place of articulation changes as for the test items (e.g., *duck–dutt*).

A female native speaker of British English recorded the sentences without pauses between the nouns and their contexts. She also produced presentation sentences introducing the correct (*Look, a boat!*) and assimilated forms (*And that's a boap!*) sentence-finally, as well as feedback, both positive (e.g., *Very good!*) and negative (*Are you sure? Try again!*). Recordings were made in a sound-attenuated booth on a standard PC through CoolEdit 2000, using a Røde NT1-A condenser microphone and an Edirol UA-25 USB sound card. The sampling rate was 44.1 kHz (mono, 16-bit). Stimuli were segmented and overall amplitude was normalized using Praat 5.2.46.

Finally, photos representing the 36 nouns and 36 photos of objects deemed unfamiliar to young children of roughly similar visual complexity were selected.

Procedure

The children took part in a larger study that involved other speech and language tests in two sessions of 30 min each, separated by an interval of 15 min to 2 days. The task described here took place at the beginning of the second testing session, preceded only by a digit span test (Pickering & Gathercole, 2001). Prior to testing, parents filled in a detailed

Table 3. Sample test stimuli.

Condition	Nasals	Plosives
Standard	*Can you find the pe**n** **d**ear?*	*Can you find the boa**t** **n**ow please?*
Assimilation	*Can you find the pe**m** **p**lease?*	*Can you find the boa**p** **m**y dear?*
Mispronunciation	*Can you find the pe**m** **d**ear?*	*Can you find the boa**p** **n**ow please?*

questionnaire about their children's hearing and language development and signed an informed consent form. The study was approved by the ethics committees of University College London and the English National Health Service.

The test was run in a quiet room on a Toshiba Portégé M780-112 laptop with a 12.1 inch widescreen touch screen, using Python 2.6.6 and Pygame 1.9.1. The auditory stimuli were presented via a Fostex 6301B loudspeaker at approximately 70 dB SPL. The study was introduced to the children as a computer game in which they would learn funny alien names for funny-looking things. They were told to listen carefully to the alien names so they could point to the correct objects on the screen later on. Thirty test trials with the nouns with final *t* and *n* were preceded by three training trials in order to familiarize the children with the method. Three catch trials were interspersed at regular intervals in order to avoid children losing attention and developing response strategies. The test trials were randomized in two blocks, the order of which was counterbalanced across participants. All trials consisted of the following three phases (see Figure 1 for an example):

Presentation. A familiar object (e.g., a boat) appeared in the middle of the screen, and a sentence naming it started 0.5 s later (e.g., *This is a boat.*). The object stayed on the screen for another 1 s after the end of the sound file, followed by a blank screen for 0.5 s. The same procedure was repeated with an unfamiliar object (e.g., an astrolabe), which was paired with an assimilated form (e.g., *And that's a boap!*).

Request. Both objects appeared on the screen side by side, and a sentence asking the child to point to one of the objects was played 0.5 s later (e.g., *Can you find the boat now please?*). The sides were chosen at random, and the sentences were counterbalanced across three subject groups and conditions, such that each child was presented with ten test trials in each condition (five with plosives and five with nasals) and saw each picture combination once. The training and catch trials involved two standards and four mispronunciations (see Appendix, Tables A2 and A3).

Feedback. After the child had chosen an object, a short feedback loop was played to maintain motivation. Each test trial was followed by a waving alien accompanied by cartoon sounds, regardless of the child's response. For training and catch trials, corrective auditory feedback was given, and the correct object bounced around the screen. If the child gave an incorrect response on training or catch trials, they were repeated until they were correct, sometimes with help from the experimenter. After each trial, a spaceship was added at the bottom of the screen to indicate the child's progress.

Results and Discussion

Overall Results

The percentage of times the familiar object was chosen was computed for each child and each condition. In order to neutralize possible individual biases toward choosing familiar or unfamiliar objects, we derived two measures of interest from the following scores: *Perception scores,* reflecting children's sensitivity to word-final place of articulation changes, were obtained by subtracting children's score in the Mispronunciation condition from their score in the Standard condition; *assimilation scores,* reflecting children's compensation for place assimilation, were obtained by subtracting children's score in the Mispronunciation condition from their score in the Assimilation condition. Figure 2 displays these scores for each listener group.

Because of the small sample size, data were analyzed with nonparametric tests. Kruskal-Wallis rank sum tests revealed that perception, χ^2 (2) = 21.50, $p < .001$, and assimilation scores, χ^2 (2) = 16.28, $p < .001$, differed among the three groups. Pairwise comparisons using Holm-Bonferroni corrected independent Wilcoxon rank sum tests revealed that children with normal hearing had higher perception scores than children with CIs, W = 31.5, $p < .001$, and with HAs, W = 18.5, $p < .001$. The latter two groups' scores did not differ, W = 77.5, $p = .723$. Children with normal hearing also had higher assimilation scores than children with CIs, W = 45, $p < .001$, and with HAs, W = 35.5, $p = .012$. Again, the latter two groups' scores did not differ, W = 65.5, $p = .334$. Finally, scores were compared to chance level (0%) by Holm-Bonferroni corrected one-tailed Wilcoxon tests. All children's perception scores were greater than expected by chance, normal hearing: median 70%, V = 190, $p < .001$; HA: 10%, V = 40, $p = .041$; CI: 20%,

Figure 1. Example training trial.

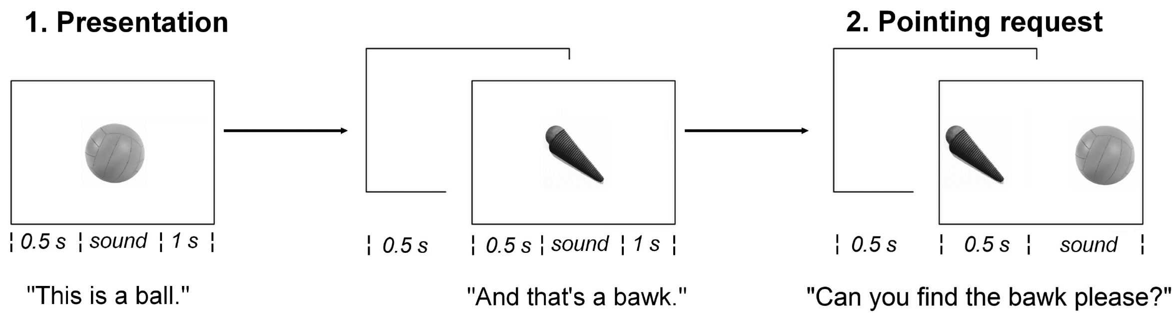


Figure 2. Overall results by condition and listener group. Boxes extend from the first to the third quartiles and whiskers extend to ±1.5 interquartile range. Dots represent individuals' performance. NH = children with normal hearing (controls); HA = children fitted with hearing aids; CI = children fitted with cochlear implants.

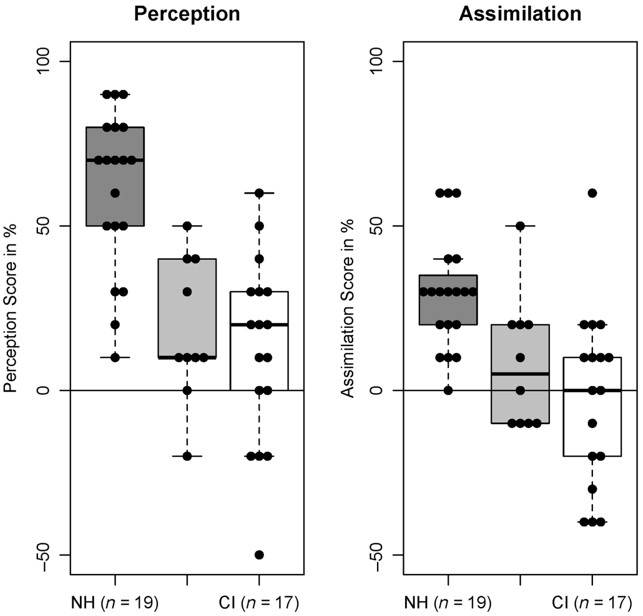
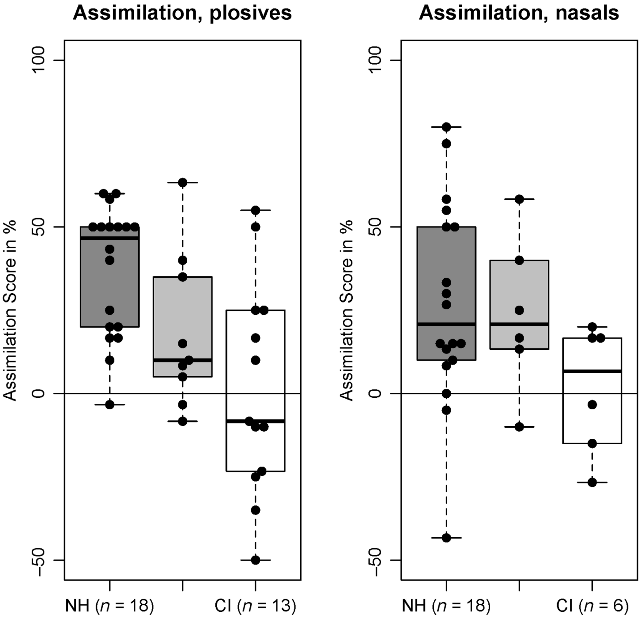


Figure 3. Assimilation scores per consonant and listener group.



V = 90, $p = .046$, but only children with normal hearing had assimilation scores that were greater than expected by chance, normal hearing: 30%, V = 171, $p < .001$; HA: 5%, V = 33; $p = .226$; CI: 0%, V = 51, $p = .707$.

In summary, both groups of children with hearing loss have perception scores that are better than chance but lower than those of children with normal hearing. This comparison should be treated with caution, however, because the groups were not matched in terms of age and other variables. Thus, children with hearing loss show some, albeit reduced, sensitivity to word-final place changes in sentences. In addition, the control children with normal hearing show assimilation effects, validating the pointing task used by Skoruppa, Mani, and Peperkamp (2013) for this age group. However, the chance-level assimilation scores in children with hearing loss indicate that they do not compensate for assimilation.

Restricted Analyses

Given the perceptual difficulties of the children with hearing loss, restricted analyses by consonant manner were carried out, only taking into account those children who had a positive perception score for the particular sounds. Assimilation scores for plosives and nasals (see Figure 3) were analyzed as before. Assimilation scores differed only among the groups for plosives, χ^2 (2) = 10.84, $p = .004$, but not for nasals, χ^2 (2) = 2.76, $p = .251$. Assimilation scores of children with normal hearing for plosives differed from those of the children with CIs, W = 43.5, $p = .010$, and with HAs, W = 38.5, $p = .049$, but the latter two groups did not differ from each other, W = 39, $p = .204$. For plosives, assimilation scores were better than chance for children with normal hearing, 46.7%, V = 170, $p < .001$, and with HAs, 10%, V = 40.5, $p = .038$, but not for children with CIs, –8.3%, V = 48.5, $p = .431$. Thus, among the children with hearing loss, better perceivers with HAs seem to be able to compensate for place assimilation in plosives. Again, this tendency should be interpreted with caution because there is a high degree of individual variability, and the performance of better perceivers with HAs does not differ significantly from that of better perceivers with CIs.

Correlation Analyses

In order to further investigate the influences on compensation for place assimilation, we explored relationships between the children's assimilation scores and other factors. The scores of children with normal hearing were not significantly correlated with age, Spearman's $\rho = .19$, $p = .426$; BPVS vocabulary raw score, $\rho = -.38$, $p = .113$; or WMTB-C digit span raw score, $\rho = -.11$, $p = .659$, suggesting that compensation for assimilation is stable across the range of ages and language abilities tested.

Similar analyses were carried out for the assimilation scores for plosives only in children with hearing loss (both groups combined because of the small sample size). There were no correlations with age, $\rho = .02$, $p = .924$; BPVS vocabulary raw scores, vocabulary: $\rho = .05$, $p = .788$; WMTB-C digit span raw scores, $\rho = .01$, $p = .945$; or DEAP phonology scores, $\rho = -.28$, $p = .162$.

General Discussion

In this study, we document that 4- to 8-year-old children with hearing loss can detect word-final changes in place of articulation in sentences, although they seem to do so less well than children with normal hearing. Good perceivers with HAs even appear to be sensitive to native place assimilations in plosives in connected speech. Thus, even reduced perceptual capacities, which lead to impoverished sensitivity to fine phonetic detail, seem to be enough for some children with hearing loss to cope with language-specific phonological variation in connected speech. This is a truly remarkable performance, given that: (a) the assimilations in this study concerned place of articulation, a difficult feature for children with hearing loss (Tyler et al., 1997); (b) assimilated sounds are often articulated less clearly than other sounds (Nolan, 1992); and (c) the perceptual abilities of children with hearing loss are certainly poorer in real-life listening conditions than in this laboratory task.

Due to the small sample size and the variability in the individual profiles of the children with hearing loss, it is hard to determine the exact factors that influence their ability to compensate for assimilation. The nature of the children's provision (HAs vs. CIs), and related to this, the severity of the impairment, the quality of children's sound perception, and the audibility of critical speech features might play a role, as compensation for assimilation could only be documented for plosives in a subgroup of hearing aid users that showed good perception of these sounds. However, the absence of a clear statistically significant difference between the two groups of children with hearing loss makes it hard to interpret this effect. Furthermore, neither age, vocabulary, digit span, nor expressive phonology were correlated with assimilation scores in the current sample. However, these and other factors, such as socioeconomic status, parental involvement, age at aiding/implantation, durations and types of interventions, device type, and speech processing strategy, may well be proven to play a role when tested in a larger scale study, as they have often been linked to speech and language outcome (for a recent review, see, for instance, Geers, Moog, Biedenstein, Brenner, & Hayes, 2009).

There are several possible reasons why most children with hearing loss failed to show compensation for assimilation in our pointing task. First, they may simply not have learned that place assimilation exists in English, due to unreliable perception of place of articulation. Second, although all the test words were early acquired nouns, they may have been less familiar to children with hearing loss than to children with normal hearing, due to reduced vocabulary and/or weaker lexical processing skills (Grieco-Calub et al., 2009). However, it is important to note that adults with normal hearing show compensation for assimilations even in nonwords (Snoeren, Gaskell, & Di Betta 2009), suggesting that assimilation is not a lexical effect and that familiarity with the assimilated words is not a necessary precondition for compensation. Third, the children with hearing loss may have approached the task differently from children with normal hearing. Our presentation phase and experience from prior extensive testing and therapy (which is mostly centered on single words) may have led them to focus on single key words and ignore word-juncture phenomena. More implicit testing—for instance, using EEG measures during passive listening—is needed in order to determine whether such a strategy is task-related or a feature of the speech perception systems of children with hearing loss in general.

The *production* of assimilations should also be tested in children with hearing loss because their production may be better than their perception. Children with CIs acquire a rich productive sound inventory within a few years of implantation (Chin, 2003; Chin & Pisoni, 2000), and their production skills can develop before perception (Kishon-Rabin et al., 2002; cf. the relatively high DEAP expressive phonology scores in this study). Children with hearing loss may use visual cues to compensate for the reduced quality of their auditory input (Tyler et al., 1997) and could thus acquire assimilations in production before compensating for them in perception.

Finally, other connected speech processes, such as final *t*/*d* elision and liaison should also be investigated, as analyses of typically developing children's productions have shown them to be mastered quite early as well (before the third birthday in a case study with a boy with normal hearing, Newton & Wells 2002).

In summary, this study highlights the importance of assessing and improving the phonological processing abilities of children with hearing loss beyond single syllables and words in order to increase their understanding of everyday connected speech.

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Appendix. Test items, training items, and catch trial items.

Table A1. Test items.

Test word	Age of acquisition
Nasals	
bin	3;8
bone	3;1
chain	3;5
clown	2;5
coin	3;1
crown	3;2
moon	2;7
pen	2;7
plane	3;2
queen	3;6
spoon	2;4
stone	3;2
swan	3;3
train	2;7
van	3;2
Plosives	
boat	2;5
foot	2;1
fruit	2;7
goat	2;6
hat	2;4
kite	2;9
knot	3;7
net	3;2
nut	2;8
plate	2;8
root	3;7
shirt	2;4
skirt	3;1
street	2;9
throat	3;0

Note. Age of acquisition = age of acquisition rating (Cortese & Khanna 2008) in years; months.

Table A2. Training items.

No.	Requested item	Other item
1	car	wug
2	bawk	ball
3	dutt	duck

Table A3. Catch trial items.

No.	Requested item	Other item
1	snate	snake
2	arm	arn
3	lan	lamb