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CHAPTER

8

How Early Auditory Experience Affects Children's Ability to Learn Spoken Words

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Abstract

It is generally assumed that deaf and hard-of-hearing children's difficulties in learning novel words stem entirely from impaired speech perception. Degraded speech perception makes words more confusable, and correctly recognizing words clearly plays an important role in word learning. However, recent findings suggest that early auditory experience may affect other factors involved in linking the sound patterns of words to their referents. This chapter reviews those findings and discusses possible factors that may be affected by early auditory experience and, in turn, also affect the ability to learn word-referent associations. These factors include forming representations for the sound patterns of words, encoding phonological information into memory, sensory integration, and quality of language input. Overall, we learn that in order to understand and to help mitigate the difficulties deaf and hard-of-hearing children face in learning spoken words after cochlear implantation, we must look well beyond speech perception.

Keywords: word learning, speech perception, phonological encoding, audiovisual integration, linguistic input, deaf, cochlear implants

Word learning is the foundation of language development. For spoken language, word learning requires children to encode spoken word forms (i.e., sequences of acoustic-phonetic information that comprise words) and then to learn the mappings between the word forms and referents out in the world. This is no simple task. To compound the problem, word learning involves more than mapping a word form to a single referent. Instead, words usually refer to a category of objects (see Xu & Tenenbaum, 2007). For example, the word *dog* refers not only to one's own pet dog, but also to many different instances. Furthermore, a single object can usually be referred to by several different words. For example, the pet dog can be referred to as *Sam*, *beagle*, *dog*, or *animal*. The word-learning problem is not a one-word-to-one-referent mapping problem, but a many-words-to-many-referents mapping problem (see Chen, Zhang, & Yu, 2018). It also involves learning how broadly one can extend and generalize a word to other referents (Bloom, 2002; Markman, 1989). Despite the complexity of the problem, it all starts with the simple association between a novel word and a single referent. In this chapter, we focus on deaf children's ability to learn simple word-referent associations after cochlear implantation.

It has long been established that deaf children with cochlear implants (CIs) lag behind their normally hearing (NH) peers in terms of their spoken word vocabulary development (Davidson, Geers, & Nicholas, 2014; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2002). This is not surprising because children with severe-to-profound sensorineural hearing loss learn little to no spoken words until after they receive access to sound through a CI, and thus they start out behind their NH peers. Research studies over the past 16 years suggest that children with CIs not only are delayed in their vocabulary acquisition, but also have more difficulty learning simple word-referent associations relative to their NH peers

(Davidson et al., 2014; Houston et al., 2003, 2005, 2012; Lund & Schuele, 2017; Majorano et al., 2017; Quittner et al., 2016; Tomblin et al., 2007; Walker & MacGregor, 2013). These findings advance our knowledge by showing that lower vocabulary levels in children with CIs are not simply due to a delay in the onset of acquiring a vocabulary; they are also due to differences in the basic, underlying mechanisms involved in learning words. This chapter summarizes what we know and do not know about the functioning of basic word-learning mechanisms in children with CIs compared to NH children. Further, it explores possible reasons (e.g., lack of access to auditory input before CI) that may explain differences in functioning. Gaining a better understanding of precisely why children with CIs struggle with learning words will move the field into a better position for developing strategies for improving word-learning skills and thus enabling children with CIs to acquire larger vocabularies. At the same time, this approach will yield insights into deaf children's learning more broadly.

Forming Representations of the Sound Patterns of Words and Encoding Them Into Memory

In order to learn a word, a child must form an acoustic-phonetic representation of that word and encode that representation into memory. These processes happen simultaneously: One cannot form a representation without involving memory. However, it is important to differentiate these two processes when thinking about what could break down in children with CIs. One process—forming the representation—is highly dependent on speech-perception skills. Infants and children with good speech-perception skills will be able to extract sound patterns of words from fluent speech and form representations of those sound patterns in enough detail that they can be simultaneously recognized when encountered later and differentiated from all the other words encountered. Children with poorer speech-perception skills may be less able to detect words from fluent speech to begin with, causing difficulty forming representations that are indistinguishable from similar-sounding words, and making it more difficult to form a vocabulary.

The other process—encoding the representations of the sound patterns of words into memory—is highly dependent on phonological working memory. Infants and children with better phonological working memory processes will be better able to store the sound patterns of words into memory and thus can recognize the words in different contexts over time better than children with poorer phonological working memory processes.

So, although forming representations of the sound patterns of words and encoding them into memory are integral processes, they tap distinct sets of mechanisms that could be differentially affected by hearing loss. Hypothetically at least, some children may be relatively good at forming detailed representations of words but are unable to store those representations in memory because of relatively poor phonological working memory skills; other children may have more limited speech-perception skills that allow them to form only coarse representations of words but have relatively good phonological working memory skills and are able to store those coarse representations in memory and recognize them across different contexts—although with significant confusion with similar-sounding words. The next two sections review the importance of forming representations of the sound patterns of words and encoding those representations into memory for word learning and provide current evidence suggesting that impairments in these sets of processes account for some of the variability in word-learning skills among children with CIs (see also Lund, this volume).

Forming Representations of Words

Forming acoustic-phonetic representations of words from the input is more challenging than it may seem at first. One part of the process is extracting sound patterns of words from the context of fluent speech. The majority of words are embedded in the context of fluent speech, even speech to infants and young children (Van de Weijer, 1999). Moreover, fluent speech does not always contain reliable acoustic cues, such as pauses, to mark the beginnings and endings of words (Cole & Jakimik, 1980). For NH children, this challenge is surmounted during infancy by implicitly learning about the probabilistic characteristics of words in their native language and by the development of general learning skills.

One characteristic of words that NH infants learn is their rhythmic properties. Infants display sensitivity to the rhythmic properties of language at very young ages. In one pioneering study, Mehler et al. (1988) investigated newborn infants' ability to discriminate different languages that were low-passed filtered at 400 Hz, which removes acoustic information that differentiates phonemes but preserves the rhythmic and intonational properties. Newborn French- and English-learning infants, who were exposed to one of the languages in utero from their mother's voices, demonstrated the ability to discriminate French and English. Follow-up research showed that newborns are able to discriminate languages that have different types of rhythmic structures even if the languages are ones that the newborn had no exposure to in utero (Nazzi, Bertoncini, & Mehler, 1998).

This sensitivity to rhythmic properties at the language level eventually develops into sensitivity to rhythmic properties at the individual word level, at least for infants exposed to some languages. By 9 months of age, but not before 6 months, English-learning NH infants attend more to bisyllabic words that follow the predominant strong/weak stress pattern of English words (e.g., doctor, candle, hamlet, kingdom) than to words with a less common weak/strong stress pattern (e.g., guitar, device, surprise, beret; Jusczyk, Cutler, & Redanz, 1993). Sensitivity to this rhythmic property has been shown to play a role in English-learning infants' ability to segment words from the context of fluent speech (Jusczyk, Houston, & Newsome, 1999). Jusczyk et al. (1999) found that 7.5-month-old English-learning infants were able to segment strong/weak words from fluent speech but not weak/strong words. However, 10.5-month-old infants were able to segment both, suggesting that during the second half of the first year of life, English-learning infants become sensitive to other language-specific properties and/or develop other skills that allow them to segment words with rhythmic properties that are less typical in English.

Other language-specific properties that play a role in segmenting words from fluent speech include phonotactic and subphonemic properties. Phonotactics refers to how sequences of phonemes are organized in a language. For example, the sequence [p] followed by [k] does not occur within syllables in English. Thus, when an English listener encounters that sequence in fluent speech, it will signal a syllable or word boundary. By 9 months of age, English-learning infants are sensitive to phonotactic probabilities in English (Jusczyk, Luce, & Charles-Luce, 1994) and can use that information to aid with segmenting words from fluent speech (Mattys & Jusczyk, 2001). Similarly, infants' sensitivity to subphonemic information, such as allophonic variation of phonemes (e.g., the variants of [t] in "night rates" vs "nitrates") and other subphonemic information (e.g., subtle differences in coarticulation across phonemes in "catalog" vs "cat a log"), have been found to play a role in English-learning infants' segmentation of words from fluent speech by the end of the first year of life (Johnson, 2008; Jusczyk, Hohne, & Bauman, 1999).

Infants enhance their speech-segmentation skills not only by developing a sensitivity to language-specific characteristics of the language(s) they are learning, but also as they develop more sophisticated general cognitive and linguistic skills that play a role in speech segmentation. Infants develop the ability to notice co-occurrences of syllables (e.g., [ma] is often followed by [mi], providing evidence that "mommy" is a word) and use this information to segment multisyllabic words from fluent speech (Saffran, Newport, & Aslin, 1996). They are also able to use familiar words (e.g., "mommy") to help identify offsets of preceding words and onsets of words that follow (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005). The combination of sensitivity to language-specific characteristics and the development of language-general learning mechanisms converge to allow infants and young children to successfully segment words from fluent speech.

Another challenge of forming word representations is forming them in a way that, when they are encoded into memory, they will be recognized when encountered later, even though the exact acoustic-phonetic properties of each encounter with a word vary. Acoustic-phonetic variability across instances of the same word is caused in part by differences among talkers in the physiology of their vocal apparatuses and in their language experiences (e.g., exposure to different dialects). Infants' ability to recognize words across talkers improves much during the second half of the first year of life (Houston & Jusczyk, 2000, 2003). For example, Houston and Jusczyk (2000) tested 7.5-month-old infants' ability to recognize words across talkers of the same and different genders. They found that 7.5-month-old infants were able to recognize words in passages after they had been familiarized with the words produced by a talker of the same gender, but not when produced by a talker of the opposite gender. By contrast, 10.5-month-old infants were able to recognize words across talkers of the opposite gender. Similar developmental changes have been observed in infants' ability to deal with dialect variability (Schmale & Seidl, 2009). Taken together, these findings suggest significant changes during the first year of life in how infants deal with nonlinguistic properties, such as talker-specific and dialect information, when forming representations of the sound patterns of words.

Different instances of the same word differ not only across talkers but also within the same talker, due to variations in emotional and physical state. Singh, Morgan, and White (2004) investigated infants' ability to recognize words across variants of words produced by the same talker but in a different affect (positive or negative). Similar to the above studies, they found that 7.5-month-old infants could not recognize words across different affective states of the same talker, whereas 10.5-month-old infants were able recognize words across such variability. Thus, at the same time that infants are improving their speech-segmentation skills, they also develop speech-perception skills that allow them to form representations of words that can be recognized across different talkers and contexts.

The above studies provide just a few examples of the perceptual skills relevant to word recognition that NH infants acquire during the first year of life (for more comprehensive reviews, see Houston, 2016; Johnson, 2016; Werker, 2018). They illustrate the complex auditory-perceptual development that unfolds during infancy and enables children to form representations of words from fluent speech that are recognizable across talkers and contexts. There is still very little known about the development of early speech-perception skills in deaf infants and young children who receive CIs (for a review, see Houston & Warner-Czyz, 2018), especially the specific speech-perception skills that are most relevant to speech segmentation. Only one study has investigated children with CIs' ability to discriminate rhythmic properties of words and found that children with CIs are able to discriminate strong/weak and weak/strong words after a year of CI experience (Segal, Houston, & Kishon-Rabin, 2016). However, little is known about the developmental trajectory of this skill and what role it plays, if any, in early speech-segmentation. Further work on speech-perception skills relevant for word segmentation and recognition would provide valuable knowledge for understanding the strengths and limitations infants and children with CIs have in forming representations of the sound patterns of words.

Although little is known about the speech-perception skills leading up to sophisticated word recognition, the ability to recognize familiar words has been assessed in children with CIs for decades as a way of evaluating the effectiveness of CIs. More recently, researchers have investigated relationships between word recognition accuracy and novel word learning as a way of determining the degree to which word-learning difficulties are due to difficulties with correctly perceiving the sound patterns of words.

In one recent study, Davidson, Geers, and Nicholas (2014) investigated the relationship between audibility and novel word learning in 6- to 12-year-old deaf children who received their CIs by 5 years of age. Word learning was assessed using a task in which children watched an animated video with a character that encountered six novel objects with nonsense names. A recognition test followed that probed which word-referent pairings the children learned. This was repeated six times for a total of 36 possible novel words learned. They found that children with relatively better audibility performed better on the novel-word-learning task and the word-recognition task. Moreover, word-recognition scores correlated positively with word learning, suggesting that the ability to form accurate representations of the sound patterns of words—as measured in the word-recognition task—accounts for some of the variance in novel word learning in children with CIs.

In a study that more directly tested the role of speech-perception skills on word learning, Havy, Nazzi, and Bertoncini (2013) tested 3- to 6-year-old children with CIs on a word-learning task in which pairs of to-be-learned nonsense words differed by either a single feature or multiple features on one phoneme. Children with CIs performed more poorly than NH children on the word-learning task when demands on speech-perception skills were increased, suggesting an important role of being able to form precise representations of words in novel word learning. Taken together, it is clear that if children have difficulty correctly perceiving the sound patterns of words, they are likely to have more difficulty differentiating words from each other and recognizing when they encounter the same words across different contexts. Difficulty recognizing words will naturally make learning them more difficult.

The above conclusion begs the question, though, of how much of the variability in novel-word-learning skills in children with CIs is accounted for by their ability to correctly form representations of the sound patterns of words. This is a crucial question for our understanding of the underlying nature of CI children's difficulty with learning novel words. If speech-perception skills do not account for all the variability in novel word learning, then auditory deprivation must affect other, basic, underlying processes associated with learning novel words not directly related to hearing and perceiving the sounds of words. Recent research by Houston and colleagues suggest that this may be the case.

In one study, Houston et al. (2012) investigated novel word learning in children implanted before 2 years of age. One goal of the study was to determine the role that novel-word-learning skills play in children's ability to achieve better language outcomes when they receive CIs at very early ages. Mounting evidence from several studies suggests that early age at cochlear implantation does not result in better speech-perception skills when the range of age at implantation is less than 2 or 3 years of age (Holt & Svirsky, 2008; Horn, Houston, & Miyamoto, 2007; Houston & Miyamoto, 2010; Leigh, Dettman, Dowell, & Briggs, 2013). However, early age at implantation within that same range is associated with better receptive and expressive language outcomes (Dettmen et al., 2007; Holman et al., 2013; Houston & Miyamoto, 2010; Leigh et al., 2013; Nicholas & Geers, 2013; Schauwers et al., 2004). Our hypothesis was that early implantation may lead to better novel-word-learning skills, which in turn lead to better receptive and expressive language outcomes. The findings supported the hypothesis—performance on the word-learning task correlated with later measures of vocabulary and receptive and expressive language.

Relevant to this chapter, Houston et al. (2012) found no relationship between novel-word-learning skills and later speech perception, in contrast to the Davidson et al. (2014) study reviewed above. The difference in findings may be explained by a critical difference between the two studies. The Davidson et al. (2014) study included children implanted between 10 months and 5 years of age, whereas the Houston et al. (2012) study had a narrower age range and included children implanted between 7 and 22 months. Thus, it is possible that the variability in speech-perception skills was much greater in the Davidson et al. (2014) study and, as a result, played a larger role in the variability in word-learning ability as compared to participants in the Houston et al. (2012) study. In other words, the variability in speech-perception skills of the early implanted children in Houston et al. (2012) may not have been large enough to have a significant impact on the development of children's word-learning skills.

If correctly perceiving the sound patterns of words does not account for all of the variability in novel-word-learning skills, especially among children who receive their CIs before 2 years of age, it suggests that more basic, underlying cognitive processes may be involved in accounting for the variability. In other words, early auditory deprivation may affect basic learning mechanisms, creating challenges for word learning above and beyond the challenges of hearing and perceiving the sound patterns of words correctly (for a theoretical model of this possibility, see Kral, Kronenberger, Pisoni, & O'Donoghue, 2016).

Encoding the Sound Patterns of Words Into Memory

To learn words, children not only must form representations of the sound patterns of words, but also must encode the sound patterns into memory. Phonological working memory is especially important for this process. Phonological working memory is the short-term storage a listener can pull from while still processing new information. It's what allows a listener to hold "pho" in memory while hearing "nological" so that they can understand that they just heard "phonological." It is also what allows the listener to store each word in an utterance long enough to understand the whole utterance. When words are repeatedly encoded into phonological working memory, they eventually get encoded into long-term memory for later recognition. For example, once the phrase "phonological working memory" is encoded into long-term memory, a listener is then able to hear and read about it in a variety of contexts and build an increasingly more complex understanding of its meaning.

There is a large amount of evidence that phonological working memory capacity is related to vocabulary and word learning in NH children. Several studies have found that children who perform better on a nonword repetition task have better vocabulary and novel-word-learning skills (Avons, Wragg, Cupples, & Lovegrove, 1998; Gathercole & Baddeley, 1989, 1990; Gathercole, Hitch, Service, & Martin, 1997). To explain these findings, Gupta and MacWhinney (1997) proposed that phonological working memory and word learning tap into the same underlying cognitive and neural processes. Both processes involve chunking sequential information (i.e., phonemes and syllables) into word forms. Gupta and MacWhinney proposed a model in which, when a new word form is encountered, a new representation (chunk) is formed with connections to a particular sequence of phonemes. These connections can decay over time, but reactivation through rehearsal or repeated encounters can strengthen the weights of the connections. A word becomes part of long-term memory when the weights of the connections reach a saturation point. In nonword repetition tasks, performance depends on the initial strength of connections and rate of decay, both of which can vary across individuals and thus account for individual differences. Variability in these same factors also plays a role in determining the probability of the weights of the connections reaching saturation, accounting for variability in word learning and vocabulary.

Baddeley, Gathercole, and colleagues proposed that shared variability between measures of nonword repetition and vocabulary are due to both being dependent on the phonological storage component of the phonological loop in Baddeley's model of working memory (Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006). When a nonword is encoded into short-term memory via phonological storage, it creates a representation with fast and temporary weights. Repeated activation of these fast and temporary weights will incrementally contribute to strengthening corresponding slow and more permanent weights in long-term memory. Nonword repetition tasks are a sensitive measure of the quality of phonological storage. Individual variability in phonological storage impacts the ability to form long-term representations of words.

Gathercole (2006) proposed that phonological storage is determined by a combination of several factors. The most intuitive is auditory processing—children who form poorer representations, as described above, would have poorer storage due to confusability of words. However, Gathercole proposed that phonological encoding of the information also plays a role. This is evidenced by studies showing that children with specific language impairment (SLI) but without any auditory processing problems still often display poor performance in nonword repetition tasks due to their impaired ability to encode phonological information. Whatever the mechanisms, the important point here is that encoding phonological information into short-term or working memory can show variability independent from the variability associated with the auditory processing of the acoustic-phonetic information, and that variability in encoding phonological information into short-term memory can impact forming representations into long-term memory, which is crucial for learning words.

Phonological working memory capacity has been shown to be smaller in children with CIs than in NH children. Evidence for this finding has been provided using several tasks, including digit span (Bharadwaj, Maricle, Green, & Allman, 2015; Burkholder & Pisoni, 2003; Cleary, Pisoni, & Geers, 2001; Harris et al., 2013; Soleymani, Amidfar, Dadgar, & Jalaie, 2014), serial recall (Nittrouer, Caldwell-Tarr, & Lowenstein, 2013), and nonword repetition tasks (Nittrouer, Caldwell-Tarr, Low, & Lowenstein, 2017; Soleymani et al., 2014). Work by Nittrouer and colleagues suggests that differences in working memory between NH children and children with CIs are primarily due to differences in sensitivity to phonological structure (Nittrouer et al., 2013; 2017; Nittrouer, Caldwell-Tarr, Sansom, Twersky, & Lowenstein, 2014). In one study, Nittrouer et al. (2014) tested nonword repetition in second graders with CIs and found that performance was predicted by a phoneme deletion task and not measures of serial recall, vocabulary, grammar, or reading. As in NH children, the phonological working memory of children with CIs correlates with language outcomes (Cleary, Pisoni, & Kirk, 2000; Geers et al., 2013; Harris et al., 2013; Kronenberger, Colson, Henning, & Pisoni, 2014; Nittrouer et al., 2013, 2017; Pisoni & Geers, 2000; Pisoni, Kronenberger, Roman, & Geers, 2011). For example, Cleary et al. (2000) tested 5- to 16-year-old children with CIs on forward and backward digit span tasks and compared the results with measures of speech perception and receptive vocabulary. They found that after other demographic variables were taken into account (e.g., age at CI, chronological age), forward digit span predicted a significant amount of variance in speech perception and receptive vocabulary skills. Nittrouer et al. (2017) looked further into the relationship between phonological working memory and language outcomes by examining phonological storage and processing components of phonological working memory and their correlation with language outcomes. Phonological storage was measured as accuracy of serial recall, whereas processing was measured using response time. Nittrouer et al. found that, compared with NH, age-matched peers, fourth graders with CIs were less accurate and exhibited somewhat slower responses. However, only the measure of accuracy correlated with language measures, which is consistent with the view that variability in phonological storage is what accounts for correlations between phonological working memory and language outcome measures across populations (Gathercole, 2006). In other words, language outcomes are determined more by the quality of acoustic-phonetic and phonological information encoded than by the speed at which it is encoded.

Only one study has examined if phonological working memory accounts for variability in word-learning skills in children with CIs (Willstedt-Svensson, Löfqvist, Almqvist, & Sahlén, 2004).

Willstedt-Svensson et al. (2004) assessed novel word learning, extension, and retention as well as phonological working memory in 6- to 12-year-old children with CIs who had a wide range of age at implantation (2–7 years), CI experience (2–8 years), and oral language ability (some primarily used sign language). They found that both age at implantation and phonological working memory were correlated with novel word learning and retention, but not independently. When both age at implantation and phonological working memory were entered into a regression to predict novel word learning, only phonological working memory was statistically significant. This finding suggests that the relationship between age at implantation and novel word learning was, in this group of children, mediated by phonological working memory. In other words, early implantation may have led to better phonological working memory, which may in turn have facilitated novel word learning and retention.

While phonological working memory clearly played a major role in accounting for word learning and retention in the study by Willstedt-Svensson et al. (2004), very little is known about the role of phonological working memory in accounting for variability in word learning and retention in more specific populations of children with CIs (e.g., those implanted earlier and who primarily use oral language). Two subsequent studies (Houston et al., 2005; Walker & McGregor, 2013) also assessed both word learning and retention of words but in children implanted earlier than the children studied by Willstedt-Svensson et al. (2004). In contrast to the Willstedt-Svensson et al. (2004) study, these two studies did not find an age-at-implantation effect for long-term retention. Given the important role that working memory plays in long-term retention, this pattern of results is surprising if it is the case that age-at-implantation effects are mediated mainly by working memory. One possibility is that at earlier ages of implantation, phonological working memory plays less of a mediating effect on word learning. Another possibility is that it still plays an equally strong role, but that age at implantation affects only initial encoding of words and not the functions of phonological working memory that are involved in making the representations more permanent.

Learning Audiovisual Associations

Thus far, the discussion has focused on the auditory side of word learning—perception and encoding of the sound patterns of words. Yet, a fundamental aspect of word learning is the ability to construct associations between the encoded sound pattern of words and their referents, and in most cases, especially during early development, these learned associations are multimodal in nature, involving both vocal and visual representations. A primary challenge in this process, and one to which the bulk of the literature on word learning in NH children has been devoted, is understanding how children learn to resolve referential ambiguity, in which one word is associated with one of multiple potential visual referents. Less attention has been devoted to the challenge of learning the association once it has been correctly identified. This may be because it is thought to be relatively straightforward for NH children. Indeed, studies on NH children's ability to "fast map" words to referents suggest that it is (see Carey & Bartlett, 1978; Estes, Evans, Alibali, & Saffran, 2007; Tomasello, 2003). However, this process may not be as straightforward for children with CIs.

Deaf children encounter the multimodal world without experience attending to, processing, and storing auditory information. Additionally, not until after cochlear implantation do deaf children with CIs obtain experience with temporally synchronous audiovisual events. Experience with audiovisual events during early infancy may constrain referential ambiguity and foster the ability to learn arbitrary associations between the sound patterns of words and their referents. Next, we briefly review audiovisual perceptual development in NH children that may form the building blocks of being able to abstract and learn arbitrary word-referent associations. In doing so, we hope to offer some considerations regarding how deaf children's lack of experience with audiovisual events during early development may affect their ability to learn arbitrary word-referent associations.

Audiovisual Perception and Integration During Early Childhood

Most events that we experience transmit redundant and temporally synchronous information across two or more sensory modalities. In utero, fetuses experience redundant and temporally synchronous information specifying their mother's voice. Maternal speech onset/offset, for example, is redundantly conveyed auditorily and vibrotactilely through vibrations of the larynx and diaphragm transmitted via bone conduction. After birth, when newborns are first held in their mothers' arms, they simultaneously hear their mother's voice and see her face and her lips move in temporal synchrony with her speech patterns; they also feel her touch and smell her scent. These experiences scaffold newborns' ability to learn some highly salient arbitrary intermodal associations soon after birth (see Sai, 2005).

It is well established that newborns display preferences for their mother's face. These strong preferences are driven, in part, by salient synchronous audiovisual experiences with their mother's voice and face. Indeed, Sai (2005) provided evidence to suggest that newborns make use of synchronous audiovisual information when constructing intermodal associations between their mother's voice and face. In these experiments, immediately after delivery, mothers consented to either 1) physically and acoustically interact with their newborns, or 2) physically interact with their newborns without providing any acoustic information. Newborns who were allowed to see and hear their mothers speak displayed discrimination of, and preference for, their mother's face over the face of a stranger. In contrast, newborns who were only allowed to see their mother's face, but not to hear her speak, displayed no discrimination or preference for their mother's face over the face of a stranger. This study demonstrates that newborns capitalize on their limited synchronous audiovisual postnatal experience when learning to detect the intermodal association between their mother's face and the salient voice they experienced in utero.

With respect to speech, infants display early preferences for temporal synchrony between speech sounds and visual articulatory information. Infants 2 months old will look longer at displays depicting synchronous (vs. asynchronous) audiovisual nursery rhymes (Dodd, 1979). When temporal synchrony is preserved, infants have been shown to integrate vocal phonemic contrasts with the visual articulatory movements of a speaker by as young as 2 months of age (Kuhl & Meltzoff, 1982; Patterson & Werker, 2003). For example, Kuhl and Meltzoff (1982) used a split-screen preferential looking paradigm to simultaneously present infants with two video events of a woman silently producing [a] on one side of the screen and the same woman producing [i] on the other side of the screen. The infants were also presented with either an auditory [i] or [a] on each trial. The investigators found that 18- to 20-week-old infants looked longer at the video that corresponded with the auditory stimulus. Subsequent work has found that infants can match auditory and visual articulatory information at even younger ages (Patterson & Werker, 2003).

The McGurk effect, an illusion that is created by the integration of auditory and visual cues, is a classic example of how temporal synchrony aids in the seemingly "automatic" binding of sensory information. The research indicates that 5-month-old infants' perception of an auditory syllable can be altered by visual cues specifying a different syllable (Rosenblum, Schmuckler, & Johnson, 1997). Moreover, infants' multisensory experience with listening to and producing vowel sounds influences their differential mapping of high-frontal and low-posterior vowels to objects of varying sizes (Peña, Mehler, & Nespor, 2011).

Infants can also form intermodal voice–face associations in nonnative languages. Infants 6 and 9 months old display integration of nonnative vocal contrasts with visual information from speech articulation (Danielson, Bruderer, Kandhadai, Vatikiotis-Bateson, & Werker, 2017). Using fluent speech samples, Lewkowicz, Minar, Tift, and Brandon (2015) demonstrated that toddlers aged 12 to 14 months can integrate both native and nonnative speech samples with visual articulatory information. Interestingly, only in the presence of temporal synchrony, but not in its absence, were toddlers able to form intermodal associations for the nonnative speech samples, suggesting that audiovisual temporal synchrony aids in early language learning.

One of the methods by which children learn words is by detecting and capitalizing on the temporal synchrony between the spoken word and the referent. When teaching infants novel word–referent associations, parents are more likely to use temporal synchrony when naming a referent and showing a referent (Gogate, Bahrick, & Watson, 2000). In fact, research has shown children are more likely to learn word–referent associations in the presence of temporal synchrony between referent naming and referent motion (Gogate & Bahrick, 1998; Gogate, Bolzani, & Betancourt, 2006). For example, a parent may spatially coordinate and temporally synchronize their vocal naming of the word *choo-choo* with the visual presentation of a toy train. By doing so, parents highlight words of importance within the stream of fluent speech and bring one referent into the foreground from the background of multiple potential visual referents, thereby effectively promoting infants' attention to, processing of, and storage of word–referent associations. In sum, young NH children gain a wealth of audiovisual experience early in life that provides the foundation for detecting and learning word–referent associations.

It is possible that limited early access to these audiovisual experiences may impact deaf children's the ability to learn word–referent (and perhaps other) associations.

Implications of Limited Early Access to Audiovisual Information During Infancy

Deaf infants have full access to the visual, tactile, and olfactory information that allows them to form concepts of objects, actions, smells, textures, and other semantic categories in the world. Until they receive CIs, they form multisensory representations of concepts (e.g., the way mom looks, acts, smells, and feels), without the sounds associated with those concepts.

There is very little work on how the lack of early access to auditory information affects audiovisual integration in infants and children with CIs. Two studies used variants of the Kuhl and Meltzoff (1982) split-screen paradigm (described above) to investigate infants' ability to match speech stimuli to its visual articulation (Barker & Tomblin, 2004; Bergeson, Houston, & Miyamoto, 2010). Both studies found that some infants and children with CIs displayed matching abilities but with a high degree of individual variability. Moreover, Bergeson et al. (2010) found that children with CIs showed audiovisual integration only during the second half of the experiment, suggesting that the integration was not automatic and may have involved learning processes during the experiment.

Studies investigating children with CIs' ability to take advantage of visual articulatory information during word-recognition tasks and their performance on McGurk tasks suggest that audiovisual integration improves with CI experience and age (Maidment, Kang, Stewart, & Amitay, 2015; Schorr, Fox, van Wassenhove, & Knudsen, 2005; Tona et al., 2015). For example, Tona et al. (2015) investigated the McGurk effect across a wide range of ages and found that only children with CIs aged 6 years and older demonstrated the McGurk effect. Fusing auditory and visual information in the McGurk task may also depend on age at implantation. Schorr et al. (2005) found that only children implanted before 2.5 years of age showed the McGurk effect, suggesting a possible sensitive period for integration of auditory speech information with its corresponding visual-articulatory information.

There may be an even earlier sensitive period for learning associations between speech information and visual events that share dynamic characteristics. Houston et al. (2003) investigated young children with CIs' ability to learn associations between patterns of speech and objects that moved in synchrony with the patterns of speech. For example, in one condition, the speech pattern "hop, hop, hop" was paired with a video of a toy kangaroo bouncing in temporal synchrony, and the speech pattern "ahhh" was paired with a video of a toy airplane moving across the table in a steady motion. Houston et al. tested one group of children who had their CIs activated before 15 months of age and another group who had their CIs activated between 15 and 24 months of age. Only the earlier-implanted children showed learning of the arbitrary intermodal associations. The later-implanted children were not as readily able to take advantage of the intersensory redundancy of the rhythmic information to learn the pairings, suggesting that early auditory experience may be important for both intersensory integration and intermodal associative learning.

Difficulty integrating and associating auditory and visual information may be due to effects on cross-modal plasticity that result from auditory deprivation. Recent electrophysiological and neuroimaging studies have provided evidence for cross-modal reorganization of auditory brain regions in deaf children (Campbell & Sharma, 2016; Kral, 2013; Kral et al., 2016; Sharma et al., 2016; Sharma, Dorman, & Spahr, 2002). These regions (e.g., superior temporal cortex) are "repurposed" for visual processing in deaf children, which may serve a compensatory function during the period of deafness. However, cross-modal changes also result in maladaptive effects on auditory processing after cochlear implantation. Although a virtually unexplored research question, it is possible that some of these neural adaptations may have implications for word learning in children with CIs.

Multiple studies provide evidence for cross-modal reorganization by vision in brain regions that control speech processing and learning. For instance, the superior, inferior, and right posterior temporal cortex responds to general visual stimuli in deaf individuals. The normal function of ~~this~~ region is to separate an auditory "object" from background noise, which could partially explain why deaf listeners struggle to process speech in noise (Campbell & Sharma, 2016). For children struggling to separate a word from the surrounding auditory environment, noise would make it more difficult to form the initial association between the word and its referent. The extent to which these brain regions reorganize during the period of deafness, and the extent to which normal functioning is recovered following implantation, may determine how much children with CIs struggle to acquire vocabulary. An example from research with adults is that frontal cortical networks—which normally serve higher-order cognitive functions—are reallocated to serve speech perception following auditory deprivation (Glick & Sharma, 2017). This resource reallocation increases overall cognitive load. For deaf children, recruitment of frontal brain regions for speech processing could come at the cost of the cognitive processes needed for associative learning and encoding words into memory.

Following implantation, brain regions show several phases of plasticity in which the auditory cortex "regains" its typical functions to a certain degree. However, reversal of cross-modal reorganization is sensitive to several critical periods—similarly to language acquisition—and children who are implanted later in development show long-term changes in their neural circuitry (Gilley, Sharma, Mitchell, & Dorman, 2010; Sharma et al., 2002). In particular, children who are implanted after age 5 demonstrate lasting changes in audiovisual integration skills relative to early-implanted children and NH children (Gilley et al., 2010). More specifically, late-implanted children demonstrate separate, parallel processing of independent auditory and visual inputs. In contrast, early-implanted children and NH children demonstrate superadditive effects that indicate a combined, integrated response to both signals.

These findings suggest that audiovisual integration in children with CIs is sensitive to a critical period, beyond which children do not achieve typical audiovisual integration. Like audiovisual integration, word learning involves combining auditory and visual information. However, in word learning, the relationship between auditory and visual information is arbitrary and so must be learned purely through associative processes, which may have their own sensitive periods. Though no studies have directly examined links between cross-modal plasticity and word learning, future work may find that cross-modal plasticity plays a role in the developmental processes that allow children to learn associations between auditory words and visual referents.

Opportunities for Word Learning

Word learning occurs within social contexts in which children and caregivers interact. These interactions often create learning opportunities in which the caregiver names an object or event that the child is attending to (Tomasello & Farrar, 1986, Yu & Smith, 2012). Studies using both experimental designs and naturalistic interactions have shown that naming an object at the moment children are already attending to it results in better word learning than naming an object by redirecting children's attentional focus (Tomasello & Farrar, 1986). Many studies have shown that hearing parents of children with hearing loss tend to be more directive in their interactions than hearing parents of NH children (Fagan, Bergeson, & Morris, 2014; Henggeler, Watson, & Cooper, 1984). For example, parents of children with hearing loss tend to use more directives and prohibitions in their speech than parents of age-matched NH children (Castellanos, Pisoni, Yu, Chen, & Houston, 2018; Chen, Castellanos, Yu, & Houston, 2019a; Fagan et al., 2014; Henggler et al., 1984). One possible outcome of these directive parental styles is that parents of children with hearing loss may be less likely to provide names of referents when their children are attending to a particular referent, because they may be less likely to follow the children's lead. This can potentially have a negative effect on children's word-learning skills, as previous studies have shown that children are more likely to learn word–referent associations when parents provide names for the referents during episodes of sustained attention (Tomasello & Farrar, 1986, Yu & Smith, 2012).

A recent study using head-mounted eye-trackers directly examined the temporal synchrony between parents' naming of novel objects and children's sustained attention to the named objects in children with hearing loss (including children with CIs and hearing aids; Chen, Castellanos, Yu, & Houston, 2019b). The investigators found that parents of children with hearing loss and parents of NH children who were matched to the hearing loss group in either chronological age or hearing age provided similar amounts of naming instances during their play interactions. Children in the three groups displayed similar amounts of sustained attention (looks longer than 3s) to the objects they played with. However, parents' naming and children's sustained attention were less synchronized in the hearing loss group than in the two comparison groups. Moreover, parents of the children in the two comparison groups were more likely to name objects within episodes of children's sustained attention than parents in the hearing loss group. Consistent with previous research, these results suggest that children with hearing loss may have fewer optimal word-learning opportunities during object play with their parents.

Having fewer opportunities to learn words may result in a smaller vocabulary than would be predicted even after taking into account children's speech perception, encoding, and audiovisual associative learning abilities. Moreover, there is evidence to suggest that increasing vocabulary can lead to better word-learning skills (Perry & Samuelson, 2011; Samuelson & Smith, 1999). This may be in part due to strengthening of learning mechanisms with continued use. Studies on children's development of shape bias have supported this proposal. Shape bias is a bias many 2- and 3-year-old children demonstrate when asked to generalize novel names for solid objects (Landau, Smith, & Jones, 1988; Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). For example, after learning that a novel solid object is called a "dax" and then being asked to choose another object that is also called a "dax" among three novel objects that are matched to "dax" on either shape, material, or color, young children tend to select the shape-matched novel object. Smith and colleagues (Gershkoff-Stowe & Smith, 2004; Samuelson & Smith, 1999; Smith et al., 2002) hypothesized that the shape bias is a learned bias. One of the reasons is that early learned object names tend to be organized around their physical shapes. For example, cups are cup-shaped and balls are balled-shaped. To investigate this possibility, Smith and colleagues (Gershkoff-Stowe & Smith, 2004; Samuelson & Smith, 1999; Smith et al., 2002) examined the relationship between children's vocabulary and their shape bias in word-learning tasks. They found that children began to demonstrate a shape bias during word generalization tasks when their expressive vocabularies contained many nouns.

In a longitudinal novel word learning study, Gershkoff-Stowe and Smith (2004) trained young children who had not yet demonstrated a shape bias to attend to the shapes of objects. They found that, as children increased their attention to object shape in the lab learning task, there was also a significant increase in their acquisition of nouns outside of the laboratory. These studies suggest that children's heightened attention to object shapes leads to shape biases during word generalization tasks and facilitates learning of novel nouns outside of the lab setting. Therefore, increasing vocabulary size leads to better word-learning skills. And better word-learning skills, in turn, facilitate increases in vocabulary size.

As suggested by the eye-tracking studies mentioned above, children with CIs may have fewer optimal word-learning opportunities. This could slow their vocabulary development, which in turn could have a negative effect on their word-learning skills. Indeed, studies have reported relationships between vocabulary size and word-learning skills in children with CIs, suggesting the possibility that children with more opportunities to learn words become better word learners (Lederberg & Spencer, 2008; Pimperton & Walker, 2018; Walker & McGregor, 2013). For example, Walker and McGregor (2013) tested a group of children with CIs (age 3 to 6 years) and their age-matched and vocabulary-matched NH peers on three tasks, each tapping a critical component in word learning: fast mapping, word extension, and retention. While the investigators did find differences in word-learning skills between the children with CIs and age-matched peers, there were no differences between children with CIs and vocabulary-matched peers. Similarly, Pimperton and Walker (2018) found that vocabulary size predicted word-learning skills in 6- to 12-year-old children with CIs. These findings and findings that children with CIs may have fewer optimal word-learning opportunities, taken together, suggest the possibility that variability in the development of word-learning skills in children with CIs may be in part due to differences in opportunities to learn words that lead to differences in vocabulary size.

However, another possibility is that the effect is primarily in the opposite direction—those with better initial word-learning skills develop more vocabulary, which in turn drives even better word-learning skills. The bidirectional bootstrapping between building a large vocabulary and improving word-learning skills can have cascading effects, in that the rich get richer and that children with a smaller vocabulary keep lagging in their rate of vocabulary development. Children with a larger vocabulary size may have more opportunities to participate in conversations. This could potentially give them more word-learning opportunities, as parents may provide explanations to the words their children do not understand, expand on what their children say, and provide more complex language (see Monday, this volume; Marschark and Knoors, this volume). Having more word-learning opportunities then allows children to practice their word-learning skills. With practice, they improve their word-learning skills, and this contributes to building a larger vocabulary.

Conclusions

Word learning is the most essential component of language acquisition, and this chapter explores key processes that may impact word learning in children with CIs. The processes vary in how directly linked they are to hearing. Speech-perception skills that are important for extracting words from fluent speech and forming representations are closely tied to audibility of the acoustic signal. For children with degraded auditory input from CIs, these skills are the most expected cause of difficulty with word learning. However, speech-perception skills do not appear to be the only processes involved in word learning that are affected by the atypical auditory experiences of children with CIs. Early auditory experiences appear to impact other systems as well. Phonological working memory can be affected by early auditory experience, which affects children's ability to store permanent representations of the sound patterns of words. Early auditory experience may also affect basic audiovisual integration and association skills. Finally, early auditory experience may affect the coordination of interactions with caregivers, which can impact opportunities to build a vocabulary and improve word-learning skills. Although the body of work on word learning in children with CIs is still limited, what has already been learned points to the importance of approaching word learning in children with CIs from the perspective of the whole child within the social context.

References

Avons, S. E., Wragg, C. A., Cupples, L., & Lovegrove, W. J. (1998). Measures of phonological short-term memory and their relationship to vocabulary development. *Applied Psycholinguistics, 19*, 583–601.

Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, *105*(1), 158–173.

Barker, B. A., & Tomblin, J. B. (2004). Bimodal speech perception in infant hearing aid and cochlear implant users. *Archives of Otolaryngology—Head & Neck Surgery*, *130*(5), 582–586.

Bergeson, T., Houston, D. M., & Miyamoto, R. T. (2010). Effects of congenital hearing loss and cochlear implantation on audiovisual speech perception in infants and children. *Restorative Neurology and Neuroscience, 28*, 157–165.

Bharadwaj, S. V., Maricle, D., Green, L., & Allman, T. (2015). Working memory, short-term memory and reading proficiency in school-age children with cochlear implants. *International Journal of Pediatric Otorhinolaryngology*, *79*(10), 1647–1653.

Bloom, P. (2002). *How children learn the meanings of words*. Cambridge, MA: MIT Press.

Campbell, J., & Sharma, A. (2016). Visual cross-modal reorganization in children with cochlear implants. *PLoS One, 11*(1), e0147793.

Bortfeld, H., Morgan, J. L., Golinkoff, R. M., & Rathbun, K. (2005). Mommy and me: Familiar names help launch babies into speech-stream segmentation. *Psychological Science*, *15*(4), 298–304.

Burkholder, R. A., & Pisoni, D. B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology*, *85*, 63–88.

Carey, S., & Bartlett, E. (1978). Acquiring a single new word. *Papers and Reports on Child Language Development, 15*, 17–29.

Castellanos, I., Pisoni, D. B., Yu, C., Chen, C. H., & Houston, D. M. (2018). Embodied cognition in prelingually deaf children with cochlear implants: Preliminary findings. In H. Knoors & M. Marschark (Eds.), *Evidence-based practices in deaf education* (pp. 397–416). New York, NY: Oxford University Press.

Chen, C., Zhang, Y., & Yu, C. (2018). Learning object names at different hierarchical levels using cross-situational statistics. *Cognitive Science*, *42*, 591–605.

Chen, C., Castellanos, I., Yu, C., & Houston, D. (2019a). Parental linguistic input and its relation to toddlers' visual attention in joint object play: A comparison between children with normal hearing and children with hearing loss. *Infancy, 24*(4), 589–612.

Chen, C., Castellanos, I., Yu, C., & Houston, D. (2019b). Effects of children's hearing loss on the synchrony between parents' object naming and children's attention. *Infant Behavior and Development*, *57*, 101322.

Cleary, M., Pisoni, D. B., & Kirk, K. I. (2000). Working memory spans as predictors of spoken word recognition and receptive vocabulary in children with cochlear implants. *The Volta Review*, *102*(4), 259–280.

Cleary, M., Pisoni, D. B., & Geers, A. E. (2001). Some measures of verbal and spatial working memory in eight- and nine-year-old hearing-impaired children with cochlear implants. *Ear and Hearing*, *22*(5), 395–411.

Cole, R., & Jakimik, J. (1980). How are syllables used to recognize words? *Journal of the Acoustical Society of America*, *67*, 965–970.

Danielson, D. K., Bruderer, A. G., Kandhadai, P., Vatikiotis-Bateson, E., & Werker, J. F. (2017). The organization and reorganization of audiovisual speech perception in the first year of life. *Cognitive Development*, *42*, 37–48.

Davidson, L. S., Geers, A. E., & Nicholas, J. G. (2014). The effects of audibility and novel word learning ability on vocabulary level in children with cochlear implants. *Cochlear Implants International*, *15*(4), 211–221.

Dettman, S. J., Pinder, D., Briggs, R. J. S., Dowell, R. C., & Leigh, J. R. (2007). Communication development in children who receive the cochlear implant younger than 12 months: Risks versus benefits. *Ear and Hearing*, *28*(Suppl. 2), 11S–18S.

Dodd, B. (1979). Lip reading in infants: Attention to speech presented in- and out-of-synchrony. *Cognitive Psychology*, *11*(4), 478–484.

Estes, K. G., Evans, J. L., Alibali, M. W., & Saffran, J. R. (2007). Can infants map meaning to newly segmented words? Statistical segmentation and word learning. *Psychological Science*, *18*(3), 254–260.

Fagan, M. K., Bergeson, T. R., & Morris, K. J. (2014). Synchrony, complexity and directiveness in mothers' interactions with infants pre-and post-cochlear implantation. *Infant Behavior and Development*, 37(3), 249-257.

Gathercole, S. E. (2006). Nonword repetition and word learning: The nature of the relationship. *Applied Psycholinguistics*, *27*(04), 513–543.

Gathercole, S. E., & Baddeley, A. D. (1989). Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. *Journal of Memory and Language, 28*, 200–213.

Gathercole, S. E., & Baddeley, A. D. (1990). The role of phonological memory in vocabulary acquisition: A study of young children learning new names. *British Journal of Psychology, 81*, 439–454.

Gathercole, S. E., Hitch, G. J., Service, E., & Martin, A. J. (1997). Short-term memory and new word learning in children. *Developmental Psychology, 33*, 966–979.

Geers, A. E., Pisoni, D. B., & Brenner, C. (2013). Complex working memory span in cochlear implanted and normal hearing teenagers. *Otology & Neurotology*, *34*(3), 396–401.

Gershkoff-Stowe, L., & Smith, L. B. (2004). Shape and the first hundred nouns. *Child Development*, *75*(4), 1098–1114.

Gilley, P., Sharma, A., Mitchell, T., & Dorman, M. (2010). The influence of a sensitive period for auditory-visual integration in children with cochlear implants. *Restorative Neurology and Neuroscience, 28*, 207–218.

Glick, H., & Sharma, A. (2017). Cross-modal plasticity in developmental and age-related hearing loss: Clinical implications. *Hearing Research, 343*, 191–201.

Gogate, L. J., & Bahrick, L. E. (1998). Intersensory redundancy facilitates learning of arbitrary relations between vowel sounds and objects in seven-month-old infants. *Journal of Experimental Child Psychology*, *69*(2), 133–149.

Gogate, L. J., Bahrick, L. E., & Watson, J. D. (2000). A study of multimodal motherese: The role of temporal synchrony between verbal labels and gestures. *Child Development*, *71*(4), 878–894.

Gogate, L. J., Bolzani, L. H., & Betancourt, E. A. (2006). Attention to maternal multimodal naming by 6-to 8-month-old infants and learning of word–object relations. *Infancy*, *9*(3), 259–288.

Gupta, P., & MacWhinney, B. (1997). Vocabulary acquisition and verbal short-term memory: Computational and neural bases. *Brain and Language*, *59*, 267–333.

Harris, M. S., Kronenberger, W. G., Gao, S., Hoen, H. M., Miyamoto, R. T., & Pisoni, D. B. (2013). Verbal short-term memory development and spoken language outcomes in deaf children with cochlear implants. *Ear & Hearing*, *34*(2), 179–192.

Havy, M., Nazzi, T., & Bertoncini, J. (2013). Phonetic processing during the acquisition of new words in 3-to-6-year-old French-speaking deaf children with cochlear implants. *Journal of Communication Disorders*, *46*(2), 181–192.

Henggeler, S. W., Watson, S. M., & Cooper, P. F. (1984). Verbal and nonverbal maternal controls in hearing mother-deaf child interaction. *Journal of Applied Developmental Psychology, 5*(4), 319–329.

Holman, M. A., Carlson, M. L., Driscoll, C. L., Grim, K. J., Petersson, R. S., Sladen, D. P., & Flick, R. P. (2013). Cochlear implantation in children 12 months of age and younger. *Otology & Neurotology*, *34*(2), 251–258.

Holt, R. F., & Svirsky, M. A. (2008). An exploratory look at pediatric cochlear implantation: Is earliest always best? *Ear & Hearing*, *29*(4), 492–511.

Horn, D. L., Houston, D. M., & Miyamoto, R. T. (2007). Speech discrimination skills in deaf infants before and after cochlear implantation. *Audiological Medicine*, *5*, 232–241.

Houston, D. M. (2016) Infant speech perception. In A. M. Tharpe & R. Seewald (Eds.), *Comprehensive handbook of pediatric audiology* (2nd ed., pp. 49–66). San Diego, CA: Plural Publishing, Inc.

Houston, D. M., Carter, A. K., Pisoni, D. B., Kirk, K. I., & Ying, E. A. (2005). Word learning in children following cochlear implantation. *The Volta Review*, *105*(1), 41–72.

Houston, D. M., & Jusczyk, P. W. (2000). The role of talker-specific information in word segmentation by infants. *Journal of Experimental Psychology: Human Perception & Performance*, *26*(5), 1570–1582.

Houston, D. M., & Jusczyk, P. W. (2003). Infants' long-term memory for the sound patterns of words and voices. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(6), 1143–1154.

Houston, D. M., & Miyamoto, R. T. (2010). Effects of early auditory experience on word learning and speech perception in deaf children with cochlear implants: Implications for sensitive periods of language development. *Otology & Neurotology, 31*, 1248–1253.

Houston, D. M., Stewart, J., Moberly, A., Hollich, G., & Miyamoto, R. T. (2012). Word learning in deaf children with cochlear implants: Effects of early auditory experience. *Developmental Science*, *15*(3), 448–461.

Houston, D. M., & Warner-Czyz, A. (2018). Speech perception and auditory development in infants with and without hearing loss. In A. Bar-On & D. Ravid (Eds.), *Handbook of communication disorders: Theoretical, empirical, and applied linguistics perspectives* (pp. 43–62). Berlin, Germany: De Gruyter Mouton.

Houston, D. M., Ying, E., Pisoni, D. B., & Kirk, K. I. (2003). Development of pre word-learning skills in infants with cochlear implants. *The Volta Review*, *103*(4), 303–326.

Johnson, E. K. (2008). Infants use prosodically conditioned acoustic-phonetic cues to extract words from speech. *Journal of the Acoustical Society of America*, *123*(6), EL144–148.

Johnson, E. K. (2016). Constructing a proto-lexicon: An integrative view of infant language development. *Annual Review of Linguistics, 2*, 391–412.

Jusczyk, P. W., Cutler, A., & Redanz, N. J. (1993). Infants' preference for the predominant stress patterns of English words. *Child Development*, *64*(3), 675–687.

Jusczyk, P. W., Hohne, E. A., & Bauman, A. (1999). Infants' sensitivity to allophonic cues for word segmentation. *Perception and Psychophysics*, *61*, 1465–1476.

Jusczyk, P. W., Houston, D. M., & Newsome, M. (1999). The beginnings of word segmentation in English-learning infants. *Cognitive Psychology*, *39*, 159–207.

Jusczyk, P. W., Luce, P. A., & Charles-Luce, J. (1994). Infants' sensitivity to phonotactic patterns in the native language. *Journal of Memory & Language*, *33*(5), 630–645.

Kirk, K. I., Miyamoto, R. T., Ying, E. A., Perdew, A. E., & Zuganelis, H. (2002). Cochlear implantation in young children: Effects of age at implantation and communication mode. *The Volta Review*, *102*, 127–144.

Kral, A. (2013). Auditory critical periods: A review from system's perspective. *Neuroscience*, *247*, 117–133.

Kral, A., Kronenberger, W., Pisoni, D., & O'Donoghue, G. (2016). Neurocognitive factors in sensory restoration of early deafness: a connectome model. *The Lancet Neurology, 15*(6), 610–621.

Kronenberger, W. G., Colson, B. G., Henning, S. C., & Pisoni, D. B. (2014). Executive functioning and speech-language skills following long-term use of cochlear implants. *Journal of Deaf Studies and Deaf Education*, *19*(4), 456–470.

Kuhl, P. K., & Meltzoff, A. N. (1982). The bimodal perception of speech in infancy. *Science*, *218*(4577), 1138–1141.

Landau, B., Smith, L. B., & Jones, S. S. (1988). The importance of shape in early lexical learning. *Cognitive Development*, *3*(3), 299–321.

Lederberg, A. R., & Spencer, P. E. (2008). Word-learning abilities in deaf and hard-of-hearing preschoolers: Effect of lexicon size and language modality. *Journal of Deaf Studies and Deaf Education*, *14*(1), 44–62.

Leigh, J., Dettman, S., Dowell, R., & Briggs, R. (2013). Communication development in children who receive a cochlear implant by 12 months of age. *Otology & Neurotology*, *34*(3), 443–450.

Lewkowicz, D. J., Minar, N. J., Tift, A. H., & Brandon, M. (2015). Perception of the multisensory coherence of fluent audiovisual speech in infancy: Its emergence and the role of experience. *Journal of Experimental Child Psychology*, *130*, 147–162.

Lund, E., & Schuele, C. M. (2017). Word-learning performance of children with and without cochlear implants given synchronous and asynchronous cues. *Clinical Linguistics & Phonetics*, *31*(10), 777–790.

Maidment, D. W., Kang, H. J., Stewart, H. J., & Amitay, S. (2015). Audiovisual integration in children listening to spectrally degraded speech. *Journal of Speech Language and Hearing Research*, *58*(1), 61–68.

Majorano, M., Guerzoni, L., Murri, A., Guidotti, L., Morelli, M., & Cuda, D. (2017). Word learning in Italian preschool children with cochlear implants. *International Journal on Disability and Human Development*, *16*(2), 157–163.

Markman, E. M. (1989). *Categorization and naming in children: Problems of induction*. Cambridge, MA: MIT Press.

Mattys, S. L., & Jusczyk, P. W. (2001). Phonotactic cues for segmentation of fluent speech by infants. *Cognition*, *78*(2), 91–121.

Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition*, *29*(2), 143–178.

Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: Toward an understanding of the role of rhythm. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 756–766.

Nicholas, J. G., & Geers, A. E. (2013). Spoken language benefits of extending cochlear implant candidacy below 12 months of age. *Otology & Neurotology*, *34*(3), 532–538.

Nittrouer, S., Caldwell-Tarr, A., Low, K. E., & Lowenstein, J. H. (2017). Verbal working memory in children with cochlear implants. *Journal of Speech Language and Hearing Research*, *60*(11), 3342–3364.

Nittrouer, S., Caldwell-Tarr, A., & Lowenstein, J. H. (2013). Working memory in children with cochlear implants: Problems are in storage, not processing. *International Journal of Pediatric Otorhinolaryngology*, *77*(11), 1886–1898.

Nittrouer, S., Caldwell-Tarr, A., Sansom, E., Twersky, J., & Lowenstein, J. H. (2014). Nonword repetition in children with cochlear implants: A potential clinical marker of poor language acquisition. *American Journal of Speech Language Pathology*, *23*(4), 679–695.

Patterson, M. L., & Werker, J. F. (2003). Two-month-old infants match phonetic information in lips and voice. *Developmental Science*, *6*(2), 191–196.

Peña, M., Mehler, J., & Nespor, M. (2011). The role of audiovisual processing in early conceptual development. *Psychological Science*, *22*(11), 1419–1421.

Perry, L. K., & Samuelson, L. K. (2011). The shape of the vocabulary predicts the shape of the bias. *Frontiers in Psychology*, *2*, 345.

Pimperton, H., & Walker, E. A. (2018). Word learning in children with cochlear implants: Examining performance relative to hearing peers and relations with age at implantation. *Ear and Hearing*, *39*(5), 980–991.

Pisoni, D., & Geers, A. (2000). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. *The Annals of Otology, Rhinology & Laryngology Supplement*, *185*, 92–93.

Pisoni, D., Kronenberger, W., Roman, A., & Geers, A. (2011). Measures of digit span and verbal rehearsal speed in deaf children following more than 10 years of cochlear implantation. *Ear and Hearing*, 32, 60S–74S.

Quittner, A. L., Cejas, I., Wang, N.-Y., Niparko, J. K., & Barker, D. H. (2016). Symbolic play and novel noun learning in deaf and hearing children: Longitudinal effects of access to sound on early precursors of language. *PLoS One*, *11*(5), e0155964.

Rosenblum, L. D., Schmuckler, M. A., & Johnson, J. A. (1997). The McGurk effect in infants. *Perception & Psychophysics*, *59*(3), 347–357.

Sai, F. Z. (2005). The role of the mother's voice in developing mother's face preference: Evidence for intermodal perception at birth. *Infant and Child Development*, *14*(1), 29–50.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*, 1926–1928.

Samuelson, L. K., & Smith, L. B. (1999). Early noun vocabularies: Do ontology, category structure and syntax correspond? *Cognition*, *73*(1), 1–33.

Schauwers, K., Gillis, S., Daemers, K., De Beukelaer, C., & Govaerts, P. J. (2004). Cochlear implantation between 5 and 20 months of age: The onset of babbling and the audiologic outcome. *Otology & Neurotology*, *25*(3), 263–270.

Schorr, E. A., Fox, N. A., van Wassenhove, V., & Knudsen, E. I. (2005). Auditory-visual fusion in speech perception in children with cochlear implants. *Proceedings of the National Academy of Science*, *102*(51), 18748–18750.

Schmale, R., & Seidl, A. (2009). Accommodating variability in voice and foreign accent: Flexibility of early word representations. *Developmental Science*, *12*(4), 583–601.

Segal, O., Houston, D. M., & Kishon-Rabin, L. (2016). Auditory discrimination of lexical stress patterns in hearing-impaired infants with cochlear implants compared to normal hearing: Influence of acoustic cues and listening experience to the ambient language. *Ear and Hearing, 37*(2), 225–234.

Sharma, A., Dorman, M. F., & Spahr, A. J. (2002). A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear and Hearing, 23*(6), 532–539.

Sharma, A., Glick, H., Campbell, J., Torres, J., Dorman, M., & Zeitler, D. M. (2016). Cortical plasticity and reorganization in pediatric single-sided deafness pre- and postcochlear implantation: A case study. *Otology and Neurotology, 37*(2), e26–e34.

Singh, L., Morgan, J. L., & White, K. S. (2004). Preference and processing: The role of speech affect in early spoken word recognition. *Journal of Memory & Language*, *51*(2), 173–189.

Smith, L. B., Jones, S. S., Landau, B., Gershkoff-Stowe, L., & Samuelson, L. (2002). Object name learning provides on-the-job training for attention. *Psychological Science*, *13*(1), 13–19.

Soleymani, Z., Amidfar, M., Dadgar, H., & Jalaie, S. (2014). Working memory in Farsi-speaking children with normal development and cochlear implant. *International Journal of Pediatric Otorhinolaryngology*, *78*(4), 674–678.

Tomasello, M. (2003). *Constructing a language: A usage-based theory of language acquisition*. Boston, MA: Harvard University Press.

Tomasello, M., & Farrar, M. J. (1986). Joint attention and early language. *Child Development*, *57*, 1454–1463.

Tomblin, J. B., Barker, B. A., & Hubbs, S. (2007). Developmental constraints on language development in children with cochlear implants. *International Journal of Audiology*, *46*(9), 512–523.

Tona, R., Naito, Y., Moroto, S., Yamamoto, R., Fujiwara, K., Yamazaki, H., . . . Kikuchi, M. (2015). Audio–visual integration during speech perception in prelingually deafened Japanese children revealed by the McGurk effect. *International Journal of Pediatric Otorhinolaryngology*, *79*(12), 2072–2078.

Van de Weijer, J. (1999). *Language input for word discovery*. (PhD thesis). Nijmegen: Radboud University Nijmegen. http://dx.doi.org/10.17617/2.2057670.

Walker, E. A., & McGregor, K. K. (2013). Word learning processes in children with cochlear implants. *Journal of Speech, Language, and Hearing Research*, *56*(2), 375–387.

Werker, J. (2018). Speech perception, word learning, and language acquisition in infancy: The voyage continues. *Applied Psycholinguistics, 39*(4), 769–777.

Willstedt-Svensson, U., Löfqvist, A., Almqvist, B., & Sahlén, B. (2004). Is age at implant the only factor that counts? The influence of working memory on lexical and grammatical development in children with cochlear implants. *International Journal of Audiology*, *43*(9), 506–515.

Xu, F., & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review*, *114*(2), 245–272.

Yu, C., & Smith, L. B. (2012). Embodied attention and word learning by toddlers. *Cognition*, *125*(2), 244–262.