Phonological Priming in Children with Hearing Loss: Effect of Speech Mode, Fidelity, and Lexical Status

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Objectives: This research determined (1) how phonological priming of picture naming was affected by the mode (auditory-visual [AV] versus auditory), fidelity (intact versus nonintact auditory onsets), and lexical status (words versus nonwords) of speech stimuli in children with prelingual sensorineural hearing impairment (CHI) versus children with normal hearing (CNH) and (2) how the degree of HI, auditory word recognition, and age influenced results in CHI. Note that the AV stimuli were not the traditional bimodal input but instead they consisted of an intact consonant/rhyme in the visual track coupled to a nonintact onset/rhyme in the auditory track. Example stimuli for the word bag are (1) AV: intact visual (b/ag) coupled to nonintact auditory (-b/ag) and 2) auditory: static face coupled to the same nonintact auditory (-b/ag). The question was whether the intact visual speech would "restore or fill-in" the nonintact auditory speech in which case performance for the same auditory stimulus would differ depending on the presence/absence of visual speech.

Design: Participants were 62 CHI and 62 CNH whose ages had a group mean and group distribution akin to that in the CHI group. Ages ranged from 4 to 14 years. All participants met the following criteria: (1) spoke English as a native language, (2) communicated successfully aurally/orally, and (3) had no diagnosed or suspected disabilities other than HI and its accompanying verbal problems. The phonological priming of picture naming was assessed with the multimodal picture word task.

Results: Both CHI and CNH showed greater phonological priming from high than low-fidelity stimuli and from AV than auditory speech. These overall fidelity and mode effects did not differ in the CHI versus CNH—thus these CHI appeared to have sufficiently well-specified phonological onset representations to support priming, and visual speech did not appear to be a disproportionately important source of the CHI's phonological knowledge. Two exceptions occurred, however. First—with regard to lexical status—both the CHI and CNH showed significantly greater phonological priming from the nonwords than words, a pattern consistent with the prediction that children are more aware of phonetics-phonology content for nonwords. This overall pattern of similarity between the groups was qualified by the finding that CHI showed more nearly equal priming by the high- versus low-fidelity nonwords than the CNH; in other words, the CHI were less affected by the fidelity of the auditory input for nonwords. Second, auditory word recognition—but not degree of HI or age—uniquely influenced phonological priming by the AV nonwords.

Conclusions: With minor exceptions, phonological priming in CHI and CNH showed more similarities than differences. Importantly, this research documented that the addition of visual speech significantly increased phonological priming in both groups. Clinically these data support intervention programs that view visual speech as a powerful asset for developing spoken language in CHI.

INTRODUCTION

Children learn phonemes—the building blocks of spoken language—through their early communicative experience. Determining which part(s) of this communicative experience is critical for phonetic learning has been the focus of much previous research. Currently, the primary view proposes that children learn phonology via hearing/overhearing a variety of talkers. For this view, access to auditory input is essential for successful phonological development (e.g., Tye-Murray 1992; Tye-Murray et al. 1995; Moeller et al. 2010; Klein & Rapin 2013).

Evidence supporting a disproportionately important role for auditory input is that children with prelingual sensorineural hearing impairment develop poorer phonological skills (e.g., Gilbertson & Kamhi 1995; Briscoe et al. 2001; Nittrouer & Burton 2001; Norbury et al. 2001; Gibbs 2004; Halliday & Bishop 2005; Delage & Tuller 2007). The phonological deficits in these children are widespread and involve phoneme discrimination (detect difference between speech sounds), phonological working memory (remember speech sound pattern for a few seconds), and phonological awareness (analyze or manipulate the sounds of speech). A qualification emphasized by these studies, however, is that performance in these children varies widely.

In distinction to the above view, a less well-established orientation proposes that phonological knowledge is not exclusively auditory in nature and can be established in nonauditory ways, such as lipreading, speech production, and reading/orthography (e.g., Dodd & Campbell 1987; Kyle & Harris 2010). Evidence supporting this view is that young adults with prelingual deafness who use sign language (Deaf and Hard of Hearing, DHH) demonstrate phonological knowledge (e.g., Hanson & Fowler 1987; Engle et al. 1989; Hanson & McGarr 1989; Hanson et al. 1991; see Treiman & Hirsh-Pasek 1983 and Ormel et al. 2010 for exceptions). As an example (from a lexical decision task), DHH show faster word response times to written rhyming (WAVE–SAVE) than nonrhyming (HAVE–CAVE) pairs (Hanson & Fowler 1987). Also on a silent reading task (i.e., make judgements about tongue twister versus control sentences), DHH make more errors for the tongue twister sentences (Hanson et al. 1991). These are the normal patterns of results, and they indicate that DHH are recoding the written words phonologically.

In addition to the evidence in DHH—and in distinction to the evidence above supporting the auditory viewpoint—children and adolescents with prelingual sensorineural hearing impairment who use aural/oral or total communication approaches (CHI) may also demonstrate phonological knowledge

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(Dodd & Hermelin 1977; Dodd et al. 1983; Dodd 1987; Leybaert & Alegria 1993; Sterne & Goswami 2000; see Campbell & Wright 1988, 1990 for exceptions). Evidence in this more aural/oral group is that—on a written letter cancellation task (strike out all the g's)—CHI strike out the pronounced g's (e.g., tiger) more often than the unpronounced g's (e.g., night; Dodd 1987). Again, this is the normal pattern of results, which is attributed to the CHI recoding the words phonologically. Other studies in CHI have focused on the recency effect of serial recall tasks. The recency effect occurs when the final item of a to-be-remembered list is recalled better than the midlist items. The recency effect is prominent for auditory input, but not for visual input (Jerger & Watkins 1988). A recency effect occurs when CHI and children with normal hearing (CNH) try to recall lipread items (Dodd et al. 1983). This pattern of results indicates that lipread items act more like auditory input than visual input in memory.

Overall, these studies indicate that DHH and CHI possess an impressive degree of phonological knowledge. This finding implies that—regardless of the input route: lipreading, speech production, orthography/reading, and/or residual hearing—perceptual and cognitive processes can encode and abstract sufficient phonological knowledge to influence performance on a variety of tasks. A noteworthy qualification of the above research, however, is that CHI generally performed poorer than CNH.

Finally, another view that has also received less attention stresses the importance of visual speech in learning the phonology of spoken language (e.g., Dodd & Campbell 1987; Locke 1993; Weikum et al. 2007; Lewkowicz & Hansen-Tift 2012). From this point of view, auditory and visual speech inputs are integrated complementary essentials. This line of research assesses whether visual speech enhances auditory speech (i.e., auditory-visual [AV] versus auditory inputs). Example evidence in infants with normal hearing (infantsNH) is that visual speech improves phoneme discrimination (Teinonen et al. 2008). Example evidence in CNH is that performance is better for AV than auditory input for (1) discrimination of visually distinct phonemes (Lalonde & Holt 2015), (2) feature contrast discrimination (Hnath-Chisolm et al. 1998), and (3) vowel phoneme monitoring (Fort et al. 2012; see Boothroyd et al. 2010 for exceptions). Some age-related variability characterizes these results. Research in CHI is scant, and the results are mixed (Jerger et al. 2002a; Eisenberg et al. 2003).

The current research was conducted within the latter school of thought: visual and auditory speech (i.e., AV versus auditory inputs) as complementary essentials in phonological development. We assessed the influence of visual speech on phonological priming by high- versus low-fidelity (intact versus nonintact onsets) auditory speech in CHI and CNH. We selected phonological priming because priming is an indirect task that assesses the quality of stored phonological knowledge without requiring children to directly access and retrieve their knowledge and formulate a response. We selected nonintact auditory onsets because visual speech is more beneficial to individuals when they process low-fidelity speech. A current research question is whether the fidelity of speech matters more to CNH than CHI whose impaired ears degrade all auditory input to a lower fidelity. Below, we detail our new stimuli, the phonological priming task, our research questions, and predicted results.

New Distractors: Nonintact Auditory Onsets

The new stimuli are words and nonwords with an intact consonant/rhyme in the visual track coupled to a nonintact onset/rhyme in the auditory track (our methodological criterion excised—from the auditory onsets—about 50 msec for words and 65 msec for nonwords, see "Materials and Methods"). Stimuli are presented as AV versus auditory input. Example stimuli for the word bag are (1) AV: intact visual (b/ag) coupled to nonintact auditory (-b/ag) and (2) auditory: static face coupled to the same nonintact auditory (-b/ag). Our question was whether the intact visual speech would "restore or fill-in" the nonintact auditory speech in which case performance for the same auditory stimulus would differ depending on the presence/absence of visual speech. Responses illustrating this influence of visual speech on a repetition task (Jerger et al. 2014) are perceiving /bag/ for AV input but /ag/ for auditory input. To study the influence of visual speech on phonological priming, these stimuli were administered via the multimodal picture word (PW) task.

Phonological Priming: Multimodal PW Task

In the original "cross-modal" PW task (Schriefers et al. 1990), participants name pictures while attempting to ignore nominally irrelevant auditory speech distractors. To study phonological priming, the relation between the [picture] and [distractor] onsets is either congruent (priming condition: e.g., [bug]–[bus]) or neutral (baseline vowel-onset condition: e.g., [bug]–[onion]). The dependent measure is picture naming times and the congruent condition—relative to the baseline condition—speeds up or primes picture naming (Jerger et al. 2002b, 2009). The congruent onset is thought to prime picture naming because of crosstalk between the phonological representations that support speech perception and production (Levelt et al. 1991). Congruent distractors activate input phonological representations whose activation spreads to corresponding output phonological representations, which speeds the selection of these speech segments for naming (Roelofs 1997). In our "multimodal" PW task (Jerger et al. 2009), the speech distractors are presented AV or auditory only (see "Materials and Methods"), a manipulation that enables us to study the influence of visual speech on phonological priming.

Orientation and Research Questions

The literature reviewed above indicates that the development of phonological knowledge in CHI may involve not only residual hearing but also nonauditory factors. An interdependence between auditory and visual speech in phonological development is widely accepted for CHI (Woodhouse et al. 2009) yet the influence of visual speech on phonological processing remains understudied in CHI. Our research addressed two questions in two separate analyses: Analysis (1) Is phonological priming in CHI versus CNH differentially affected by the characteristics of the stimuli (i.e., mode, fidelity, and lexical status)? Analysis (2) In CHI, is the influence of visual speech on phonological priming uniquely affected by the degree of HI, auditory word recognition, and/or age?

Analysis 1: Predicted Results

Mode and Fidelity • Research indicates that the relative weighting of auditory and visual speech is modulated by the

relative quality of each input. To illustrate, when responding to McGurk stimuli with incongruent visual and auditory inputs (visual aka; auditory apa), CHI who are cochlear implant users listening to ear-degraded speech and CNH who are listening to experimentally degraded auditory speech respond more on the basis of the intact visual input (Huyse et al. 2013). When listening to conflicting inputs such as auditory "meat" coupled with visual "street," CNH and CHI with good auditory word recognition respond on the basis of the auditory input (Seewald et al. 1985). In contrast, CHI with more severe impairment—and more degraded perception of auditory input—respond more on the basis of the visual input. To the extent that these data obtained with conflicting auditory and visual inputs apply to our study, these results predict that both CNH and CHI may weight the intact visual speech more heavily than the nonintact auditory speech—and this should produce a significant influence of visual speech for our low-fidelity auditory speech in both groups. When this "fidelity" effect (with its relatively greater weighting of the intact visual speech) is coupled with the relatively greater weighting of the phonetic-phonological content for nonwords (Mattys et al. 2005, see immediately below), a significantly greater influence of visual speech will be observed for nonwords than words.

Words Versus Nonwords (e.g., Bag Versus Baz) • The hierarchical model of speech segmentation (Mattys et al. 2005) proposes that listeners assign the greatest weight to (1) lexical-semantic content when listening to words and (2) phonetic-phonological content when listening to nonwords. It is also assumed that familiar monosyllabic words such as our stimuli (bag) may activate their lexical representations without requiring phonological decomposition whereas nonwords (baz) require phonological decomposition (Morton 1982; Mattys 2014). If these ideas generalize to our task, word stimuli should be heavily weighted in terms of lexical-semantic content, whereas nonword stimuli should be heavily weighted in terms of phonetic-phonological content for both AV and auditory speech. A greater weight on phonetics phonology for the nonwords should increase children's awareness of the phonetic-phonological content and produce greater priming for the nonwords.

Previous Results on the PW Task • Previous results in CHI are perplexing: Intact congruent phonological distractors produced significant priming on the cross-modal PW task with nonsense syllable distractors—e.g., [picture]–[distractor]: [pizza]–[pi] (Jerger et al. 2002b)—but not on the multimodal PW task with word distractors—e.g., [picture]–[distractor]: [pizza]–[peach] (Jerger et al. 2009). These results predict that the intact auditory nonword distractors, but not the intact word distractors, will significantly prime picture naming in CHI. Previous results in CNH (Jerger et al. 2016) on the multimodal PW task with the new distractors of this study showed significant priming by all auditory and AV distractors (with a minor exception). Furthermore, overall picture naming times showed greater priming from the intact than nonintact distractors and from the AV than auditory distractors. The addition of visual speech boosted priming significantly more for the nonintact nonwords than nonintact words. If these results in CNH generalize to CHI, we predict that all of the AV and auditory distractors, but particularly the intact onsets, will significantly prime naming. Furthermore, we predict significant greater priming by the AV distractors, particularly for the nonintact nonwords.

Analysis 2: Predicted Results

We analyzed the influence of visual speech as a unique function of degree of HI, auditory word recognition, and age. We defined "unique" statistically as the independent contribution of each variable after controlling for the other variables (Abdi et al. 2009). Below, we focus on a few relevant points about these child factors.

Degree of HI, Suprathreshold Auditory Word Recognition, and Age • Sensorineural HI impairs not only the threshold hearing sensitivity but also the processing of suprathreshold sounds (e.g., because of reduced spectral and temporal resolution, Moore 1996). The outcome of these dual impairments is that suprathreshold auditory word recognition in CHI with the same threshold hearing sensitivity loss can vary widely (Erber 1974). These findings indicate that the influence of visual speech may be more readily predicted by auditory word recognition (a measure of functional hearing status taking into account suprathreshold distortions) than by degree of HI (a measure of threshold impairment for pure tones). A previous study in cochlear implant users supports this idea, showing that CHI who are better at recognizing auditory words benefit more from visual speech (Lachs et al. 2001). With regard to age, previous results on the multimodal PW task with the new distractors in CNH (Jerger et al. 2016) showed one significant age effect, namely greater overall priming in younger than older children. By contrast, visual speech influenced performance in all CNH from 4 to 14 years, with greater priming by the AV than auditory distractors. If these results in CNH generalize to CHI, we predict a significant visual speech effect (VSPE) at all ages, with significantly greater overall priming in younger CHI.

Recapitulation

The evidence reviewed above establishes that perceiving everyday speech is an AV event with visual speech serving as an important source of phonological knowledge. Despite this backdrop, phonology and speech perception are typically studied only in the auditory mode—even in CHI. The current research will provide critical new information about how visual speech contributes to phonological priming in CHI. Such data could have clinical implications for current intervention programs that emphasize listening in the auditory mode only as the optimal approach for developing spoken language (e.g., Lew et al. 2014).

MATERIALS AND METHODS

Participants

Groups • Participants were 62 CHI with early-onset sensorineural loss (55% girls) and 62 CNH (55% girls). The CNH group—whose ages yielded a group mean and group distribution akin to that in the CHI group—was formed from a pool of 132 CNH from associated projects (Jerger et al. 2014, 2016). Ages (yr; mo) ranged from 4; 1 to 14; 9 (M = 9; 2) in the CHI and 4; 2 to 14; 5 (M = 9; 1) in the CNH. The racial distributions were 73% Whites, 22% Blacks, and 5% Asian in CHI and 82% Whites, 6% Blacks, 8% Asian, and 4% multiracial in CNH, with 9% of CNH reporting Hispanic ethnicity. All participants met the following criteria: (1) English as a native language, (2) ability to communicate successfully aurally/orally, and (3) no diagnosed or suspected disabilities other than HI and its accompanying speech and language problems.

TABLE 1. Average age and performance (standard deviation in parentheses) on set of nonverbal, verbal, and speech perception measures in the CNH vs. CHI

	Groups	
	CNH N = 62	CHI N = 62
Age (yr; mo)	9; 1 (3; 0)	9; 2 (3; 3)
Nonverbal skills		
Simple reaction time (msec)		
Auditory	578 (161)	611 (240)
Visual	771 (255)	754 (318)
Visual perception (standard score)	114.34 (14.08)	99.73 (15.50)
Verbal skills		
Vocabulary (standard score)		
Receptive	120.50 (11.25)	94.39 (16.23)
Expressive	120.52 (11.91)	87.43 (12.16)
Articulation proficiency (# errors)	0.73 (1.70)	4.98 (8.39)
Phonological awareness (%)	78.02 (10.68)	66.16 (26.07)
Word recognition (%)		
Auditory	99.87 (0.71)	89.35 (11.94)
AV	*	95.92 (10.49)
Lipreading onsets†	66.57 (15.56)	68.87 (21.96)

Simple reaction times were estimated by a laboratory button push task quantifying the speed of detecting and responding to a predetermined auditory or visual target. Visual perception was estimated by the Beery-Buktenica Developmental Test of Visual Perception (Beery & Beery 2004). Vocabulary skills were estimated with the Peabody Picture Vocabulary Test-III (Dunn & Dunn 2007) and the Expressive One-Word Picture Vocabulary test (Brownell 2000). Articulation proficiency was estimated with the Goldman Fristoe Test of Articulation (Goldman & Fristoe 2000). Phonological awareness was estimated with subtests of the pre-reading inventory of phonological awareness (Dodd et al. 2003). Spoken word recognition at 70 dB SPL was estimated with the WIPI test (auditory mode; Ross & Lerman 1971) and the CAVET (auditory, AV, and visual only (lipreading) modes; Tye-Murray & Geers 2001).

*Test was not administered in the AV mode due to ceiling performance in the auditory only mode.

†Lipreading onsets was selected because we are assessing phonological priming by onsets; lipreading words averaged 17.38% in CNH and 24.27% in CHI.

AV, auditory-visual; CAVET, Children's Audiovisual Enhancement Test; CHI, children with prelingual sensorineural hearing impairment; CNH, children with normal hearing; WIPI, word intelligibility by picture identification.

Audiological Characteristics • Hearing sensitivity in the CNH at hearing levels (HLs) of 500, 1000, and 2000 Hz (pure-tone average, PTA; American National Standards Institute, ANSI 2004) averaged 2.83 dB HL (SD = 4.66; right ear) and 3.68 dB HL (SD = 5.35; left ear). The PTAs in the CHI averaged 49.80 dB HL (SD = 21.43; right ear) and 52.39 dB HL (SD = 24.34; left ear). Average PTAs on the two ears were distributed as follows: ≤20 dB (5%), 21 to 40 dB (27%), 41 to 60 dB (36%), 61 to 80 dB (27%), and 81 to 102 dB (5%). The children with PTAs of ≤20 dB had losses in restricted frequency regions. Hearing aids were used by 90% of the children. Participants who wore amplification were tested while wearing their devices. The estimated age at which the children who wore amplification received their first device averaged 2.79 years (SD = 2.09); the estimated duration of device use averaged 6.17 years (SD = 3.21). Forty-six children were mainstreamed in a public school setting and 16 children were enrolled in an aural/oral school for CHI.

Comparison of Groups • Table 1 compares results of the CNH and CHI on a set of nonverbal and verbal measures. The nonverbal and verbal measures were analyzed with mixed design analyses of variance with one between-participants factor (group: CNH versus CHI) and one within-participants factor (measure). The nonverbal measures were standardized scores for simple auditory reaction time (RT), simple visual RT, and visual perception. The verbal measures were standardized scores for receptive vocabulary, expressive vocabulary, articulation, phonological awareness, auditory word recognition, and lipreading.

The nonverbal results indicated a significant difference between groups and a Significant Measures × Groups interaction, respectively $F(1,122) = 23.74$, mean square error (MSE) = 0.178, $p < .0001$, partial $\eta^2 = 0.163$ and $F(2,244) = 11.36$, MSE = 0.438, $p < .0001$, partial $\eta^2 = 0.085$. Multiple t tests with the problem of multiple comparisons controlled with the false discovery rate procedure (Benjamini & Hochberg 1995) indicated that the speed at which the CNH and the CHI could detect auditory and visual inputs (simple RT) did not differ. By contrast, visual perception was significantly better in the CNH than the CHI. The reasons for this latter difference are unclear. Performance for both groups, however, was within the average normal range.

The verbal results indicated a significant difference between groups and a Significant Measure × Group interaction, respectively $F(1,122) = 25.48$, MSE = 1.497, $p < .0001$, partial $\eta^2 = 0.173$ and $F(5,610) = 21.24$, MSE = 0.721, $p < .0001$, partial $\eta^2 = 0.148$. Multiple t tests controlled with the false discovery rate correction indicated that auditory word recognition, phonological awareness, articulation proficiency, and receptive and expressive vocabulary were significantly better in the CNH, whereas lipreading onsets did not differ between the groups. In short, the CHI versus CNH showed mostly similarities in their nonverbal skills and differences in their verbal skills as expected. Interestingly—to foreshadow our results—these significant differences in verbal skills observed on direct tasks (i.e., children were informed about the targets of interest and were consciously responding during a post stimulus interval) did not produce significant differences in phonological priming on our indirect PW task (i.e., children were not informed about nor asked to attend to or consciously respond to the distractors, our targets of interest; see Jordan & Bevan 1997 for similar results between direct versus indirect measures for lipreading). Finally, we should acknowledge that vocabulary scores in the CNH indicated higher than average vocabulary knowledge, and that such performance could potentially affect the generalizability of these results to CNH with more "average" vocabulary abilities.

Materials and Instrumentation: PW Task

Pictures and Distractors • The pictures and word/nonword distractors consisted of experimental items (8 pictures beginning with /b/ or /g/ and 12 distractors beginning with /b/ or /g/ or a vowel) and filler items (16 pictures and 16 distractors beginning with consonants other than /b/ or /g/; see Appendix A in Supplemental Digital Content, http://links.lww.com/EANDH/A278, for items and see Jerger et al. 2016 for details). As noted above, the relation between the experimental [picture]–[distractor] onsets was manipulated to be congruent (priming condition: e.g., [bug]–[bus/buhl]) or neutral (baseline vowel-onset condition: e.g., [bug]–[onion/onyit]). The filler items consisted of [picture]–[distractor] pairs not sharing an onset and not beginning with /b/ or /g/, for example, [cookies]–[horse/hork]. To ensure that the subsequent results were reflecting performance for words versus nonwords, the participants' understanding of

the meaning of the experimental word distractors was assessed (see Supplemental Appendix B, http://links.lww.com/EANDH/A279).

Stimulus Preparation • The distractors were recorded by an 11-year-old boy actor. He started and ended each utterance with a neutral face and closed mouth. The color video signal was digitized at 30 frames/s with 24-bit resolution at a 720 × 480 pixel size. The auditory signal was digitized at 48 kHz sampling rate with 16-bit amplitude resolution and adjusted to equivalent A-weighted root mean square sound levels. The video track was routed to a high-resolution monitor, and the auditory track was routed through a speech audiometer to a loudspeaker. The intensity level of the distractors was approximately 70 dB SPL. The to-be-named colored pictures were scanned into a computer as eight-bit PICT files (Jerger et al. 2016).

Editing the Auditory Onsets • We edited the auditory track of the phonologically related distracters by locating the /b/ or /g/ onsets visually and auditorily with Adobe Premiere Pro and Soundbooth (Adobe Systems Inc., San Jose, CA) and loudspeakers. We applied a perceptual criterion to operationally define a nonintact onset. We excised the waveform in 1 msec steps from the identified auditory onset to the point in the later waveforms for which at least 4 of 5 trained listeners heard the vowel—not the consonant—as the onset in the auditory mode. Splice points were always at zero axis crossings. Using this perceptual criterion, we excised on average 52 msec (/b/) and 50 msec (/g/) from the word onsets and 63 msec (/b/) and 72 msec (/g/) from the nonword onsets (Jerger et al. 2016).

All stimuli were presented as quicktime movie files, and we next formed AV (dynamic face) and auditory (static face) presentations. In our experimental design, we compare results for the auditory versus AV nonintact stimuli. Any coarticulatory cues in the auditory input are held constant in the two modes; thus any influence on picture naming due to coarticulatory cues should be controlled and allow us to evaluate whether the addition of visual speech influences performance.

AV and Auditory Inputs • For the AV input, the children saw: (1) 924 msec (experimental trials) or 627 or 1221 msec (filler-item trials) of the talker's still face and upper chest, followed by (2) an AV utterance of a distractor and presentation of a picture on the talker's T-shirt 165 msec before the auditory onset of the utterance (auditory distractor lags picture), followed by 3) 924 msec of still face and picture. For the auditory mode, the child heard the same event with the video track edited to contain only the talker's still face and upper chest. The onset of the picture occurred in the same frame for the intact and nonintact distracters. The relation between the onsets of the picture and the distractor—called stimulus onset asynchrony (SOA)—is also a key consideration for the PW task.

SOA • Phonologically related distracters typically produce a maximal effect on naming when the auditory onset of the distractor lags the onset of the picture by about 150 msec (Schriefers et al. 1990; Damian & Martin 1999). Our SOA was 165 msec as used previously (Jerger et al. 2009). We acknowledge, however, that the nonintact auditory onset altered the target SOA of 165 msec. Our experimental design should control for any performance differences produced by the altered SOA, however, because we compare results for the auditory versus AV nonintact stimuli, with the auditory onset held constant in the two modes. Thus any influence on picture naming produced by the shift in the auditory onset is controlled and this allows us to evaluate whether the addition of visual speech influences performance.

We also acknowledge that the nonintact onset slightly alters the normal temporal asynchrony between the auditory and visual speech onsets. Previous evidence suggests that this shift in the auditory onset of the nonintact stimuli will not affect our results. Specifically, AV speech is normally asynchronous, with visual speech leading auditory speech by variable amounts (Bell-Berti & Harris 1981; Ten Oever et al. 2013). Adults with NH synthesize visual and auditory speech—without any detection of the asynchrony and without any effect on intelligibility—even when visual speech leads by as much as 200 msec (Grant et al. 2004). CNH of 10 to 11 years perform like adults for AV asynchrony when visual speech leads (Hillock et al. 2011), but CNH of 4 to 6 years have a wider window and do not detect AV asynchrony until visual speech leads by more than 366 msec (Pons et al. 2013). Below, we summarize our final set of materials.

Final Set of Items • Two presentations of each auditory and AV experimental item (i.e., baseline and intact versus nonintact phonetically related distractors) were randomly intermixed with the filler items and formed into four lists (presented forward or backward). Each list contained 57% experimental and 43% filler items. The items of a list varied randomly under constraints such as (1) no onset could repeat, (2) the intact and nonintact pairs (e.g., bag and /-b/ag or vice versa) could not occur without at least two intervening items, (3) one-half of items must occur first AV and one-half first auditory, and (4) all types of onsets (vowel, intact /b/ and /g/, nonintact /b/ and /g/, and not /b/ or /g/) must be dispersed uniformly throughout the lists (Jerger et al. 2016).

Naming Responses • To quantify picture naming times, the computer triggered a counter/timer with better than 1 msec resolution at the initiation of each movie file. The timer was stopped by the onset of the naming response into a unidirectional microphone which was fed through a stereo mixing console amplifier and attenuator to a voice-operated relay. A pulse from the voice-operated relay stopped the timing board via a data module board. The counter timer values were corrected for the amount of silence in each movie file before the onset of the picture.

Procedure

The children completed the multimodal PW task along with other procedures in three sessions occurring (1) on 3 days for the CNH and (2) on 1 (16%), 2 (40%), or 3 (44%) days for the CHI. The interval between testing days averaged 12 days in each group. The order of presentation of the word versus nonword conditions was counterbalanced across participants in each group. Results were collapsed across the counterbalancing conditions. In the first session, the children completed three of the word (or nonword) lists; in the second session, the children completed the fourth word (or nonword) list and the first nonword (or word) list; and in the third session, the children completed the remaining three nonword (or word) lists. A variable number of practice trials introduced each list.

At the start of the first session, a tester showed each picture on a card, asking children to name the picture and teaching the

target names of any pictures named incorrectly. Next, the tester flashed the picture cards quickly and modeled speeded naming. Speeded naming practice trials went back and forth between the tester and child until the child was naming the pictures fluently. Minipractice trials started the other sessions.

For formal testing, a tester sat at a computer workstation and initiated each trial by pressing a touch pad (out of child's sight). The children, usually with a cotester alongside, sat at a distance of 71 cm in front of an adjustable height table containing the computer monitor and loudspeaker. Trials that the tester or cotester judged flawed were deleted online and readministered after intervening items. The children were told that they would see and hear a boy whose mouth would sometimes be moving and sometimes not. For the words, participants were told that they might hear words or nonwords because some of the nonintact words (e.g., /-B/ag) may be perceived as nonwords (e.g., ag), especially in the auditory mode. For the nonwords, participants were told that they would always hear nonwords. Participants were told to focus on (1) watching for the picture that would pop up on the boy's T-shirt and (2) naming it as quickly and as accurately as possible. The participant's view of the picture subtended a visual angle of 5.65 degree vertically and 10.25 degree horizontally; the view of the talker's face subtended a visual angle of 7.17 degree vertically (eyebrow–chin) and 10.71 degree horizontally (at eye level). This research protocol was approved by the Institutional Review Boards of University of Texas at Dallas and Washington University, St. Louis.

RESULTS

Preliminary Analyses

The quality of the PW data (e.g., number of missing trials) is detailed in Appendix B in Supplemental Digital Content (http://links.lww.com/EANDH/A280). Initially, we also analyzed the PW data to determine whether results could be collapsed across the distractor onsets (/b/ versus /g/; see Appendix C in Supplemental Digital Content, http://links.lww.com/EANDH/A280, for results). In brief, separate factorial mixed design analyses of variance were performed for the baseline distractors and the phonologically related distractors. Findings indicated that the different onsets influenced results only for the phonologically related distractors; overall picture naming times were facilitated slightly more for the /b/ than /g/ onset (−142 versus −110 msec). Despite this statistically significant outcome, the difference in performance due to onset was minimal (32 msec), and no other significant onset effects were observed. These results agree with our previous findings (Jerger et al. 2016); phonological priming by /b/ and /g/ onsets does not show the pronounced differences that characterize identifying these phonemes on direct measures of speech reading (see Jordan & Bevan 1997 for similar results). Thus, for the analyses below, naming times were collapsed across the onsets to promote clarity and accessibility.

Analysis 1: Lexical Status, Mode, and Fidelity

Baseline Distractors • Figure 1 shows average picture naming times in the groups for the auditory versus AV word (left) and nonword (right) baseline distractors. Results were analyzed with a factorial mixed design analysis of variance with one between-participants factor (group: CHI versus CNH) and two within-participants factors (lexical status: words versus nonwords and
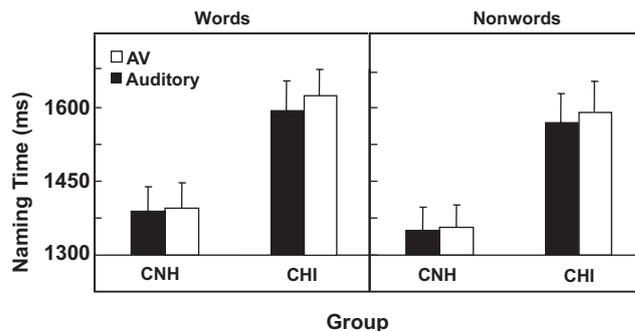

Fig. 1. Average picture naming times for the groups in the presence of the baseline vowel-onset distractors for the words (left) and nonwords (right) presented as auditory or AV input. Error bars are one standard error of the mean.

mode: auditory versus AV). Table 2 summarizes the results (significant results are bolded). Overall picture naming times were significantly faster for the CNH than the CHI, respectively, 1372 versus 1591 msec. Overall naming times were also significantly faster for (1) auditory than AV speech (1473 versus 1489 msec) and (2) nonwords than words (1464 versus 1499 msec), but these numerical differences were notably small (16 and 35 msec). No other significant effect was observed.

The above difference in the baseline times between groups was large enough (about 220 msec) that it could be problematic for our traditional approach of quantifying phonological priming with adjusted naming times (derived by subtracting each participant's baseline naming times from his or her phonologically related naming times; Jerger et al. 2002a, 2009). The different baselines could muddle an unequivocal interpretation of any group differences. To control the differences in baseline performance, we quantified priming proportions—derived by dividing each participant's adjusted naming times by his or her corresponding baseline naming times (Damian & Dumay 2007). Greater priming is indicated by a larger negative proportion.

Phonologically Related Distractors • Figure 2 depicts average priming proportions in the CHI versus CNH for the high-versus low-fidelity stimuli presented as auditory and AV speech (left versus right panels). Results are presented for the words (Fig. 2A) and nonwords (Fig. 2B). An initial multifactorial analysis with all factors yielded a complex higher order interaction (Lexical Status × Fidelity × Mode, elaborated at the end of the results section). Thus—before considering the effects of lexical status—results were analyzed separately for the words and nonwords with a factorial mixed design analysis of variance with one between-participants factor (group: CHI versus CNH) and two within-participant factors (fidelity: low versus high; mode: auditory versus AV). Table 3 summarizes the results.

Words • Overall priming for the words did not differ in the CNH versus CHI (Fig. 2A). The other main factors, however, did significantly influence the phonological priming of picture naming, with a significant effect of fidelity and mode. Both the CNH and CHI showed greater priming by the intact than nonintact distractors (respectively −0.074 versus −0.050 when collapsed across mode). Both the CNH and CHI also showed greater priming from the AV than auditory distractors (−0.075 versus −0.049 when collapsed across fidelity). This latter result is particularly relevant because this pattern highlights a significant benefit of visual speech on performance for all children.

TABLE 2. Summary of statistical results for baseline distractors

Factors	Mean Square error	F	p	Partial η²
Group	**691,843.11**	**8.60**	**.004**	**0.066**
Mode	**6116.18**	**5.65**	**.019**	**0.044**
Lexical status	**28,495.62**	**5.34**	**.023**	**.042**
Group × Mode	6116.18	1.49	ns	-
Group × Lexical Status	28,495.62	0.06	ns	-
Mode × Lexical Status	4063.39	0.18	ns	-
Group × Mode × Lexical Status	4063.39	0.08	ns	-

Results of a mixed design analysis of variance with one between-participants factor (group: CHI vs. CNH) and two within-participants factors (mode: auditory vs. AV; lexical status: words vs. nonwords). The dependent variable is the baseline naming times in msec. The degrees of freedom are 1,122 for all factors.
AV, auditory visual; CHI, children with prelingual sensorineural hearing impairment; CNH, children with normal hearing; ns, not significant.

No other significant effect was observed. Results in the CNH and CHI did not differ for the word stimuli.

Nonwords • Overall priming for the CHI and CNH again did not differ (Fig. 2B). The other main factors that significantly influenced phonological priming were (1) fidelity, showing greater priming by the intact than nonintact distractors (respectively −0.111 versus −0.081 when collapsed across mode) and (2) mode, showing greater priming by the AV than auditory distractors (−0.114 versus −0.078 when collapsed across fidelity). As seen in Table 3, however, significant interactions between and among all possible factors complicated a simple account of these main effects. To clarify the interactions, we reanalyzed results for each mode separately with a factorial mixed design analysis of variance with one between-participants factor (group: CHI versus CNH) and one within-participant factors

(fidelity: high versus low). The results are summarized at the bottom of Table 3.

The separate analyses revealed that the previously noted Group × Fidelity × Mode interaction occurred because of the differences in the pattern of results for the two modes. For the AV input, the priming of picture naming in the CNH and CHI did not differ. The only significant effect was that the intact distractors produced greater priming than the nonintact distractors (respectively −0.122 versus −0.106). For the auditory mode, the fidelity of the stimuli again affected priming, but this time with a Fidelity × Group interaction. Priming by the

TABLE 3. Summary of statistical results for phonologically related distractors

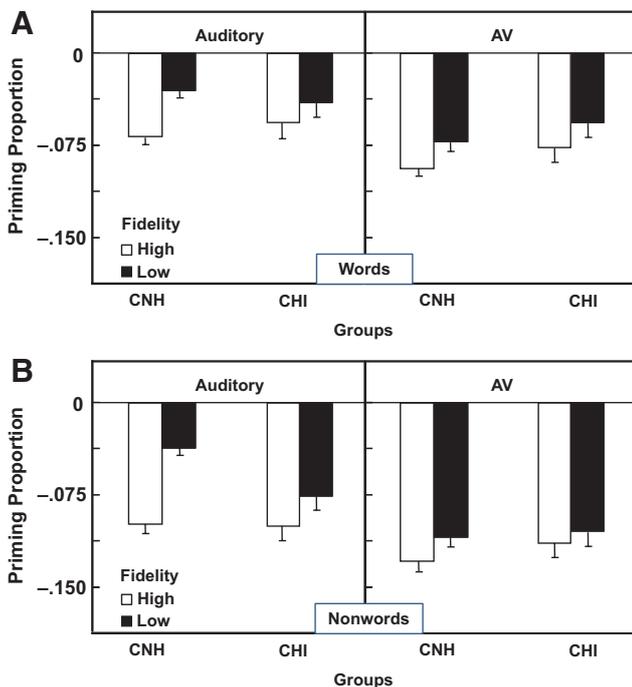| Factors	Mean Square Error	F	p	Partial η²
Words				
Group	0.016	0.54	ns	-
Fidelity	0.072	**32.04**	**< .0001**	**.209**
Mode	0.087	**22.25**	**< .0001**	**.155**
Group × Fidelity	0.004	1.92	ns	-
Group × Mode	0.007	1.83	ns	-
Fidelity × Mode	0.002	1.52	ns	-
Group × Fidelity × Mode	0.003	2.42	ns	-
Nonwords				
Group	0.002	0.15	ns	-
Fidelity	0.107	**63.95**	**<.0001**	**0.347**
Mode	0.156	**33.01**	**<.0001**	**0.215**
Group × Fidelity	0.018	**10.63**	**.001**	**0.082**
Group × Mode	0.028	**5.87**	**.017**	**0.047**
Fidelity × Mode	0.027	**15.74**	**.0001**	**0.117**
Group × Fidelity × Mode	0.007	**4.13**	**.044**	**0.033**
Nonwords for each mode separately				
AV				
Group	0.010	0.69	ns	-
Fidelity	0.001	**10.43**	**.002**	**0.078**
Group × Fidelity	0.001	1.04	ns	-
Auditory				
Group	0.009	2.75	ns	-
Fidelity	0.002	**57.33**	**<.0001**	**0.319**
Group × Fidelity	0.002	**10.67**	**.001**	**0.081**

Fig. 2. Average priming proportions in the CHI vs. CNH for the high (intact) and low (nonintact) fidelity stimuli presented as auditory (left) or AV (right) input. Results are presented for the words (A) and nonwords (B). Error bars are one standard error of the mean. We derived the priming proportions by dividing each participant's adjusted naming times by his or her corresponding baseline naming times. Greater priming is indicated by a larger negative proportion. CHI, children with prelingual sensorineural hearing impairment; CNH, children with normal hearing.

Results of a mixed design analysis of variance with one between-participants factor (group: CHI vs. CNH) and two within-participants factors (fidelity: intact vs. nonintact; mode: auditory vs. AV) followed by analyses of the nonwords for each mode separately. The dependent variable is the priming proportions ([mean time in the phonologically related condition minus mean time in the baseline condition] divided by [mean time in the baseline condition]). The degrees of freedom are 1,122 for all factors. Significant p values are in bold.
AV, auditory visual; CHI, children with prelingual sensorineural hearing impairment; CNH, children with normal hearing; ns, not significant.

TABLE 4. Summary of F contrast results

	High (Intact) Fidelity				Low (Nonintact) Fidelity			
	Mean Square Error	$F_{contrast}$	p	Partial η^2	Mean Square Error	$F_{contrast}$	p	Partial η^2
Group								
Words								
CNH	0.001	18.13	**<.0001**	0.129	0.001	47.32	**<.0001**	0.279
CHI	0.001	10.73	**.001**	0.081	0.001	7.75	**.006**	.060
Nonwords								
CNH	0.002	16.68	**<.0001**	0.120	0.002	96.10	**<.0001**	0.441
CHI	0.002	3.63	.06	0.029	0.002	14.53	**.0002**	0.106

Significant p values are bolded. df = 1,122.
CHI, children with prelingual sensorineural hearing impairment; CNH, children with normal hearing.

intact versus nonintact auditory distractors differed significantly more in the CNH (respectively −0.099 versus −0.037) than in the CHI (−0.100 versus −0.076). Stated differently, the high-fidelity auditory input primed picture naming similarly in the CHI and CNH (−0.100 versus −0.099), whereas low-fidelity auditory input primed picture naming to a greater extent in CHI than in CNH (−0.076 versus −0.037). Priming in the CHI was less affected by the fidelity of the auditory input. Next, we determined whether phonological priming was greater for the nonwords than words as predicted.

Lexical Status • The initial multifactorial analysis with all factors can be used to address the effects of lexical status. This analysis indicated significantly greater overall priming for the nonwords than the words, respectively, −0.096 versus −0.062, $F(1,122) = 42.62$, MSE = .007, $p < .0001$, partial $\eta^2 = 0.259$. As noted above, however, a significant complex interaction was also observed, Lexical Status × Fidelity × Mode: $F(1,122) = 4.06$, MSE = .002, $p < .040$, partial $\eta^2 = 0.034$. Although we did not have sufficient statistical power to detect the higher fourth order interaction (Lexical Status × Fidelity × Mode × Group), the significant third order interaction is most easily understood by the above differences for mode and fidelity that were observed for the nonwords but not for the words (and which also involved the group). No other significant effects or interactions for lexical status were observed. In addition to these results addressing differences between the groups, it is also relevant to consider whether priming within each group differed for auditory versus AV speech.

Did the Addition of Visual Speech Produce Significantly Greater Priming? • To evaluate whether priming by auditory versus AV speech differed significantly for each condition in each group, we carried out planned orthogonal contrasts (Abdi & Williams 2010). Table 4 summarizes the results. The CNH showed

a significant benefit from visual speech—subsequently called the VSPE—for both words and nonwords in the high- and low-fidelity conditions. The CHI showed a significant VSPE for both conditions for the words, but only for the low-fidelity condition for the nonwords. That said, results for the high-fidelity nonwords in the CHI approached significance. Next, we consider whether/how the results were influenced by the children's hearing status and age.

Analysis 2: Unique Effect of Degree of HI, Auditory Word Recognition, and Age in CHI

To understand the unique effects of degree of HI, auditory word recognition, and age on phonological priming, we carried out separate multiple regression analyses for the words and nonwords. We defined "uniquely" statistically as expressed by part correlations, which reveal the independent contribution of a variable after controlling for all the other variables (Abdi et al. 2009). We did not include fidelity in these analyses because stimulus intactness influenced results only minimally in the CHI (for high versus low fidelity, respectively, −0.087 versus −0.069 for CHI and −0.098 versus −0.062 for CNH). The degree of HI was quantified by the average four-frequency (500 to 4000 Hz) PTA of the two ears. The dependent variable was the priming proportions; the independent variables were the standardized scores for auditory word recognition, degree of HI, and age. The intercorrelations among this set of variables were as follows: (1) Auditory word recognition versus degree of HI (0.271) and age (0.194) and (2) Age versus degree of HI (0.113). Results of the multiple regression analysis indicated that degree of HI, auditory word recognition, and age did not influence priming by the word stimuli. Thus only results for the nonwords are elaborated.

Table 5 shows the slopes, part correlation coefficients, and partial F statistics evaluating the variation in nonword

TABLE 5. The part correlation coefficients and p values evaluating the variation in the priming proportions for the nonwords uniquely accounted for (after removing the influence of the other variables) by auditory word recognition, age, and degree of hearing loss

Mode	Auditory				AV			
Variables	Slope	Part r	Partial F	p	Slope	Part r	Partial F	p
Auditory word recognition	0.000	0.000	0.162	.987	**0.024**	**0.285***	**5.062**	**.028**
Age	−0.004	0.055	0.000	.689	0.009	0.110	0.731	.396
Degree of loss	0.011	0.122	0.001	.351	−0.004	0.055	0.161	.689

Results are presented for auditory and AV speech (collapsed across fidelity). Significant results are bolded and starred. The multiple correlation coefficients for all of the variables considered simultaneously were 0.133 for auditory and 0.327 for AV. df's = 1,58 for part r and 3,58 for multiple R.
AV, auditory visual.

performance uniquely accounted for by each individual variable (Abdi et al. 2009). The multiple correlation coefficients for all of the variables considered simultaneously are provided below the table for interested readers. The part correlations indicated that only auditory word recognition uniquely impacted results and only for AV speech. In short—with age and degree of HI controlled—auditory word recognition influenced priming when visual speech was added to the input.

DISCUSSION

This research assessed the influence of visual speech on phonological priming by high-(intact) versus low-(nonintact) fidelity auditory speech in CHI. The low-fidelity stimuli were words and nonwords with an intact visual consonant + rhyme coupled to a nonintact auditory onset + rhyme. Our research protocol investigated whether phonological priming was (1) differentially affected in CHI versus CNH by the fidelity (high versus low), mode (AV versus auditory), and lexical status (words versus nonwords) of the stimuli and (2) uniquely affected by degree of HI, auditory word recognition, and/or age in CHI. Below, we consider these issues.

Did Fidelity and Mode Differentially Affect Phonological Priming in CHI Versus CNH?

For words as well as nonwords, both CHI and CNH consistently showed greater phonological priming from high- than low-fidelity input (when collapsed across mode) and from AV than auditory speech (when collapsed across fidelity). The latter result is particularly relevant because the pattern highlights a significant VSPE in these children. When the VSPE was examined as a function of fidelity, we found many similarities in the CHI and CNH. Both groups showed a significant VSPE for the high- and low-fidelity words and for the low-fidelity nonwords. A seeming contrast between the groups was that CNH showed a significant VSPE for high-fidelity nonwords whereas CHI did not; however, the latter result in CHI clearly showed a numerical difference that approached statistical significance.

Results for the VSPE underscore the importance of visual and auditory speech as complementary resources for phonological development in both CHI and CNH. This proposal is bolstered by the findings of delayed and/or different phonology and early expressive language skills in individuals with early-onset blindness (e.g., Mills 1987; McConachie & Moore 1994; Ménard et al. 2013). Our children participants—like adults—perceive speech by eye and ear. The VSPE findings clearly endorse visual speech as a vital resource for learning spoken language.

Finally, with regard to effects of hearing impairment, results indicate that the priming of picture naming by congruent phonological distractors did not generally differ in CHI versus CNH. Thus, these CHI had sufficiently well-specified phonological onset representations to support priming. A possible qualification is that all of the current CHI communicated successfully aurally/orally (see "Materials and Methods").

Did Lexical Status Differentially Affect Phonological Priming in CHI Versus CNH?

Phonological priming in both the CHI and CNH was significantly greater for nonwords than words. This result is consistent with our predictions that children will weigh phonetic-phonological content more heavily when listening to nonwords, and this increased weighting will increase priming (Mattys et al. 2005). This overall pattern of similarity between the groups was qualified, however, by the finding that phonological priming in the CHI versus CNH differed for nonwords but not for words. The difference occurred because the fidelity of the auditory input affected phonological priming by unfamiliar nonwords more in CNH than CHI. Apparently, CHI can benefit from unfamiliar low-fidelity auditory input more than CNH, perhaps because CHI regularly experience ear-degraded auditory speech.

Did Degree of HI, Auditory Word Recognition, and Age Affect Phonological Priming in CHI?

We analyzed the unique contribution of each of these individual variables with the effects of the other variables controlled. Neither the degree of HI nor age uniquely affected phonological priming in CHI. By contrast, the auditory word recognition skills of the CHI did uniquely influence phonological priming of the nonwords by AV speech. As before, we hypothesize that the nonwords were affected because (1) listeners assign the greatest weight to phonetic-phonological content for nonwords and (2) the processing of nonwords requires phonological decomposition (Morton 1982; Mattys et al. 2005; Mattys 2014). Evidence from the literature—illuminating the link between auditory word perception by CHI and the priming of picture naming by AV speech—is discussed below.

A close bidirectional link between the developing speech production and speech perception systems is proposed by the native language magnet theory expanded (Kuhl et al. 2008). This link between speech production/visual speech and auditory speech perception is clearly supported by previous research in infantsNH, such as Kushnerenko et al. (2013) who demonstrated a significant relation between looking-time patterns to AV speech—to the eyes versus the mouth—at 6 to 9 months and auditory speech comprehension at 14 to 16 months. The evidence in CNH (e.g., Erdener & Burnham 2013) also supports this linkage by showing that perceptual tuning to the phoneme contrasts of the native—as opposed to non-native—language predicts AV speech perception. Stated differently from the viewpoint of this discussion, the Erdener and Burnham data also seem to support the idea that the more highly tuned children are to visual speech, the better they learn the phoneme contrasts of the ambient language and hence the better they learn words. This idea agrees with studies showing that visual speech improves feature contrast discrimination, phoneme monitoring, and/or phoneme discrimination in infantsNH and CNH (Hnath-Chisolm et al. 1998; Teinonen et al. 2008; Fort et al. 2012; Lalonde & Holt 2015).

Overall, results suggest that greater sensitivity to visual speech yields better phoneme discrimination and hence better word comprehension, which supports our finding of a relation between phonological priming by AV speech and auditory word recognition. This type of linkage—between benefit from visual speech and auditory word recognition—has been observed previously in CHI who use cochlear implants (Lachs et al. 2001). Visual speech clearly seems a vital enriching complement to auditory speech for developing phonological knowledge, particularly for CHI.

CONCLUSIONS

With minor exceptions, phonological priming in CHI and CNH showed more similarities than differences. Importantly, the addition of visual speech significantly increased phonological priming in both groups. Auditory word recognition also significantly impacted the influence of visual speech on phonological priming. Clinically these data support intervention programs that view visual speech as a powerful asset for developing spoken language in CHI.

SHORT SUMMARY

This research assessed how visual speech influenced phonological priming in children with prelingual sensorineural hearing impairment (CHI) versus normal hearing. With minor exceptions, results documented that both CHI and children with normal hearing exhibited greater phonological priming from (1) high- than low-fidelity stimuli, 2) nonwords than words, and (3) AV than auditory inputs. Importantly, the addition of visual speech significantly increased phonological priming in both groups. Clinically, these data support intervention programs that view visual speech as a powerful asset for developing spoken language in CHI.

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