Representation and access in phonological impairment

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Children with Phonological Impairment (PhI) have highly inaccurate speech production in the absence of a condition that would otherwise cause them to do so. This paper reports a meta-analysis of three experiments designed to examine the locus of PhI in children. In Experiment 1, children with PhI were not found to have slower speed of lexical access than children with typical phonological development (TD). In Experiment 2, children with PhI were not found to have less-efficient phonological encoding processes than children with TD. In Experiment 3, children with PhI were found to have a reduced ability to learn perceptual representations for novel words than children with TD. Together, these results suggest that PhI is associated with deficits in the ability to learn perceptual representations for words. Interpreted in light of current models of speech production (Guenther, 1995), these results suggest that the habitually inaccurate speech production by children with PhI might be the consequence of less robustly specified perceptual targets for speech production.

1. Introduction

1.1. Phonological impairment

Young children's productions of words are characterized by systematic mismatches relative to the adult target. By approximately six years of age, most children have begun to produce words whose phonological shape matches the adult target. There is, however, a well-defined population of children in whom speech-production errors persist. These errors can occur in the absence of a clear medical, developmental, or psychosocial condition that would predispose children to make speech-production errors, such as hearing impairment, cerebral palsy, a craniofacial anomaly, or developmental disability. These children are less intelligible than their typically developing peers, and may require speech-language therapy to achieve intelligible speech. They are sometimes given the label *phonological impairment* (henceforth PhI, sometimes called *phonological disorder* [*PD*]).

PhI is a commonly occurring childhood communication impairment. Shirberg, Tomblin, and McSweeny (1999) estimate that PhI occurs in 3.8% of 6-year-old children. The causes of PhI are unknown. Conjectures about the origin of PhI generally start with the observation that these children often produce errors that are systematic, and which resemble the errors of younger, typically developing children. For example, a child with PhI might produce a sound that is perceived to be an alveolar obstruent in place of a velar obstruent, as in the production of [dʌt] for *duck* or [tæt] for *cat*. This pattern is sometimes called *velar fronting*. These errors occur in the absence of frank problems in speech perception and language comprehension. That is, a child with PhI may be highly unintelligible, but have normal hearing sensitivity and age-appropriate performance on standardized measures of language comprehension. This has lead some to conclude that the production problems of children with PhI are the consequence of output processes operating on essentially adult-like phonological representations. For example, a child with velar fronting might be presumed to have adult-like representations of the words *duck* and *cat*, as assessed by the child's accurate recognition of these items on tests of vocabulary, and accurate perception of these sounds in hearing evaluations. The alveolar sound is thought to occur because of an output process, such as a derivational rule that an underlying velar to an alveolar, or a well-formedness constraint preferring alveolar sounds over velar sounds (e.g., Barlow & Gierut, 1999; Bernhardt & Stoel-Gammon, 1996).

1.2. Types of phonological knowledge

Upon closer inspection, PhI appears to be a much more complex phenomenon than the previous paragraph would suggest. The view of PhI in the previous paragraph is based on the assumption that knowledge and representations of sounds are highly abstract. Recent research on phonological development and adult phonological competence suggests that knowledge of sound structure is comprised of multiple types of knowledge. A starting point in investigating the bases of PhI is considering the different types of phonological knowledge that individuals have. One taxonomy of types of phonological knowledge is presented by Beckman, Munson, and Edwards (in press, see also Pierrehumbert, 2003, for a similar proposal). Beckman et al. review a growing body of literature that suggests that individuals' representations of the sound structure of words are comprised of at least two distinct levels of representation. First, individuals' representations of words include detailed information about the range of physical variation – variation in articulatory and acoustic-perceptual characteristics of the word as it has been produced and perceived in ongoing language use. Evidence for this level of encoding comes from studies showing that individuals have detailed memories of individual tokens of words that they have heard, and that these memories influence their subsequent production and processing of words (e.g., Goldinger & Azuma, 2004). This type of knowledge can be used to infer the phonological category structure of the language (Maye et al., 2002). It also allows individuals to learn the fine phonetic detail needed to convey social-indexical information.

Second, knowledge of the sound structure of language encompasses more abstract knowledge of the structure of phonological categories. That is, individuals have knowledge of the ways in which the many articulatory and acoustic variants of sounds are used to convey linguistically meaningful differences. This type of knowledge is responsible for individuals' sensitivity to token frequency, such as the influence of phonotactic probability and phonological neighborhood density on the processing of real-word and nonword stimuli (Vitevitch & Luce, 1999). Pierrehumbert (2003) and Beckman, Munson, and Edwards (in press) argue that individuals' abstract phonological knowledge emerges as they make generalizations over the phonetic knowledge that they have encoded.

Given that phonological knowledge is comprised of at least two distinct types of knowledge, it is logically possible that PhI may be a consequence of deficits in either or both of these types of knowledge. That is, a deficit in encoding information about the continuous articulatory and acoustic variation in sounds might be implicated in PhI. Alternatively, PhI might be the consequence of a fundamental difficulty in forming abstract representations for speech sounds from phonetic encodings that are largely similar to those of their typically developing peers.

A variety of investigations have shown that children with PhI have deficits in multiple types of phonological knowledge. First, children with PhI have clear deficits in articulatory knowledge. This can be seen, for example, in their reduced ability to compensate for articulatory perturbations: Edwards (1992) found that children with PhI were less able than children with TD to produce acoustically equivalent tokens of the vowel /æ/ when their jaw was fixed in place. Articulatory knowledge deficits were also documented by Towne (1994), who showed that children with PhI are slower than children with TD in repeating sequences of nonsense syllables in jaw-fixed and jaw-free conditions. Further evidence of articulatory knowledge deficits in children with PhI was documented by White (2001) and Gibbon (1999). These investigators showed that a subset of children with PhI with an apparent velar fronting pattern produced a merged lingual gesture intermediate between the alveolar and velar places of articulation for target alveolar and velar sounds.

Though children with PhI appear to have intact perception skills when simple tasks are used, more incisive tasks often reveal deficits in knowledge of sounds' perceptual characteristics. Rvachew and Jamieson (1989) showed that children with PhI have less sigmoidal identification functions than children with TD for a variety of synthetic speech continua. Edwards, Fourakis, Beckman, and Fox (1999) and Edwards, Fox, and Rogers (2002) showed that children with PhI require more acoustic information than children with TD to identify spoken words. Forrest, Chin, Pisoni, and Barlow (1995) showed that the spoken word recognition of children with PhI was more susceptible to noise-related decrements than children with TD. Nathan and Wells (2001) showed that children with PhI had a reduced ability to process speech produced in an unfamiliar regional accent than children with TD.

Finally, children with PhI have been shown to have deficits in more-abstract phonological knowledge. Rvachew, Nowak, and Cloutier (2004) examined abstract knowledge using metaphonological awareness tasks – i.e., tasks in which children were asked to make overt judgments about the sound-structure of words. Rvachew et al. found that children with PhI were less accurate than children with TD in judging the structure of spoken words. Storkel (2004) presented the results of a word-learning study suggesting that children with PhI rely more than children with TD on existing lexical representation when learning novel words. Again, this suggests less-robust abstract phonological knowledge.

The previous three paragraphs suggest that PhI is associated with deficits in many different types of phonological knowledge. Any or all of these could be causally related to the speech-production errors that are characteristic of this population. Guenther (1995) and Perkell et al. (1999) argue that detailed acoustic-perceptual and somatosensory representations serve as targets in speech production. Individuals achieve these targets through their knowledge of the 'forward map' between articulatory movements and their sensory consequences. Hence, the acoustic-perceptual deficits in children with PhI could lead to more poorly developed acoustic targets, which could lead to speech production difficulties. The articulatory knowledge deficits in children with PhI might reflect a primary weakness in learning the association between articulatory movements and perceptually defined targets. In contrast, the deficits in higher-level knowledge might reflect a fundamental weakness in the representation of phonological forms in the mental lexicon.

Understanding the underlying bases of PhI is important for at least two reasons. First, achieving a consensus on the nature of PhI has the potential to shape and refine intervention practices for this population. Current intervention approaches are eclectic, with some approaches emphasizing the facilitation of more-abstract aspects of phonological knowledge (Dean & Howell, 1986;

Hodson & Paden, 1984), and others emphasizing the development of low-level articulatory (McDonald, 1964) or perceptual (Rvachew et al., 2004) abilities. Having a precise understanding of the locus of PhI could lead to intervention practices that are more uniform and, potentially, more effective than current regimens.

Second, studies of children with PhI are a window into the cognitive-linguistic and perceptual-motor bases of variation in speech. A central endeavor in the field of laboratory phonology is to understand variation in speech production. The great majority of works in this area have examined variation within individuals, both cataloguing the range of variation in speech production within individuals and across languages, and developing cognitive models that account for this variation. In comparing children with PhI to children with TD, we are able to extend this line of inquiry by examining predictors of variation in speech production in a population that is otherwise homogeneous in their language exposure and in their lack of cognitive, medical, or psychosocial impairments. By understanding the basic-level skills that differentiate children with PhI from their TD peers, we gain a window into the possible mechanisms that underlie variation in speech production in the general population. In this way, our use of PhI to make inferences about normal speech production processes is analogous to research programs that examine specific language impairment in children (i.e., impairments in morphosyntax and semantics in the absence of an obvious cause) or acquired aphasia in adults (i.e., language impairments secondary to cortical damage) to make generalizations about normal language processes.

Quantifying different types of knowledge deficits in PhI was the topic of a recent study by Munson, Edwards, and Beckman (2005). Munson et al. examined 40 children with PhI and 40 age-matched peers with typical phonological development. Munson et al. reported on three experimental tasks which were designed to measure different types of phonological knowledge. Articulatory knowledge was measured by articulatory accuracy on a series of picture-naming tasks, including both standardized and nonstandardized measures. Perceptual knowledge was measured with the gated-word recognition task reported in Edwards et al. (2002). Abstract phonological knowledge was measured using a nonword repetition task. Twenty-two pairs of nonwords were created. Each pair contained two nonwords with the same prosodic structure. One member of the pair contained a diphone sequence that occurs in many real words of English (such as the sequence /ju/, which occurs in words like *you*, *youth*, *use*, etc.), and the other nonword contained a phonetically similar sequence that occurs in few or no real words (e.g., /jɑʊ/, which occurs in no native monomorphemic words of English). Following Edwards, Beckman, and Munson (2004), Munson et al. reasoned that children could repeat high-frequency sequences of phonemes by accessing knowledge from existing lexical representations. For example, a child could repeat /ju/ by using their knowledge of the acoustic and articulatory characteristics of the sequence in known words, like *you* and *use*. In contrast, the sequence /jɑʊ/, which does not occur in any known words, could only be repeated accurately if children had abstracted knowledge of the phonemes /j/ and /ɑʊ/ away from the words in which they occur. Munson et al. reasoned that the difference in repetition accuracy between high- and low-frequency sequences indexed the robustness of children's knowledge of the fine-grained phonemic structure of language. Children with more-robustly abstracted knowledge of phonemes would be presumed to have a smaller difference in repetition accuracy between high- and low-frequency sequences than children with less mature knowledge. If PhI were associated with specific deficit in abstract knowledge of words' phonemic structure, then they would be predicted to show a larger effect of diphone frequency on repetition accuracy than children with TD.

Munson et al. found that children with PhI differed from TD on measures of articulatory accuracy and speech perception. On the nonword repetition task, children with PhI differed from TD children in overall accuracy on the nonword repetition task, but did not show a larger effect of phonotactic probability. These findings suggest that PhI is associated primarily with problems in representing information in the primary perceptual and articulatory domains.

1.3. The purpose and scope of the current investigation

The results of Munson et al. (2005) suggest that sensory knowledge deficits are a defining feature of PhI. The purpose of the current investigation is to examine further the nature of phonological knowledge deficits in children with PhI. This study expands on Munson et al.'s earlier work in three key ways. First, knowledge of the acoustic-perceptual characteristics of sounds is assessed in this study with a measure of children's ability to implicitly learn representations for novel words, rather than through static measures of phoneme identification or spoken-word recognition. Performance on the perceptual-learning task is presumed to reflect the perceptual processes that underlie real-world speech-sound acquisition more closely than static identification and recognition measures do.

Second, this project measures knowledge of abstract characteristics of speech sounds by assessing children's abilities to phonologically encode lexical representations in an on-line language formulation task, picture naming. This is presumed to reflect the ways that children use abstract phonological representations during real-time language formulation more closely than static measures of abstract phonological representation, such as the nonword repetition task described by Munson et al. (2005).

Third, this investigation considers whether PhI is associated with deficits in the semantic stage of lexical access. Many models of word production argue for two distinct stages in the lexical access process, a semantic stage, in which a word's meaning is access, followed by a phonological stage, in which the word's conceptual representation is associated with its sound structure (Levelt, 1989; Levelt, Roelofs, & Meyer, 1999). Support for the two-stage hypothesis comes from a variety of studies showing different time-courses for semantic and phonological priming effects (Shriefers, Meyer, & Levelt, 1991). Given this purported dissociation, it seems unlikely that the semantic stage of lexical access would be problematic in children with PhI, as these children's speech-production errors may occur in the absence of a frank impairment in lexical knowledge. Throughout the remainder of the paper, the semantic stage of lexical access is called simply *lexical access*, and the phonological stage is called *phonological encoding*.

Recent studies, however, have shown a closer relationship between lexical access and phonological encoding than was thought previously. Jurafsky, Bell, and Girand (2002) reported that the frequency of different syntactic variants of words with arguably identical abstract phonological representations affected variation in pronunciation. That is, variation in a form such as /ðæt/ differed depending on whether it served as a complementizer, a pronoun, or a determiner. Munson (in press) demonstrated that the influence of word frequency on vowel-space dispersion was mediated by on-line lexical access processes. These findings suggest that lexical access may affect phonological encoding, and, ultimately, variation in pronunciation. This study examines whether children with PhI have deficits in lexical access.

This paper reports a post-hoc analysis of the results of three experiments designed to measure perceptual learning, lexical access, and phonological encoding in children with TD and children with PhI. Qualitative comparison across the three experiments allows us to make inferences regarding the locus of PhI in children.

1.4. Design of the project

The three experiments presented in this paper were administered as part of a large-scale study on PhI. This section describes measures and procedures that were common to the entire project. Subsequent sections describe in detail the procedures in the three target experiments.

1.4.1. Measures

Children's speech production accuracy was assessed using the Goldman-Fristoe Test of Articulation-2 (GFTA, Goldman & Fristoe, 2000). Briefly, the GFTA is a picture-naming task. Children's productions are phonetically transcribed. The total number of errors is compared to a normative sample to calculate percentile ranks for each child. GFTA scores were supplemented by standard scores from the *Kahn Lewis Phonological Analysis* (KLPA, Kahn & Lewis, 2001). KLPA scores reflect the child's use of commonly occurring simplification processes. Children's vocabulary knowledge was assessed with the *Peabody Picture Vocabulary Test-III (* PPVT, Dunn & Dunn, 1997), which measures receptive vocabulary, and the Expressive Vocabulary Test (EVT, Williams, 1997), which measures productive vocabulary. Nonverbal IQ was measured in children aged 4 and over with the *Kaufman Brief Intelligence Test* (K-BIT, Kaufman & Kaufman, 1991).

Two measures assessed children's perceptual abilities. The first was a hearing screening. Children responded to pure tones at 0.5, 1, 2, and 4 kHz bilaterally. Children's tympanic function was also assessed. The second task was a minimal-pair identification task, the goal of which was to gauge the participants' speech perception. In this task, children were presented with pairs of pictures that represented objects whose names differed in only one phoneme. A single word was played, and children pointed to the picture that the word represented. The words were produced by an adult male talker of the local dialect, and were judged to be 100% intelligible by a group of adult listeners in a pilot test. Rationalized Arcsine Transformed percent correct scores (Studebaker, 1985) were calculated for each subject.

1.4.2. Participants

Seventy-three children aged 3 to 7 participated in the project. Participants were recruited from a variety of locations in the metropolitan Minneapolis/Saint Paul, Minnesota area. Children were classified as PhI if they met the following criteria: a percentile rank on the GFTA of 16 or lower, standard scores on the EVT, PPVT, and K-BIT (if available) of 85 or higher. Children with PhI had an average standard score of 77 on the KLPA, indicating that their error patterns were generally systematic. Children with TD scored at the 40^{th} percentile or higher on the GFTA, and had scored of 85 or higher on the other standardized tests. All children passed a hearing screening at 0.5, 1, 2, and 4 kHz bilaterally.

Each child with PhI was matched individually with a child with TD for age within +/−3 months. This resulted in 25 matched pairs of participants. However, not all participants were able to complete all experimental tasks, resulting in slightly different *n*'s for the three experiments.

2. Experiment 1: Delayed picture naming

The first experimental task was designed to examine the relative contribution of lexical access and post-lexical access processes on speech production accuracy in children with PhI. It employed a delayed naming paradigm (Edwards & Lahey, 1996). A full discussion of this experiment can be found in Munson, Yim, Brincks, and White (2006). In this paradigm, children see a picture and are instructed not to name it until a response prompt has been presented. The delay between when the picture is shown and when the response prompt is given varies. The prompt can be concurrent with the presentation of the picture, or after it. The dependent measure in these studies is naming latencies for correctly named pictures. At shorter delay intervals, response characteristics are presumed to reflect both lexical access and phonological encoding, as children must access the lexical item and form and execute a phonological plan for production. Responses following longer delay intervals are presumed to occur after lexical access has taken place, and thus reflect the influence of phonological processing only.

Delayed naming was used to examine whether children with PhI differ from children with TD in the ability to access lexical items. A finding that the naming latencies between children with PhI and TD differ more for shorter delay intervals than for longer ones would indicate that children with PhI have relatively poorer lexical access abilities than children with TD. A finding of statistically equivalent group differences across delay intervals would suggest a primary problem with post-access processes, such as phonological encoding.

Three delay intervals were used, 0 ms (i.e., the participants named the picture immediately after it was presented), 500 ms, and 1000 ms. Fifteen pictures were presented per delay interval. Pictures were simple line drawings that represented objects with CV and CVC names. The pictures were chosen because their names contained only early-acquired sounds. Fifteen pictures were named at each delay interval.

Results of this experiment are presented in Figure 1, which plots data for 38 TD and PhI participants. This group consists of 19 pairs of participants matched for age (M_{TD} = 58.8 months, M_{PhI} = 59.7 months). The two groups differed significantly in their GFTA-2 percentile ranks (M_{TD} = 64.9, M_{PhI} = 10.0) and KLPA-2 standard scores (M_{TD} = 107.8, M_{PhI} = 77.3), but did not differ significantly in age. All participants scored at or above 85 on the EVT, PPVT-III, and K-BIT standard scores.

Figure 1 plots the response latencies for correctly named pictures at the 0 ms, 500 ms, and 1000 ms delay intervals. These were submitted to an ANOVA like that used to examine naming accuracy. Delay interval (three levels: 0 ms, 500 ms,

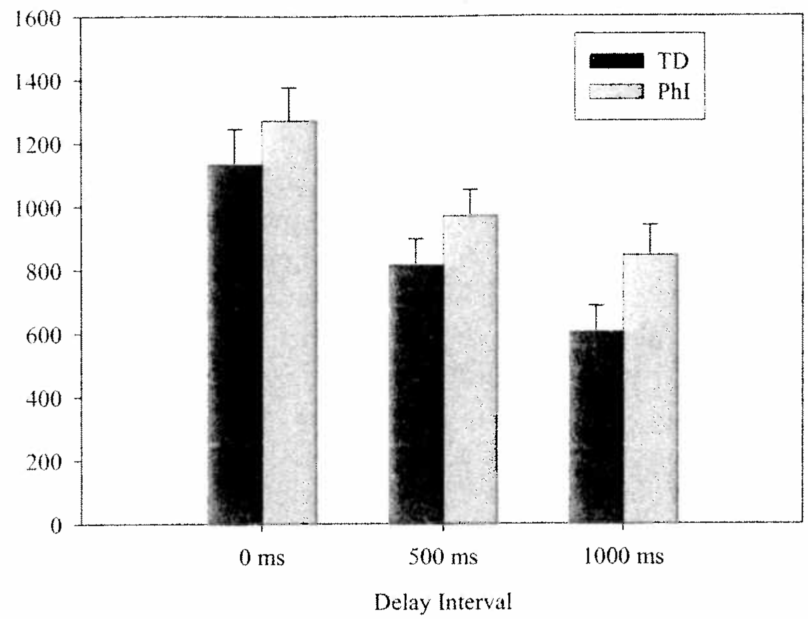

Figure 1. Naming latencies for children with PhI and children with TD at the three delay intervals.

and 1000 ms) were the within-subjects factor, and group (TD and PhI) were the between-subjects factor. The average naming latencies for children with PhI were longer than those for children with TD (M_{PhI} = 1098 ms; M_{TD} = 932 ms); however, this effect was not significant $F[1,26] = 1.7, p = 0.20$, partial $\eta^2 = 0.05$. There was a significant main effect of delay interval, $F[2,72] = 55.2, p < 0.001$, partial $\eta^2 = 0.61$. Post-hoc Scheffe tests indicated that pictures were named more quickly at the 500 ms and 1000 ms delay intervals than at the 0 ms delay interval. Pictures were named more quickly at the 1000 ms delay interval than the 500 ms delay interval; however, this difference only approached significance ($p = 0.083$). Finally, there was no interaction between group and delay interval, $F[2,72] < 1, p > 0.05$.

A set of regressions examined predictors of naming latencies at the three delay intervals, as well as predictors of the difference in response time between the 0 ms and 1000 ms delay intervals. The latter can be considered an estimate of time needed to complete lexical access. In all four regressions, age was forced as the first variable entered into the regression. On the second step, GFTA-2 percentile rank, KLPA-2 standard score, EVT standard score, PPVT-III standard score, and K-BIT standard score were entered if they accounted for a significant proportion of variance ($p < 0.05$) beyond what was accounted for by all of the variables entered in the previous steps. For the three individual delay intervals, age accounted for a significant proportion of variance. GFTA-2 raw score accounted for a significant proportion of variance beyond age. For the 0 ms delay interval, EVT standard score accounted for an additional proportion of variance beyond that accounted for by age and GFTA-2.

The results of these analyses suggest that children with PhI do not differ from children with TD primarily in their lexical access abilities. The extent to which they name pictures more slowly than their TD peers is statistically equivalent at different delay intervals. Moreover, an estimate of severity of PhI, GFTA-2 standard score, predicted naming latencies equally well at all three delay intervals.

3. Experiment 2: Cross-modal picture-word interference

The second experiment was designed to examine phonological encoding processes in children with PhI. This was studied using a cross-modal picture-word interference paradigm, modeled after Brooks and MacWhinney (2000). Full details about this experiment can be found in Krause, Munson, and Blasing (2006). As with all cross-modal tasks, the PWI task requires participants to attend to one aspect of a stimulus while ignoring another. In the PWI task reported here, participants see a picture and hear a word, referred to as the interfering word (IW), which they are instructed to ignore. The IW's similarity to the picture's name varies systematically. For example, a picture of a cat might be presented with an identical IW (*cat*), an onset-related IW (*could*), a rime-related IW (*hat*), or a phonologically unrelated IW (*hope*). In addition, a nonverbal auditory condition is typically included, in which a nonlinguistic auditory stimulus is presented instead of an IW. This condition is intended to be a baseline to measure the influence of auditory stimuli on picture naming. The IW is presented 150 ms prior to, concurrent with, or 150 ms after the picture's presentation. This is referred to as stimulus onset asynchrony (henceforth *SOA*). The dependent measure is naming latency. Previous research with normal adults (e.g., Shrieffers, Meyer, & Levelt, 1990) has found that picture-naming latencies are longest when the IW is phonologically unrelated to the picture's name, and shortest when the IW is identical. When the IW is phonologically similar (i.e., onset- or rime-related) the latencies are intermediate between the two other latencies. This is particularly pronounced at the +150 ms SOA. This is interpreted as evidence that the phonologically related IW enhances the phonological encoding of lexical items. That is, the phonologically related IWs increase the activation associated with some of the phonemes that will be used in the speech-production plan needed to produce the picture's name.

In this experiment, PWI was used to examine whether children with PhI show decreased phonemic encoding abilities relative to their typically developing peers. We reasoned that, if Children with PhI had difficulty encoding phonemes during speech production, then they would show a smaller difference in naming latencies between phonologically unrelated and phonologically related IWs on naming latencies than children with TD.

In the PWI experiment, children were trained the names of 9 pictures representing CVC objects (*bed*, *boat*, *cat*, *dog*, *foot*, *hat*, *knife*, *pen*, and *wood*). They then named the pictures while listening to an IW that was presented prior to, concurrent with, or after the picture's name. The IW was either identical to the picture's name, phonologically unrelated, onset-related, or rime-related. A nonverbal auditory condition (a warble tone) was also included. Semantic relatedness of the picture's name and the IW was measured to ensure that all picture-word combinations were equally semantically unrelated. The average neighborhood density and log frequency of the IWs did not differ significantly across conditions. The Praat signal-processing program (Boersma & Weenink, 2006) was used to normalize the duration of the IWs to 480 ms, to ensure that naming latencies across IW type were not an artifact of differences in IW duration. The duration-normalized IWs were all 100% intelligible to naïve listeners when presented in quiet.

Eighteen pairs of subjects participated in this task. These two groups were well separated in their expressive phonology: the average GFTA-2 percentile rank was 8.4 for the children with PhI and 65.6 for the children with TD; similar-magnitude differences were found for the KLPA-2 standard scores. All of the children had PPVT-III, EVT, and K-BIT standard scores at or above 85. The children in the two groups were matched for age. The average age was 62.1 months for the children with PhI and 61.2 month for the children with TD.

Figures 2 and 3 show picture-naming latencies for the 36 children who completed this task. As in Brooks and MacWhinney (2000) and other investigations, these figures show naming latencies relative to the latency in the nonverbal auditory condition. Figure 2 shows the average picture-naming latencies for 18 children with TD, and Figure 3 shows the latencies for 18 children with PhI. The data in these figures do not support the hypothesis that children with PhI show a reduced ability to phonologically encode words during speech production. The influence of IW type on naming latencies is statistically equivalent for the two groups. A three-factor mixed-model ANOVA examined the influence of one between-groups factor, group (2 levels, PhI and TD), IW type (4 levels, rime-related, onset-related, identical, and phonologically unrelated), and SOA (3 levels, −150 ms, 0 ms, +150 ms) on picture-naming latencies relative to the nonverbal auditory condition. There was a significant main effect of group,

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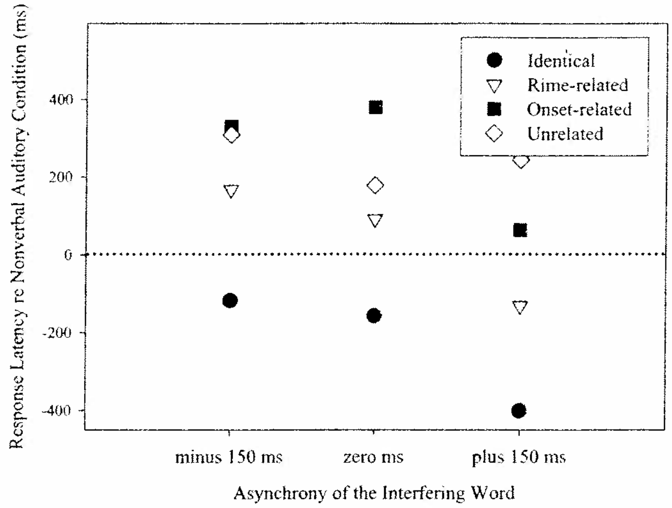

Figure 2. Picture naming latencies (relative to the average latencies for the nonverbal auditory condition, which is represented by the dotted line) for children with TD, separated by interfering word type and SOA.

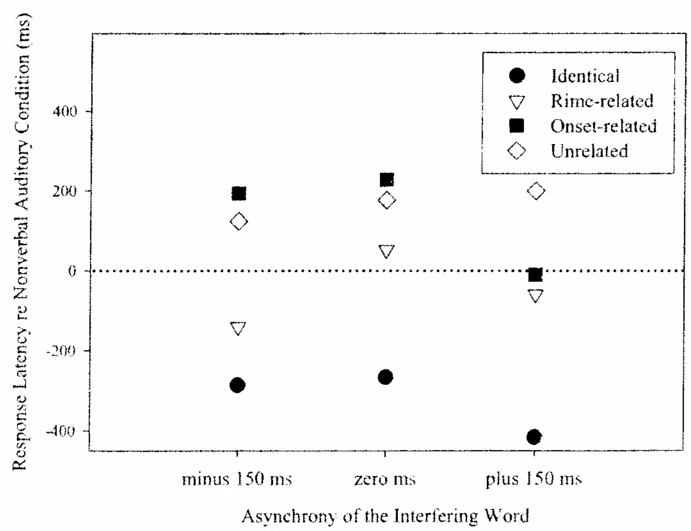

Figure 3. Picture naming latencies (relative to the average latencies for the nonverbal auditory condition, which is represented by the dotted line) for children with PhI, separated by interfering word type and SOA.

$F[1, 34] = 5.82$, $p = 0.021$, partial $\eta^2 = 0.15$. Across SOAs and IWs, children with PhI were, on average, 105 ms closer to the nonlinguistic baseline nonlinguistic auditory condition than children with TD. Significant main effects were also found for IW type, $F[3, 102] = 47.15$, $p < 0.001$, partial $\eta^2 = 0.58$

and SOA, F[2, 68] = 4.47, $p = 0.015$, partial $\eta^2 = 0.12$. These interacted significantly, F[6, 204] = 3.68, $p = 0.002$, partial $\eta^2 = 0.10$. No other interactions achieved statistical significance. These patterns did not appear to be due to group differences in performance on the nonverbal auditory condition. Though RTs in this condition were affected significantly by SOA (F[2, 68] = 4.83, $p = 0.011$, partial $\eta^2 = 0.12$, $M_{-150\ ms}$ = 1461 ms, $M_{0\ ms}$ = 1528 ms, $M_{+150\ ms}$ = 1621 ms), the two groups did not differ in their RTs in this condition, and group did not interact with SOA.

The interaction between SOA and IW type can be seen by comparing Figures 2 and 3. For both groups, naming latencies associated with identical IWs were shorter than those for other IW types, and were faster than the nonverbal auditory condition across all three onset asynchronies. There was a robust phonological facilitation effect for both groups at both the −150 ms and +150 ms onset asynchronies: the RTs for rime-related IWs were faster than those for unrelated IWs. Surprisingly, this effect did not achieve statistical significance at the 0 ms SOA for either group. The onset-related IW did not facilitate production. Indeed, onset-related IWs were associated with RTs that were generally as slow as the unrelated word. This finding is consistent with the findings of Brooks and MacWhinney, who found that onset-facilitation effects were not present in five-year-old children. The children in the current study may have been too young to show these effects.

In sum, Experiment 2 demonstrated that children with PhI do not suffer deficits in phonological encoding relative to children with TD. The influence of IW type on picture-naming latencies of children with PhI is similar to the influence for children with TD.

4. Experiment 3: long-term repetition priming

The third experiment examined children's ability to learn perceptual representations for novel words based on minimal exposures. Full details about this experiment can be found in Munson, Baylis, and Simmons (2006).

Experiment 3 used a long-term repetition priming paradigm, modeled after Fisher et al. (2001). Fisher et al. found that children repeat nonwords more accurately if they had been presented previously in a passive-listening task than if they had not. This suggests that children can learn perceptual representations for nonwords that support accurate repetition from minimal exposures. As in Fisher et al. (2001), this experiment involved two phases. In the *study* phase, children were presented with a string of nonsense words auditorily (over speakers at 65 dB HL), and were instructed not to respond. These had CVC and CVCVC wordshapes; all of the phoneme sequences in the nonwords existed in at least one real word in a corpus of children's speech. They contained only the early acquired sounds /p/, /b/, /t/, /d/, /k/, /g/, /m/, /n/, /ŋ/, /w/, /j/, /h/, and /f/, and the vowels /u/, /ɪ/, /eɪ/, /ɛ/, /ɑ/, /ʌ/, /u/, /ʊ/, and /æ/. Stimuli were spoken by either a male or a female talker. All of the nonword stimuli used in the experiment were highly intelligible, as shown by their being repeated accurately by at least 90% of naïve listeners in a pilot study; most were repeated 100% accurately. Following a short distracter task (an oral-motor examination), children completed the *test* phase, in which they repeated 52 nonwords. Twenty-six of these (the *unprimed* nonwords) were not presented during the study phase. Thirteen of these nonwords were identical to those presented in the study phase (the *identically primed* nonwords). Finally, 13 of the nonwords presented in the test phase were of the same wordshape as ones presented in the study phase, but were presented in the test phase by a different talker (the *form-primed* nonwords). The phonetic composition of the stimuli in the three conditions was counter-balanced. The accuracy and latency of responses of the three stimulus types were measured. We predicted that if PhI were associated with a reduced ability to learn perceptual representations for novel words from minimum exposures, then they should show a smaller influence of priming on repetition accuracy and latency than children with TD.

Twenty-five children with PhI, and 25 age-matched children with TD participated. The average age of the children with PhI was 58.2 months, and the average age of the children with TD was 57.8 months. This difference was not significant, $F[1,43] < 1$. These two groups were well separated in their expressive phonology: the average GFTA-2 percentile ranking for the children with PhI was 9.9, and their average KLPA-2 standard score was 77. In contrast, the average GFTA-2 percentile rank for the children with TD was 63.6 and their average KLPA-2 standard score was 108. All of the participants scored at or above 85 on the PPVT-III, EVT, and K-BIT, indicating age-appropriate vocabulary knowledge and nonverbal intelligence.

The average percent phonemes correctly repeated for CVC nonwords were averaged separately for the three stimulus types. Accuracy of production was calculated relative to the target form; the habitual phonological errors of children with PhI were not counted as correct. A rationalized arcsine transform was applied to these data; the resulting data did not meet the normality assumptions required to use parametric statistics. Instead, these were analyzed with a series of nonparametric statistical tests. Two Friedman's ANOVAs by ranks examined the effect of prime type on repetition accuracy. A significant effect was found for children with TD, $\chi^2_{[df=2, n=25]} = 8.96$, $p = 0.011$. Children with TD repeated the identically primed nonwords more accurately than the unprimed nonwords and the form-primed nonwords. Consistent with predictions, a significant effect

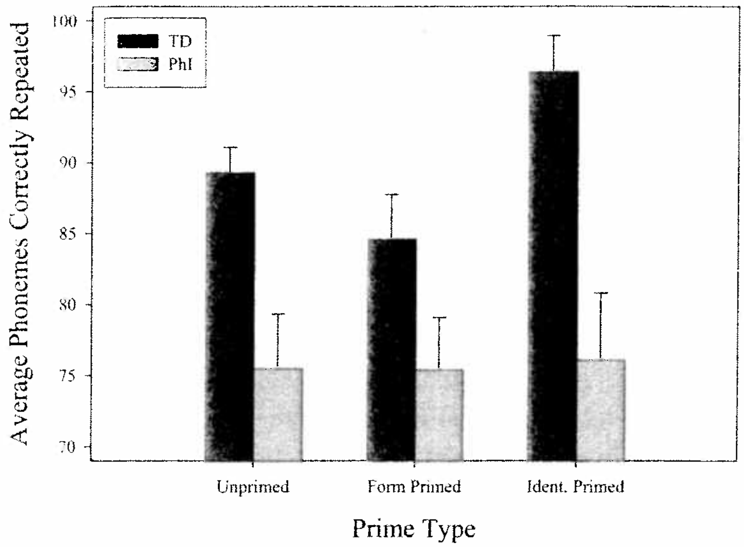

Figure 4. Nonword repetition accuracy for children with PhI and children with TD, separated by priming condition.

was *not* found for children with PhI, $\chi^2_{[df=2,n=25]} = 0.626$, $p = 0.73$. These data are shown in Figure 4.

Children with PhI by definition produce speech less accurately than children with TD. One possible conjecture is that their reduced priming effect is a consequence of these differences in phoneme-production accuracy. This appears unlikely, as group differences in phoneme-production accuracy would presumably affect all stimulus types equally. However, it is possible to examine this conjecture statistically by comparing children's repetition accuracy on the implicit priming task with their production accuracy for the same phonemes in real words. To do this, we calculated the average production accuracy in real words for the phonemes comprising the identically primed, unprimed, and form-primed nonwords, weighted by how frequently the phonemes appeared in the stimuli. The real words were taken from the GFTA-2. We then calculated the difference between the production accuracy scores in real words and the repetition accuracy scores in nonwords for the three stimulus types. These scores were submitted to two Friedman's ANOVAs by ranks tests. The results closely paralleled the early analyses. A significant effect was found for children with TD, $\chi^2_{[df=2,n=25]} = 9.88$, $p = 0.007$. The children with TD produced phonemes in unprimed nonwords disproportionately less accurately than their production of the same phonemes in real words would suggest. This was not found for children with PhI, $\chi^2_{[df=2,n=25]} = 1.152$, $p = 0.56$. This finding confirms that the effect of priming illustrated in Figure 4 is not an artifact of group differences in phoneme-production accuracy.

A second analysis examined predictors across subjects of the magnitude of the priming effect, operationally defined as the difference in repetition accuracy between the primed and unprimed nonwords. A stepwise hierarchical regression was used. Age and discrimination accuracy were forced as the first variables in this regression. In the second step, GFTA-2 raw score, KLPA standard score, EVT raw score, PPVT-III raw score, and discrimination arcsine-transformed percent correct were entered into the regression if they accounted for a significant proportion of variance (a < 0.05) beyond what was accounted for on the previous step. The same predictors emerged for the two dependent measures. Age and discrimination scores accounted for a marginally significant proportion of variance on the first step ($R^2 = 11.5\%$, $F[2,46] = 2.99$, $p = 0.06$). On the second step, GFTA-2 raw score accounted for a significant proportion of accuracy in the two measures ($R^2 = 10.9\%$, $F[1,45] = 6.29$, $p = 0.016$). This finding suggests that the magnitude of the priming effect is proportional to children's speech production accuracy. Children with less-accurate speech production show a smaller priming effect than children with more-accurate speech production.

The third analysis examined nonword repetition latencies. Average repetition latencies for the three types of stimuli are shown in Figure 5. These were submitted to two Friedman's ANOVAs by ranks. Again, a significant effect was found for children with TD, $\chi^2_{[df=2,n=25]} = 12.09$, $p = 0.002$. In this analysis, however, a

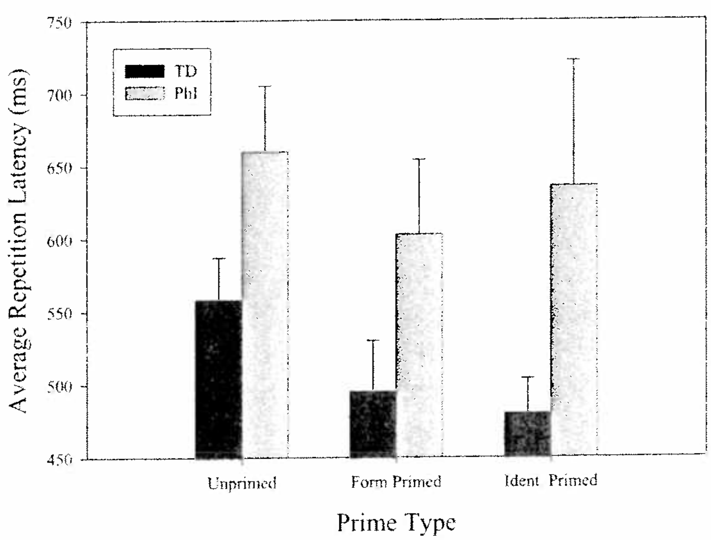

Figure 5. Nonword repetition latency for children with PhI and children with TD, separated by priming condition.

significant effect was found for children with PhI, $\chi^2_{[\mathrm{df}=2, n=25]} = 14.29, p = 0.001$. As Figure 5 shows, the influence of prime type on response latencies for children with TD was in the expected direction: the two primed nonword types were repeated more rapidly than unprimed nonwords. In contrast, the effect of priming for children with PhI appeared to be due to the form-primed nonwords being repeated more quickly than the unprimed ones. It was somewhat remarkable that this condition, rather than the identically primed condition, elicited the fasted repetitions. Inspection of Figure 5 shows that the identically primed condition elicited the most variable response latencies of all three conditions, and its failure to differ significantly from the unprimed condition is arguably a consequence of this variability. Further analyses of response latencies for individual items are presented in Munson, Baylis, and Simmons (in preparation).

A series of regression analyses examined predictors of the influence of priming on repetition accuracy, operationally defined as the difference in repetition latency between the unprimed and identically primed nonwords. The independent measures were identical to those in the regression analysis described earlier in this section. No predictors were found for repetition latency.

In sum, the results of experiment 3 suggest that children with PhI have a reduced ability to implicitly learn perceptual representations for nonwords based on minimal exposures. They show a smaller effect of priming on nonword repetition accuracy and latency than children with TD.

5. General discussion

The three experiments described in this paper were designed to examine differences between children with TD and children with PhI in different types of phonological knowledge. Specifically, we examined whether children with PhI differ from children with TD most strongly in experimental measures of lexical access, phonological encoding, or perceptual learning. The only group differences between children with PhI and children with TD that were found were in the ability to learn perceptual representations for novel words based on minimal exposures. Children with PhI did not differ from children with TD in their ability to access lexical items, nor did they demonstrate a reduced ability to phonologically encode lexical items in a picture-word interference task.

The notion that perceptual processes underlie PhI is consistent with much previous research. Munson, Edwards, and Beckman (2005) found larger group differences between children with PhI and children with TD in measures of perception than in an experimental measure of knowledge of abstract phonological categories. Rvachew (1994) and Rvachew, Nowak, and Cloutier (2004) found that training speech perception in children with PhI facilitated improvements in speech production. This deficit may be causally related to children's speech production errors. One prominent theory of speech production, the DIVA model (Guenther, 1995; Perkell et al., 2000) emphasizes that sensory representations, including acoustic representations, serve as targets for speech production. A deficit in the ability to learn perceptual representations would presumably lead to speech production targets that were poorly defined and poorly differentiated from one another. One logical topic for future research is to delimit the relationship between perceptual-learning deficits and children's specific error patterns. At least one recent study, Shriberg et al. (2003), provided some evidence for a fairly direct relationship between sensory input and error patterns in children with perception problems of a known organic origin, recurrent otitis media with effusion. However, the relationship between perception deficits and production patterns need not be direct and transparent. In the absence of robust acoustic-perceptual targets, children's production attempts might default to patterns that are articulatorily easy, well established, or frequent in the ambient language. Another logical area of future research is to examine in more detail articulatory knowledge deficits in children with PhI. The DIVA model emphasizes that the targets for speech production are both acoustic and somatosensory. It is possible that children with PhI have deficits in the ability to encode information in multiple sensory domains. Our ongoing research on PhI attempts to quantify the relative contribution of deficits in these different types of knowledge to PhI.

The results of this study, in combination with the results of our earlier work, suggest that children with PhI do not have a deficit in the ability to create or access abstract representations for sounds and words. Together, these findings suggest that children with PhI may have a deficit in encoding acoustic-perceptual information, but that they are able to use this acoustic perceptual information to form abstract phonological categories. This stands in sharp contrast to traditional descriptions of this disorder. These argue that the systematicity of children's errors in the face of apparent normal perception and comprehension are evidence that the error patterns are due to deficits in more-abstract aspects of phonological knowledge. By implication, our findings suggest that remediation programs for children with PhI should focus on facilitating perceptual knowledge (as in Rvachew, 1994, and Rvachew et al., 2004) rather than facilitating more-abstract aspects of phonological knowledge (as in Dean and Howell, 1986). Our ongoing work examines further the nature of the perceptual-learning deficit in children with PhI. In particular, this work attempts to tease apart whether this deficit is in *encoding* or *retention* of novel stimuli, and whether it reflects an implicit learning deficit that spans different sensory domains. The results of this ongoing work will further refine our understanding of the relationship between perceptual deficits and the nature, assessment, and treatment of PhI.

The findings in the three experiments reviewed in this paper have implications for our understanding of the origin of variation in speech production in the broader population. The fact that a measure of perceptual ability best differentiated between children with PhI and children with TD is consistent with recent experimental findings suggesting that episodic perceptual memories drive ongoing change in speech production (e.g., Goldinger & Azuma, 2004). Together, these findings support models of variation in speech production in which perceptual abilities and experiences, rather than variation in abstract phonological knowledge, underlie variation in speech production within populations.

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