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Point vowel duration in children with hearing aids and cochlear implants at four and five years of age

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Abstract

The present work investigates developmental aspects of the duration of point vowels in children with normal hearing compared to those with hearing aids and cochlear implants at four and five years of age. Younger children produced longer vowels than older children, and children with hearing loss produced longer and more variable vowels than their normal hearing peers. In the current study, children with hearing aids and cochlear implants did not perform differently from each other. Test age and hearing loss did not interact, indicating parallel but delayed development in children with hearing loss compared with their typically-developing peers. Variability was found to be concentrated among the high vowels /u, i/ but not in the low vowels /æ, ɑ/. The broad findings of the present work are consistent with previous reports and contribute a detailed description of point vowel duration not in the literature.

Keywords

linguistic timing; phonetic development; speech production; hearing aids; cochlear implants; childhood hearing disorders

Development of articulatory timing control is an important aspect of spoken language acquisition. Speech timing and 'temporal aspects of speech production [...] may be the most important critical factor in skilled motor performance' (Kent, 1976: p. 438). Duration is the primary articulatory feature for contrasts such as voice-onset time in stops (Liberman, Delattre, and Cooper, 1952; Lisker and Abramson, 1964) and contributes as a secondary feature to accurate expression of contrasts in vowels and other segments (Jakobson, Fant, and Halle, 1952/1963; House, 1961; Umeda, 1975; Rosen, 1992). Control of duration has also been shown to improve the intelligibility of talkers with hearing loss (Metz, Samar, and Schiavetti, 1990).

Durational control in speech production is evident before a child's first intelligible productions with refinements continuing until around 15 years of age (Lee, Potamianos, and Narayanan, 1999; Oller, 2000; Vorperian and Kent, 2007). In general, shorter segmental duration typically indicates more mature productions (Smith, 1978; Kent and Forner, 1980; Robb and Saxman, 1990), likely due to increased motor practice and planning and greater general linguistic skills. The English point vowels /æ, ɑ, u, i/ have been given attention in the literature because they define the extremes of the articulation space, are relatively easy, reliable segments to measure, and are typically the first vowels learned by native talkers (Donegan, 2002). Developmental reduction in overall vowel duration is evident for all vowels, while the point

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Declaration of interest

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vowels in particular are special targets of durational reduction at four and five years of age. Lee and colleagues (1999) collected vowel durations of ten different vowels from 436 English speaking children. They found that the youngest children in their study, 5-year-olds, produced the longest durations in the four point vowels (and in / /), but in the course of development the differences among the vowels tended to flatten out. They showed that the point vowels necessarily were more reduced than other vowels both relatively and absolutely in the course of development. Thus, developmental reduction in vowel duration ought to be most easily observed in the point vowels.

Typically-developing children have also been shown to have shorter vowels than children with phonological disorders (Weismer, Dinnsen, and Ebert, 1981; Smit and Bernthal, 1983; Robb, Bleile, and Yee, 1999), stuttering problems (Riley and Ingham, 2000), Williams Syndrome (Setter, Stoyanovik, van Ewijk, and Moreland, 2007), Fragile X Syndrome (Zajac, Harris, Roberts, and Martin, in press), and apraxia (Blech, Springer, and Kröger, 2007). Speech production characteristics in young children with hearing loss have been examined in the phonetic domain (Engen, Engen, Clarkson, and Blackwell, 1983; Blamey, Sarant, Paatsch, Barry, Bow, Wales, Wright, Psarros, Rattigan, and Tooher, 2001; Tobey, Geers, Brenner, Altuna, and Gabbert, 2003; Moeller, Hoover, Putman, Arbitaitis, Bohnenkamp, Peterson, Wood, Lewis, Pittman, and Stelmachowicz, 2007), and a few studies described below address vowel duration in particular (for a review, see Pratt and Tye-Murray, 2008).

Osberger and Levitt (1979) found that 13–15 year old children with severe to profound hearing loss (HL) produced vowels in running speech about twice as long as peers with normal hearing (NH) in both stressed and unstressed syllables. Similarly, Ryalls and Larouche (1992) found that six to nine year-olds with mild to severe HL had longer vowels and greater durational variation than their NH peers. Uchanski and Geers (2003) found that in eight and nine year old children vowel durations for children with CIs were up to 132 ms longer than in their peers with NH. Unfortunately, these studies did not report results from individual or natural classes of vowels, but rather provided mean values across all vowels. One study reported individual vowel duration in German-speaking 21-year-olds, finding that /e / and /i / were longer for CI users than NH participants (Neumeyer, Harrington, and Draxler, 2010).

Monsen (1974) tested 13–16 year old children with severe-to-profound HL reading words from a list and measured durations of /i / and /ɪ / in various following-consonant contexts, finding that adolescents with HL failed to produce vowel distinction by quality but instead used duration in an absolute manner to distinguish vowels. In English the duration of a vowel is allophonic, so durational ranges of vowels varying by quality overlap for typically developing talkers, but talkers with HL tended to fix the duration of /i / and /ɪ / into mutually exclusive, non-overlapping categories. Monsen's study suggests that duration might be a better predictor of vowel identity for children with HL because they may use duration as a distinctive feature for vowel identity while those with NH do so to a lesser extent.

Another area of interest in children with HL is the influence of cochlear implants (CI) on speech production. Some studies have found that children with HAs perform speech production tasks better than those with CIs (Miyamoto, Kirk, Robbins, Todd, and Riley, 1996; Tomblin, Spencer, Flock, Tyler, and Ganz, 1999). Other studies fail to find differences between children with HAs and CIs (Osberger, Maso, and Sam, 1993) or suggest that CI users perform similarly to children with NH in certain speech production tasks (Tye-Murray, Spencer, Bedia, and Woodworth, 1996; Goffman, Ertmer, and Erdle, 2002; Tobey, et al, 2003). With respect to durational control in particular, children with CIs have been shown to have longer durations at utterance-level rate (Pisoni and Geers 2000; Burkholder and Pisoni, 2003), in nonword repetition rate (Dillon, Cleary, Pisoni, and Carter, 2004), and for vowel duration (Uchanski and Geers, 2003). Interestingly, Uchanski and Geers further found that the CI users in their

study produced vowel durations in a more absolute manner rather than relative to contextual linguistic cues, a finding in concord with Monsen's findings reviewed above. In general, the literature does not offer a clear picture of how temporal control may or may not differ between children with HAs and those with CIs. Differences within the HL subgroups notwithstanding, the literature does suggest that children with HL, as a pooled group, have consistently longer durations than those with NH.

Another issue with pediatric CIs concerns the well-documented benefits of early intervention and implantation (Connor, Craig, Raudenbush, Heavner, and Zwolan, 2006; Niparko, Tobey, Thal, Eisenberg, Wang, Quittner, and Fink, 2010), although to date there are no longitudinal reports of vowel duration in young children with CIs. It is unknown how children implanted at a young age produce vowel durations with respect to their peers with HAs and NH, or how vowel production characteristics might develop from four to five years of age.

Finally, as a result of improved technology (newborn hearing screening, digital hearing aids, CIs, FM systems) children with HL today receive earlier intervention with better technology than those children examined in studies such as those reviewed above published decades ago. Early intervention and earlier auditory experience have been linked to a wide variety of improved outcomes (Yoshinaga-Itano, Sedey, Coulter, and Mehl, 1998; Moeller, 2000) including vowel duration (Uchanski and Geers, 2003; Dwyer, Robb, O'Beirne, and Gilbert, 2009). However, because greatly improved intervention strategies change the nature of the population being sampled, comparisons between older and more recent studies may be impossible or imprudent. Because of this complication, much previous work must be re-evaluated to be understood in terms of the present population, namely one that has had earlier identification, earlier intervention, and more advanced technology—essentially a different auditory experience. This longitudinal study will offer empirical evidence of children at four and five years of age with access to modern resources.

The main questions of the current work are (1) how does hearing loss affect the development of point vowel duration from four to five years of age, and (2) do point vowel durations differ for children with HL as a function of device, acoustic hearing aid or electrical stimulation via CI? Durations of point vowels were compared across groups of children with NH, HAs, and CIs to investigate whether they varied as a function of hearing status, device, age, or vowel type. The outcomes of this study will contribute to a gap in the literature offering empirical evidence of speech characteristics of children with HAs and CIs and those with normal hearing.

Method

Participants

The 27 children (12 with NH, 7 with HAs, 8 with CIs) in this study were tested at about four ($M = 3;11$, $SD = 2.5$ months) and five ($M = 5;0$, $SD = 2.5$ months) years of age. There was a main effect of age separating the groups ($z = -6.713$, $p < 0.0001$), but no interaction between hearing status or device type and age. All children and experimenters used their native American English exclusively.

Normal-hearing status was confirmed by distortion product otoacoustic emission (DPOAE) measures and visual reinforcement audiometry (VRA). Children with NH were typically developing and had no specific concerns for speech or language development as confirmed by age-appropriate performance on the Peabody Picture Vocabulary Test-3 (PPVT3; Dunn and Dunn, 1997).

Audiometric details are given in Table 1 by individual child with HL and by average for the groups with HAs and CIs. For all children, a combination of test techniques (VRA, conditioned

play audiometry, and DPOAEs) was used to diagnose and characterize the children's hearing loss. Target gain values specified by the Desired Sensational Level procedure (DSL [i/o] v4.1) (Moodie, Seewald, and Sinclair, 1994; Seewald, Cornelisse, Ramji, Sinclair, Moodie, and Jamieson, 1997) were used in conjunction with probe-microphone measures of gain and output as a function of frequency to determine hearing-instrument settings for the children wearing hearing aids. 'NR' indicates the child provided no response at the limits of the audiometer.

Children with HAs had mean better ear unaided pure tone averages¹ (PTAs) of 43 dB HL, and a mean aided Speech Intelligibility Index (a measure of the proportion of speech audible to the child with HAs) of .74. Children with CIs had mean better ear unaided PTAs greater than 91 dB HL, and mean aided thresholds of 24.8 dB HL. Children who later received CIs wore hearing aids for a period of 7–35 months before being implanted at an average age of 21 months. Three children with CIs were implanted bilaterally. Twelve of the children were identified with HL in the first year of life, and three of the children with HAs (S13, S14, S15) were identified later (at 20, 25, and 39 months of age, respectively). Later-identified children pattern similarly to other children with HL (detailed below) and are thus not considered as a separate group throughout. All children received prompt intervention being fitted with hearing aids on average within 1.4 (SD = 1.1) months of identification and were typically-developing in areas other than communication verified with developmental scales that included cognitive, social, and motor domains. Table 1 also includes the children's standard scores on the PPVT3 administered at 54 months of age.

Materials

Target words in the present study were selected from a subset of the Children's Speech Intelligibility Test (CSIT, Kent, Miolo, and Bloedel, 1992), a word imitation test targeting specific phonological contrasts. The procedures and words are at a basic level, appropriate for very young children or those with cognitive or motor limitations, but also appropriate for typically developing children. The subset of 18 CSIT words containing the point vowels /æ, α, u, i/ selected for the present study are shown in Table 2.

Procedure and data analysis

Children performed a live-voice, listen-and-repeat task with the experimenter, using the full set of about 40 CSIT target words and vowels in isolation. Children were tested in a laboratory playroom setting familiar to the children. After the child understood the task, the experimenter produced the model of the word and asked the child to repeat it. Upon repetition of the target item (and occasionally children would produce multiple consecutive targets), the experimenter allowed the child to feed wooden chips to a purportedly hungry jack-in-the-box type puppet to reinforce the child and maintain attention.

Children's productions were digitally recorded during each session and later segmented into individual files. Children wore a custom made vest fitted with a wireless microphone (Sennheiser EW 500 G2). The audio was routed through an amplifier (Shure M367) and recorded to mini DV media (Panasonic AG-DV2500) at a sampling rate of 44.1kHz to a single channel. Phonological segment boundaries were marked in each child's production using P_{RAAT} version 5.0.09 (Boersma and Weenink, 2009) by inspection of spectrographic and waveform displays and audio playback. Consonants and vowels were identified by characteristic order, transitions, spectral profile, voicing, and periodicity.

Raw duration values were log-transformed before being subjected to statistical analyses, but reported in (i.e. reconverted into) integer values to facilitate real-world interpretation. Mann-

¹Pure tone averages were calculated by averaging the hearing thresholds obtained at 4 frequencies: 0.5k, 1k, 2k and 4k Hz.

Whitney ranksum tests were performed to obtain z -values, Levene's test of equal variance was performed to test for difference in variance between samples in question, and 95% confidence intervals were computed based on bootstrap resampled means. Duration was plotted in logarithmic scale.

Results

Vowel duration was examined by hearing status (HL, NH), device type (HA, CI), age (4-years, 5-years), and vowel type (/æ, α, u, i/). The dependent measure was vowel duration (ms).

Influence of hearing status, device type, and age

Children with HL (collapsed across age, device type, and vowel type) had longer vowel durations than their peers with NH. Figure 1 shows the mean and confidence interval of vowel duration plotted on the ordinate for four groups of children: NH, HL, HA, and CI. The HL group comprises the pooled subjects from the HA and CI groups. As expected for vowel duration of children with HL, the central tendencies were significantly longer vowel durations ($M_{HL}=263$ ms, $Mdn_{HL}=235$ ms, $M_{NH}=213$ ms, $Mdn_{NH}=200$ ms, $z=-5.785$, $p<0.0001$), and significantly larger confidence intervals ($M_{NH}=16$ ms, $M_{HL}=21$ ms, $F=4.547$, $p=0.033$) than for children with NH.

Vowel durations by device type, HA and CI, are shown on the right of Figure 1. Vowel durations for children with HAs ($M_{HA}=267$ ms, $Mdn_{HA}=235$ ms) and children with CIs ($M_{CI}=260$ ms, $Mdn_{CI}=235$ ms) were not significantly different ($z=0.3785$, $p=0.705$). There were significant effects between the group with NH and both the group with HAs and CIs ($z=4.923$, $p<0.001$; $z=4.714$, $p<0.001$, respectively). Also as expected, Levene's test indicates variance was not the same between the group with NH and both the group with HAs and CIs ($F=46.137$, $p<0.001$; $F=40.726$, $p<0.001$, respectively).

As for the age effect on vowel duration, five year old children (collapsed across hearing status, device type, and vowel type) had shorter vowel durations ($M_{5yo}=232$ ms, $Mdn_{5yo}=211$ ms) than four year olds ($M_{4yo}=249$ ms, $Mdn_{4yo}=225$ ms). Although the difference does not reach traditional Fisherian significance ($z=1.898$, $p=0.0578$), the observed differences were in the expected direction and of the approximate expected magnitude, so the possibility of reliably shorter vowels at older ages should not be ruled out. The issue of an age effect, and its possible interaction with other factors, will be revisited below. Although a larger variance was expected at the younger age in accord with many previous reports (discussed in the introduction), there was not a significant difference in variance between four and five year olds (20ms for each) ($F=2.637$, $p=0.105$). Shorter durations at older ages, however, have a mild effect likely mediated by interacting factors not explored here such as anatomical changes, sex differences, or degree of hearing loss.

To explore the possibility that age and hearing status interact, the effect of age was tested independently for each level of hearing status and device type. Figure 2 presents means and confidence intervals by age group and hearing status (collapsing across device type and vowel type). For children with NH at four and five years of age, neither vowel duration ($M_{4yo}=219$ ms, $Mdn_{4yo}=204$ ms; $M_{5yo}=206$ ms, $Mdn_{5yo}=195$ ms; $z=1.464$, $p=0.143$) nor the variance ($F=0.0334$, $p=0.855$) was significantly different. Similarly, for children with HL at four and five years of age neither the mean vowel duration ($M_{4yo}=273$ ms, $Mdn_{4yo}=248$ ms; $M_{5yo}=254$ ms, $Mdn_{5yo}=229$ ms; $z=1.311$, $p=0.189$) nor the variance ($F=3.164$, $p=0.0757$) was significantly different.

For children with HA, there was a marginally significant effect of age on vowel duration ($M_{4yo}=287$ ms, $Mdn_{4yo}=248$ ms; $M_{5yo}=246$ ms, $Mdn_{5yo}=224$ ms; $z=-1.964$, $p=0.0495$); the

difference in variance was significant ($F=3.164, p<0.003$). There was no significant vowel duration difference between four and five year old children with CIs ($M_{4yo}=259$ ms, $Mdn_{4yo}=247$ ms; $M_{5yo}=262$ ms, $Mdn_{5yo}=231$ ms; $z=-0.1283, p=0.898$); similarly, the variance was not significantly different ($F=0.3091, p=0.5786$). Holding age constant, there were no significant group differences between the mean vowel productions of children with HA and those with CI (4-years-old: $z=1.268, p=0.205$; 5-years-old: $z=-0.7757, p=0.438$).

Influence of vowel type

There was a main effect of vowel type ($\chi^2(4, n=1211)=427.98, p<0.0001$), collapsed across age, hearing status, and device type. Duration of /æ/ ($M=172$ ms, $Mdn=161$ ms) and /ɑ/ ($M=158$ ms, $Mdn=150$ ms) were not reliably different from each other ($z=1.155, p=0.124$). Similarly, duration of /u/ ($M=319$ ms, $Mdn=322$ ms) and /i/ ($M=294$ ms, $Mdn=288$ ms) were not reliably different from each other ($z=0.3719, p=0.355$). Considering the low vowels /æ/ and /ɑ/ together and the high vowels /u/ and /i/ together, there was a significant difference between low vowels ($M=167$ ms, $Mdn=158$ ms) and high vowels ($M=306$ ms, $Mdn=302$ ms) ($z=-20.567, p<0.001$). Further, mean durations were shorter at older ages for the high vowels /u/ ($z=3.031, p<0.003$) and /i/ ($z=2.003, p<0.045$), but not for the low vowels /æ/ ($z=0.0526, p=0.958$) and /ɑ/ ($z=1.424, p=0.154$).

Table 3 gives means, medians, z-scores, and probability of difference between subgroups permuted by vowel type, age, hearing status, and device type. Age and vowel type interacted for /i/ and /ɑ/, but not for the other vowels. The relationship between age, individual vowels, and hearing status is also shown in Figure 3. In Figure 3 the duration of each vowel is plotted at four- and five-years old for children with NH and HL.

The effect of device type was not significant at any level of vowel type, confirming the failure to find a main effect of device type reported above. Data indicate that point vowel durations of children with HAs and those with CIs were similar, but children with HL were different from children with NH.

Figure 4 shows that some participants with HL and NH had longer vowels at the older age, some shorter at the older age, and others had no change in vowel duration as a function of age. The low vowels /æ/ and /ɑ/ were generally closer to the Cartesian origin than the high vowels /u/ or /i/, indicating the low vowels were generally shorter than the high vowels at either developmental age.

Figure 4 also shows the distributions of children with HL (open markers) and their age-mates with NH (filled markers) are overlapped to some degree for all vowels, but a difference between distributions as a function of hearing status (open versus filled markers) is more apparent in the high vowels. For the low vowels /æ/ and /ɑ/, the distributions of vowel durations for children with HL and those with NH do not appear to be systematically related. With the high vowels /u/ and /i/, however, the vowel durations and hearing status do seem to be systematically related such that the vowel duration distributions for children with HL are shifted primarily longer (i.e. relatively farther from the graph's origin). Although vowel-specific differences by hearing status are suggested in the high vowels in Figure 4, the overlap of distributions in all panels indicates, importantly, that group differences between children with HL and children with NH may not clearly differentiate individual children as members of one group or another.

Finally, recall that three of the children with HAs were identified with HL in the second or third year of life and four were identified in the first six months of life. This difference raises the possibility that later-identified children with HL might pattern differently than their peers with HL. However, Mann-Whitney tests revealed no effects of early or late identification

($M_{early}=264\text{ms}$, $Mdn_{early}=234\text{ms}$; $M_{late}=258\text{ms}$, $Mdn_{late}=242\text{ms}$; $z=-0.2889$, $p=0.773$), no effect of age within the late-identified children ($M_{4yo}=254\text{ms}$, $Mdn_{4yo}=245\text{ms}$; $M_{5yo}=262\text{ms}$, $Mdn_{5yo}=240\text{ms}$; $z=0.8995$, $p=0.3448$), and no difference from children with CIs ($M_{late}=258\text{ms}$, $Mdn_{late}=242\text{ms}$; $M_{CI}=260\text{ms}$, $Mdn_{CI}=236\text{ms}$; $z=-0.1522$, $p=0.879$). Thus, the later-identified children appear to pattern with other children with HL, not as a group to be considered separately. Additionally, one participant, S3 shown in Table 1, was implanted at 47 months while the other children received implants much younger, at 13–27 months of age. The age at implantation could indeed affect vowel production outcomes. While inspection of the data did not reveal participant S3 as a clear outlier, the data were not well suited to fully address this issue.

Discussion

The present work offers a detailed account of point vowel duration in children with HAs, CIs (with current technologies) and NH at four and five years old, showing that children with HL had longer vowel duration than children with NH, and younger children generally had longer vowel duration than older children. Children did not vary as a function of device type. Variability was larger for children with HL, but when grouping children by age only, variability was about the same between the ages tested here. There was no observed interaction between hearing status and age, which indicates that the children with HL developed vowel durational control at a similar rate to their peers with NH, despite longer absolute durations. This result indicates a parallel but delayed acquisition of durational control in the point vowels for children with HL. Although there was some expected individual variation, groups cluster in the same ways as the statistical analyses indicated. Two clear classes of vowels by duration emerged: high and low. High vowels are apparently the source of vowel durational differences by hearing status and at the ages tested; low vowels, although much shorter in duration, did not differentiate subgroups as the source of change by hearing status or test age.

Overall, children with HL had longer and more variable vowel durations than did their peers with NH, which is consistent with previous reports in the literature on children with HAs (Monsen, 1974; Osberger and Levitt, 1979; Ryalls and Larouche, 1992) and with CIs (Uchanski and Geers, 2003). There is, however, considerable overlap in the distributions of children with NH and HL (Figure 4). Differences in vowel duration between children with NH and HL are not of the magnitude seen in previous research (Monsen, 1974; Osberger and Levitt, 1979) likely due to advances in technology. In terms of HL, this is interpreted to indicate that vowel production development is lagging in absolute terms, but the historically large gap between children with HL and NH is less than has been reported in previous studies (Angelocci, Kopp, and Holbrook, 1964; Monson, 1974; Smith, 1978; Osberger and Levitt, 1979; Stevens, Nickerson and Rollins, 1983). It remains to be seen if this difference reflects a consistent trend that might be further improved via early intervention and technological advances.

Because device type consistently failed to differentiate children with HA and those with CI, the pooled group of children with HL will be considered henceforth. The relationships among vowel type, hearing status, and age reveal several important patterns. First, low vowels pattern together and high vowels pattern together into coherent groups. There is no overlap between the groups at any grouping or interval. Second, despite the guarded finding of an effect of age-related reduction in vowel duration, the expected trend to shorten at the older age is evident in the data in Figure 3 and partially confirmed in Table 3. That is, although negative slopes indicating age-related shortening are clear for all but one comparison (i.e., children with HL producing /æ/), the effect is significant only for /ɑ/ and /i/. Overall, an age effect is a clear possibility, but requires further observation. Third, children with HL have consistently longer point vowel productions than children with NH. The effect is more pronounced in the high vowels /u/ and /i/ and is consistent with respect to vowel type and age. Fourth, most effects

of duration are found in the high vowels. The effects of hearing status and age appear to be driven by differences in the high vowels, not by differences in the low vowels.

The primary issues not addressed in the literature are why the high vowels patterned differently from the low vowels and why the high vowels were a better indicator of hearing status. Previous studies addressing vowel productions of children with HL do not report duration details of individual vowel type differences. Broader findings of speech production characteristics of children with HL might help formulate expectations about vowel duration details, but the literature does not offer a uniform description of durations of certain vowels. For example, two studies with similar methods and goals on vowel production accuracy in 8 to 15 year old children with HL report inconsistent results. In one study, /ɑ/ is produced accurately most often, followed by /u/ and /æ/ each with about 25% less accuracy than /ɑ/, and /i/ is least accurate (Smith, 1975). Another study reports a more narrow spread and higher overall scores in production accuracy, with /i/ the most accurate rather than the least accurate (McGarr, 1987). The literature reporting production characteristics by vowel height features is also inconsistent. In one study Angelocci and colleagues (1964) report that adolescents with hearing loss produced more errors on low vowels than high vowels, while in a review article including data from children with both HAs and CIs, Pratt and Tye-Murray synthesize the literature on vowel duration in talkers with HL: 'speakers with hearing loss tend to produce low vowels more correctly than high and middle vowels' (2008: 204). Some difficulty in interpreting the literature may stem from differences in samples studied by era (i.e., the children investigated by Pratt and Tye-Murray (2008) had more advanced amplification technology than was available to the children in the Angelocci, et al (1964) sample), ages reported, data collection techniques (the current study used live-voice elicitations while other studies used different methods such as combined imitation-orthography used by Uchanski and Geers, 2003), or data analysis procedures (e.g., Uchanski and Geers (2003) report pooled duration values but the present work reports duration values by individual vowel type). Before an underlying mechanism can be seriously considered, a clear description must first be obtained.

There are two additional possible sources why high and low vowels pattern differently: physical production characteristics and linguistic context effects. The physical requirements of low vowels demand jaw lowering and are thus expected to have longer production times when compared with high vowels (Klatt, 1976). In the present work, the opposite effect of significantly shorter low vowels was observed across the board, thus suggesting that physical characteristics do not play a role in control of vowel duration for the present sample.

Linguistic context effects might also help explain the difference: properties of particular stimulus words, such as adjacent consonants or lexical status, might influence the production of those words. To assess this possibility, a leave-one-out cross-validation (LOOCV) test evaluated duration differences as a function of age, vowel type, and hearing status. LOOCV calculates the desired statistic on the data set that remains when one observation—in this case all observations from one target word—is excluded from analysis. The procedure is then repeated for every word in the data set, and results can be compared for difference. LOOCV results revealed no effect of individual word, suggesting that phonological or consonantal context, lexical status, or other word-specific details did not affect the present results.

Subgroup variability

The failure to find differences among subgroups of children with HL suggests that children with HL produce point vowel duration similarly, as a singular group without distinction between those with HAs and those with CIs. This is clearest in the high vowels, but the strong grouping effect is nonetheless robust.

There is some evidence that when compared with NH children, children with HL might experience a more rapid rate of acquisition of some features of speech production, although that accelerated rate was not observed at the ages represented in the present work. Moeller, et al, (2010) examined longitudinal development of four children with late-identified HL who wore HAs, and measured speech production at four and five years of age. They found that three of the four children appeared to resolve early delays by five years of age. Since these children were initially delayed but later performed in the average range, their rate of change was accelerated compared to children with NH. In other studies, Snow and Ertmer (2009) looked at the development of intonation in preschool children with CIs, and Ertmer and Inniger (2009) looked at the development of utterance frequency and complexity in two young children with CIs. These studies with children with HAs and CIs suggest that those children with HL may have experienced more rapid acquisition of certain linguistic features than their peers with NH, resulting in similar attained outcomes in a shorter time span. In the present work, however, the rate of change of vowel duration was not shown to be different between groups of children with NH and HL, but the direction and magnitude of changes are generally comparable to expectations based on the findings of Moeller and colleagues and Ertmer and colleagues. Given the small sample sizes in all these studies, the measures or domains used to evaluate children's performance, differences in age of children examined, and details reported, variability among these studies is expected. Nonetheless, gains by children with HL in the direction of the NH sample in all cases is an encouraging direction of change.

Overall, the present study demonstrated that children with HL control high vowel duration differently from children with NH, which may point to variable strategies used by children according to hearing status. There were no clear differences by device type, indicating children with HAs and CIs produced similar vowel durations. Finally, age is likely to affect vowel duration, but the differences at the ages tested may be attenuated by developmental or social factors not directly considered here. Further investigation into the sources of variability in the speech production of children with HL may lead to improved intervention strategies and resources.

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Figure 1.

Duration of point vowels by hearing status. Means and 95% confidence intervals are plotted for children with normal hearing (NH), hearing loss (HL), hearing aids (HA), and cochlear implants (CI). The combined groups of children with HAs and CIs comprise the group with HL.

Figure 2.

Vowel duration by age and by hearing status. NH = normal hearing; HL = hearing loss; yo = years old. Mean pooled point vowel duration is given on the ordinate, and error bars indicate 95% confidence intervals about the mean.

Figure 3.

Point vowel duration in four- and five-year-old children by hearing status. The low vowels /æ/ and /ɑ/ pattern together and the high vowels /u/ or /i/ pattern together, but the high vowels do not pattern with the low vowels. Duration values are log-scaled.

Figure 4.

The development of vowel duration among children with NH and HL at four and five years old. Panels a–d show point vowels /æ, α, u, i/, respectively. Log-scaled durations at 4 years old are plotted on the ordinate and at 5 years old on the abscissa, and the logarithmic scales are matched between ages and among all panels. Each filled marker indicates a child with HL and each open marker indicates a child with normal hearing. A dashed vector is plotted bisecting each coordinate through the origin with slope equal to 1 (i.e. for all $y = mx + b$, $y = x$, $m = 1$, and $b = 0$). Thus, a marker coincident with the reference vector indicates no age-related change in duration from four to five years old. Markers above the reference vector indicate developmental increase in vowel duration, and markers below indicate developmental decrease in vowel duration with age.

Table 1

Audiological Details of Children with HL.

Individual subject data and means are given for children with HAs (1a) and CIs (1b). Unaided better ear pure tone averages (BEPTAs), aided measures (Speech Intelligibility Index or SII, a measure of proportion of speech that is audible with amplification for HA group; aided auditory threshold for CI group), age of identification of hearing loss, age aided, age at cochlear implant (if implanted), and Peabody Picture Vocabulary Test Standard Score (at 54 months) are given. All ages are given in months and hearing thresholds in dB HL. Where two dates of CI age are listed, a second CI was implanted at the older age; if one age of implant is shown, that child had a unilateral implant with contralateral HA. The mean value for CI age is based on the age of first implant only.

(1a)						
participant	sex	Hearing Status		ID age (mo)	HA age (mo)	PPVT at 54 mos (SS)
		Unaided BEPTA (dBHL)	Aided Speech Intelligibility Index			
S9	m	67	.62	1	2	77
S10	f	36	.81	1	3	100
S11	f	63	.76	6	6	96
S12	m	30	.96	3	5	116
S13	m	22	_*	20	21	96
S14	f	52	.69	25	26	68
S15	f	33	.80	39	41	87
mean HA	-	43	.74	13	15	91

(1b)						
participant	sex	Hearing Status		ID age (mo)	HA age (mo)	PPVT at 54 mos (SS)
		Unaided BEPTA (dBHL)	Aided auditory threshold (M)			
S1	f	92	20.0	9	10	100
S2	f	97	26.3	0	5	98
S3	f	95	23.8	11	12	73
S4	m	NR	26.3	1	2	94
S5	f	80	26.3	3	4	91
S6	f	79	23.8	2	4	81

(1b)						
participant	sex	Hearing Status		ID age (mo)	HA age (mo)	CI age (mo)
		Unaided BEPTA (dBHL)	Aided auditory threshold (M)			
S7	m	85	27.5	10	10	18, 33
S8	m	112	25.0	6	7	14
mean CI	-	> 91	24.8	5.3	6.8	21
						91
						87
						104

* measure not appropriate for S13 (bone conduction aid); With the exception of S13, all children wore bilateral hearing aids.

Table 2

Words with Target Vowels

	vowel			
	æ	ɑ	u	i
	<i>bat</i>	<i>pot</i>	<i>do</i>	<i>beat</i>
	<i>pat</i>	<i>spot</i>	<i>zoo</i>	<i>tea</i>
word	<i>tap</i>	<i>hop</i>	<i>hoop</i>	<i>key</i>
	<i>cap</i>		<i>moon</i>	<i>see</i>
	<i>hat</i>		<i>new</i>	<i>mean</i>

Table 3

Central tendency duration and comparisons among vowels

Vowel duration comparisons among 4- and 5-year old children with normal hearing (NH) and hearing loss (HL). All children with HL use assistive hearing device(s), either hearing aids (HA) or cochlear implants (CI), and comparisons are considered as a function of device type as well. Rows are blocked by vowel type, giving the comparison under consideration and the levels of the factor in each row. Probability value (*p*), the standardized *z*-score computed from Mann Whitney tests, and the means and medians are calculated from bootstrapped resampled procedures. Labels **a** and **b** indicate the factor as indicated in the **factor** column, respectively.

	factor(a, b)	sig	<i>p</i>	<i>z</i> -score	<i>M</i> (a)	<i>M</i> (b)	<i>Mdn</i> (a)	<i>Mdn</i> (b)
/ æ /	Hearing (HL, NH)		0.126	-1.527	178	163	165	158
	Device type (HA, CI)		0.847	0.192	179	177	166	160
	Age (4yo, 5yo)		0.958	0.052	171	172	159	170
	4yo		0.885	-0.143	173	167	175	160
	Device type (HA, CI)		0.671	0.423	174	172	159	156
	5yo	*	0.040	-2.046	183	159	176	150
/ ɑ /	Device type (HA, CI)		0.806	-0.245	185	181	186	173
	Hearing (HL, NH)	*	0.035	-2.098	167	145	162	141
	Device type (HA, CI)		0.435	-0.779	171	163	164	161
	Age (4yo, 5yo)	*	0.002	3.031	169	145	171	136
	4yo		0.097	-1.659	180	156	178	162
	Device type (HA, CI)		0.375	-0.885	185	175	180	176
/ u /	Hearing (HL, NH)		0.094	-1.672	154	133	143	129
	Device type (HA, CI)		0.901	-0.124	157	152	140	144
	Hearing (HL, NH)	**	<0.001	-5.113	354	277	357	286
	Device type (HA, CI)		0.713	0.367	363	346	354	364
	Age (4yo, 5yo)		0.154	1.424	332	307	324	312
	4yo	**	<0.001	-3.291	367	288	368	301
/ i /	Device type (HA, CI)		0.132	1.503	399	340	404	365
	Hearing (HL, NH)	**	<0.001	-4.011	341	268	353	281
	Device type (HA, CI)		0.347	-0.939	329	351	360	337
	Hearing (HL, NH)	**	<0.001	6.454	326	248	251	326
	HL (HA, CI)		0.994	0.006	333	319	314	336

	factor(a, b)	sig	p	z-score	M (a)	M (b)	Mdn (a)	Mdn (b)
	Age (4yo, 5yo)	*	0.045	2.003	307	279	299	284
	4yo	**	<0.001	-4.746	343	258	341	258
	5yo	**	<0.001	-4.408	309	239	315	239