27 Social Interaction and Language Acquisition: Toward a Neurobiological View

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Introduction

Social interaction is critical for children's language acquisition (Adamson, 1995; Bloom, 2000; Bruner, 1981; Hollich *et al.*, 2000; Nelson, 2007; Tomasello, 1992). From the moment they are born, children engage in social interaction (Meltzoff & Moore, 1977), and a child's language development is dependent on the social environment. As Nelson (1985) suggests, "language learning takes place within the framework of social interaction" (p. 109). In fact, children are exposed to language in social settings with parents and caregivers from the beginning (Bloom & Tinker, 2001; Clark, 2003). Children learn more than new words by engaging with social partners. As parents and children interact, parents demonstrate the rules of social interactions by engaging infants in a give-and-take format (Hirsh-Pasek & Golinkoff, 1996; Snow, 1997). These "proto-conversations" (Snow, 1997) begin to model conversational structure for the child (Clark, 2003). Eventually, children's developing language abilities allow them to become true conversational partners.

In this chapter, we review the brain and behavioral data on the effects of social interaction on language acquisition in children, discuss related work on children with autism that demonstrates dual impairments in social and linguistic processing, and relate these findings to the acquisition of communicative repertoires in non-human animals. Using this evidence, we advance the hypothesis that social interaction "gates" language learning (Kuhl, 2007; 2011). We then review candidate brain systems that could explain the existing results. Finally, the chapter discusses new approaches to the question, including neuroscience studies conducted in our laboratory, which may provide breakthrough data about the role of social factors in language acquisition.

Social interaction matters: Humans vs. machines

The role of social cues in language learning is grounded in a rich theoretical litera-ture and researchers have begun to test this claim in the laboratory. In each case, children's ability to learn language from a live social interaction is compared to learning from an equivalent non-social source, machines. These machines—videos, audio recordings, or robots—do not allow children to engage in the back-and-forth exchanges that are characteristic of social interactions with live humans and therefore provide a useful non-social medium to test the importance of social interactions.

In one study from our laboratory, Kuhl and colleagues (2003) investigated infants' ability to learn foreign language phonemes through social and non-social contexts. Given that children who are exposed to a second language early in a natural setting discriminate sounds in both of their languages (e.g., Garcia-Sierra *et al.*, 2011), the researchers asked whether monolingual children would learn from foreign language exposure under both the social and non-social con-ditions. Nine month olds were exposed to Mandarin Chinese in twelve 25-minute laboratory visits. Each infant experienced one of three exposure styles: a speaker on video, an audio recording of the same speaker, or a live social interaction. Four native Mandarin speakers served as the tutors. Phonemic learning was assessed in a Conditioned Head Turn procedure in which infants were trained and then tested on their ability to turn their head toward a loudspeaker when they detect a target phoneme interspersed among the background sounds, called standard sounds (Werker, Polka, & Pegg, 1997). Learning was also assessed using Event Related Potentials, or ERPs (Kuhl, 2011). Results of both the behavioral and the brain measures demonstrated that phonetic learning was not supported by video displays or by audio recordings, but that children exposed to live Mandarin speakers discriminated the foreign phonemes as well as native Mandarin speakers.

A related line of research used Spanish to replicate nine month olds' phonetic learning (Conboy & Kuhl, 2011). Infants participated in exposure sessions with live Spanish tutors who played with toys and read books to the infants for a total of five hours of exposure over four weeks. Using ERP to detect voltage fluctua-tions in neural activity, researchers employed a "double oddball" ERP paradigm to test Spanish phonetic learning both prior to social exposure to Spanish (at 9 months of age) and after social exposure to Spanish (at 11 months of age). In the test, the "standard" phonetic unit, an unaspirated [ta], was common to both Spanish and English, although perceived as/da/in English and/ta/in Spanish. Two "deviant" sounds, [tʰa] used only in English, and [da] used only in Spanish, examined the change in the brain measures for both English and Spanish as a result of exposure to Spanish. Infants' ERP responses to English revealed that their brain responses showed evidence of learning between 9 and 11 months: Infants' responses to Spanish revealed no discrimination at 9 months, and discrimination at 11 months. In other words, infants demonstrated phonetic learning for Spanish as a function of exposure.

The results of Kuhl and colleagues' social exposure studies, which show a lack of learning in the absence of a socially responsive person, appear inconsistent with studies on "statistical learning" that demonstrate phonetic (e.g., Maye *et al.*, 2008; Yoshida *et al.*, 2010; Teinonen, 2009, Bosseler *et al.*, 2016) and word (Saffran, Newport, & Aslin, 1996) learning without any social cues. However, these studies differ in the type of language material to be learned: in Kuhl and colleagues' social exposure studies, infants hear large amounts of natural complex language in a socially interactive setting, over 30,000 syllables during exposure. In contrast, the typical statistical learning experiment presents infants with a set of 8-10 syllables or 8 pseudo-words from a loudspeaker without any social cues or interaction available. One hypothesis that can be tested in future research is that natural language, with all its attendant complexity and variation, may require social interaction, at least in the early learning phases, whereas simple syllable and word learning, when isolated from natural language, does not. This is an empirical question that can be addressed and answered in future studies.

The influence of social context on language learning is not limited to phonemes. Conboy and Kuhl (2010) also used an ERP word paradigm to assess the brain's response to Spanish words infants had heard during the Spanish exposure sessions (described above) versus a set of control Spanish words they had not heard during Spanish exposure. As these children were from English-speaking households, the only Spanish exposure they had was through the exposure session. Analyses revealed the role of social interactions during social exposure to Spanish. During the exposure sessions, measures of infants' social behaviors, in this case, eye gaze shifts between the foreign language speaker and the toys that were the referent of her speech, predicted both phonetic, as well as word learning (Conboy, Brooks, Meltzoff, & Kuhl, 2015). The more adept infants were at enlisting their social skills during a social interaction, the better their language learning. Interestingly, other researchers have investigated the reverse relationship, that hearing words might influence infants' phonetic learning. Yeung and Nazzi (2014) demonstrated that after hearing object labels highlighting a stress contrast, infants showed evidence of phonemic discrimination. Together, these results link infant phonetic learning and word learning, while also highlighting the importance of social cues for language acquisition.

Another example leads to the same conclusion, in this case investigating children's ability to learn action words, or verbs, which can be difficult for young children to master (Gentner, 1982; Gentner & Boroditsky, 2001). Video clips from *Sesame Beginnings* presented two novel verbs (e.g., *blicking*) to children aged 30 to 42 months (Roseberry, Hirsh-Pasek, Parish-Morris, & Golinkoff, 2009). These video clips were perceptually salient to children and the verbs were presented in full grammatical context (e.g., "Look at Dad *blicking* Elmo!"). These videos also allowed for the manipulation of social cues: Whereas some of the children saw the novel verbs presented entirely on video, others saw half of the presentations on video and half delivered by a live social partner. Children were tested on their ability to extend the novel verb to a new actor performing the same action (e.g., if children learned that a bouncing action was *blicking* from Elmo and his dad, children were

tested on their ability to recognize real people *blicking*). Results indicated that tod-dlers who interacted with an adult while watching a video were able to learn the novel verbs at a younger age than children who passively viewed the video. Although this research found evidence of word learning from video, whereas Kuhl and colleagues (2003) did not, the results may differ due to the age of the participants—Kuhl's work was done with infants at 9 months, whereas the action word studies were done with children between 30 and 42 months of age. Together, the findings represent a developmental trajectory in children's ability to learn language from screens. As others have reported, infants do not show language learning from video (Robb, Richert, & Wartella, 2009) whereas older toddlers and preschoolers show increasing language acquisition from screens (Krcmar, Grela, & Lin, 2007; Sachs, Bard, & Johnson, 1981). In line with previous research (Krcmar *et al.*, 2007; Reiser, Tessmer, & Phelps, 1984), Roseberry and colleagues (2009) dem-onstrated that even though children older than three years gained some information from video alone, this learning was not as robust as learning from live social interactions.

Recent evidence suggests that the relative advantage of learning language from social interactions cannot be attributed to some drawback of the machine presen-tation itself. One study used video chats to ask if 24 to 30 month olds can learn language in a video context that is social (Roseberry, Hirsh-Pasek, & Golinkoff, 2014). Video chats present a speaker via screen media, yet this particular technology differs from traditional video in several important ways. Video chats approximate live social interactions in that children and the speaker can participate in a two-way exchange. Adults can be responsive to children and ask questions that are relevant to them. Although the speaker's eye gaze is often distorted in video chats because of the placement of the camera relative to the screen, video chat preserves many of the qualities of social interactivity that help children learn (Csibra, 2010). In fact, when 24 to 30 month olds were exposed to novel verbs via video chat, chil-dren learned the new words just as well as from live social interactions. Toddlers showed no evidence of learning from non-interactive video. Similarly, research with robots has discovered that a robot's social behavior influences children's ability to learn from this machine. For example, when robots oriented their heads toward 18- to 24-month-old children and named a toy in Finnish, the English-speaking children begin to follow the robot's eye gaze and learn the Finnish names for common objects (Kuhl, 2011; Meltzoff, Kuhl, Movellan, & Sejnowski, 2009; Movellan, Eckhardt, Virnes, & Rodriguez, 2009).

Taken together, empirical evidence highlights the crucial contributions of social interactions to natural language learning. Importantly, this holds across different levels of linguistic analysis (phonemes and words), across social interac-tions of different durations (extended over many sessions or isolated in one labo-ratory visit) and across specific media (video, audio, and robots). These studies are among many to offer compelling evidence that social or pragmatic cues are related to language outcomes (Bloom, Lightbown, & Hood, 1975; Childers & Tomasello, 2002, 2006; Hoff, 2006; Naigles, Hoff & Vear, 2009; Nelson, 2007; Tomasello & Farrar, 1986).

Social interaction matters: Children with autism

In typically developing children, social interactions appear to have a positive influence on language learning. Yet, the same does not hold for children with autism. Dual impairments in both the language and social domains are characteristic of children with autism. Although there is considerable variability in the language abilities of children with autism, 42% of the population is impaired in both receptive and expressive language (Chan, Cheung, Leung, Cheung, & Cheung, 2005) and there is some evidence that specific types of language, such as relational terms or mental state verbs, are particularly affected (Tager-Flusberg, 1992). Similarly, the effects of social deficits in children with autism range from decreased abilities to orient to social stimuli (Dawson, Meltzoff, Osterling, Rinaldo, & Brown, 1998) to difficulty tracking eye gaze (Grice, Halit, Farroni, Baron-Cohen, Bolton, & Johnson, 2005) and a reduced frequency in engaging in joint attention with social partners (Dube, MacDonald, & Mansfield, 2004).

Language and social deficits in autism should not be considered independently. Increasingly, evidence suggests that the social impairments in children with autism may, in fact, influence their ability to acquire language. One tool that typically developing children use to learn language is child-directed speech (CDS). Characterized by generally slower speech and word lengthening, longer vowel sounds, and greater variation in frequency (Brand & Tapscott, 2007; Fernald & Kuhl, 1987; Garnica, 1975; Golinkoff & Alioto, 1995; Grieser & Kuhl, 1988; Papousek, Bornstein, Nuzzo, & Papousek, 1990), typically developing infants prefer this type of speech as early as two days post birth (Cooper & Aslin, 1990; Fernald, 1985). Furthermore, this type of speech exaggerates the acoustic cues that distinguish phonemes and thus words (Kuhl *et al.*, 1997). Children who are exposed to a greater degree of acoustic exaggeration in CDS exhibit greater sensitivity to phonological contrasts when tested in the laboratory (Liu, Kuhl, & Tsao, 2003), and infants who hear more parentese at home, especially in one-on-one social interactions, have higher concurrent and future language abilities; this has been shown in both monolingual (Ramirez-Esparza, Garcia-Sierra, & Kuhl, 2014) and bilingual children (Ramirez-Esparza, Garcia-Sierra, & Kuhl, in press, 2017). CDS facilitates children's ability to segment words within a stream of speech (Golinkoff & Alioto, 1995). Both phonological sensitivity and word segmentation skills are known to facilitate language learning. In fact, recent research suggests that infants who are better at segmenting streams of speech at 7 months of age have larger vocabularies at 24 months of age (Singh, Reznick, & Xuehua, 2012).

Given that CDS is an inherently social cue and that children with autism do not tend to prefer social cues, researchers have asked whether children with autism have a preference for CDS. One investigation tested this directly (Kuhl, Coffey-Corina, Padden, & Dawson, 2005). To gauge auditory preference, children were given a choice of listening to eight-sec clips of CDS or a nonspeech signal that matched the spectrum and duration of the CDS speech samples. Children with autism indicated their choice by making slight head turns to the

left or right (with location of CDS randomized across children). Interestingly, typically developing children attended to both sounds. Although younger infants typically show a preference for CDS, the children in this study were matched to the children with autism on mental age. This yielded a slightly older participant group (range = 13 months to 48 months, M = 27.78), which may explain their lack of preference. In contrast to the typically developing children, children with autism showed a strong preference for the non-speech signal. The non-speech preference of children with autism was significantly correlated to the severity of their autism symptoms, as well as to their ability to discriminate phonemes when tested neurally.

That children with autism show such a strong preference for a non-social (non-speech) signal over a social signal (CDS) has many implications for the relationship between language learning and social interaction. Children with autism fail to attend to the very signal that supports language learning. Children with autism are therefore limited in their ability to benefit from CDS in the same way as typically developing children. Without CDS to highlight phonological contrasts and facilitate speech segmentation, children with autism may not have sufficient language learning tools in their repertoire.

In fact, recent data from our laboratory suggests that the level of social functioning in two year olds with autism is related to the children's brain responses during word processing (Kuhl, Coffey-Corina, Padden, Munson, Estes, & Dawson, 2013). Using an ERP task, children with autism and typically developing children listened to a series of words that included known words, unknown words, and known words presented backwards. Children with autism who were categorized as having less severe social symptoms according to the Autism Diagnostic Observation Schedule (ADOS; Lord, Rutter, & Le Couteur, 1994) showed differential processing of known and unknown words that was localized to the left temporal/parietal electrode sites. This activation was similar to the typically developing matched control group. In contrast, children with more severe social symptoms showed a more diffuse response across the right hemisphere. Using the strength of individual children with ASD's responses to known words at the parietal site at the age of two years as a predictor, our results showed that these children's linguistic, cognitive, and adaptive response abilities were strongly predicted at the age of four years and six years, with correlations improving over time. In fact, regression analysis showed that this early brain measure of responses to known words in children with autism at the age of two years was more highly correlated with later linguistic, cognitive and adaptive skills than early cognitive ability (at two years) which is a frequently reported predictor of functional outcome in children with ASD (Anderson, Lord, Risi, DiLavore, Shulman, *et al.*, 2007; Munson, Faja, Meltzoff, Abbott & Dawson, 2008). Moreover, the neural measure predicted future behavior regardless of the two types of treatment that the children with autism had received in the interim. Although causal relationships cannot be established with these correlational data, the findings strengthen the argument that social interaction is strongly linked to language learning, both at the individual and group levels.

Social interaction matters: Non-human animals

The research linking social interactions to human communication is clear. Yet social interactions also appear to be critical for species other than humans. Communicative songbirds, for example, rely on several forms of social interactions to hone their song production. In a laboratory setting, zebra finches expect that their social environment will include visual cues to song learning from their tutor (Eales, 1989). When visual cues are available, they are so powerful that zebra finches are likely to learn enemy songs, like that of a Bengalese finch, if they are fed by the alien bird (Immelmann, 1969). White-crowned sparrows are similarly reliant on social information: although live tutors effectively teach their song, sparrows are unable to learn from equivalent audio taped information (Baptista & Petrinovich, 1986).

Like human infants, songbirds recruit social information from a variety of cues. Blindfolded zebra finches, for example, are able to learn their songs through non-visual interactions such as pecking and grooming, or through contingently responsive audio of their songs (Adret, 1993). Furthermore, female cowbirds do not sing, but are able to give social feedback to young male cowbirds through their wingstrokes (West & King, 1988).

In sum, evidence from human infants, children with autism and non-human animals suggests a very powerful role for social interactions. Yet, it is unclear why social interactions facilitate language acquisition as they do. In the following section, we explore the specific social cues that have been implicated and we discuss some possible underlying mechanisms.

Mechanisms of social interactions

The importance of social interaction emerges clearly in research that has investigated human infants, children with autism, and even non-human animals. Kuhl (2007) has gone so far as to argue that social information "gates" natural language learning suggesting that social experience is important for language learning. The more children have access to social cues and the better children's ability to use social cues, the greater their ability to learn language. This aligns with the research reviewed above on typically developing children (e.g., Kuhl *et al.*, 2003; Roseberry *et al.*, 2014) as well as children with autism (e.g., Kuhl *et al.*, 2013). How social interaction "gates" language learning is less well understood, and investigations are now directed toward answering this question.

Researchers have identified many different social cues that may contribute to the "gating" process. Eye gaze, for example, has been shown to facilitate word learning in young children. Even infants show remarkable sophistication in their use of these social cues. Children distinguish between adults' open and closed eyes, and only follow an adult's gaze when their eyes are open (Brooks & Meltzoff, 2002, 2005). This suggests that infants are sensitive to a social partner's eyes and are not merely following head turns. Children also recruit an adult's eye gaze to

help them narrow the possible referents for an unknown word (Baldwin, 1993; Dunham, Dunham & Curwin, 1993). Language learning is supported by children's ability to follow gaze direction. Novel labels typically refer to the referent in the speaker's visual field (Baldwin, 1993; Bloom, 2002; Tomasello, 1995) and in fact, when the referent of a novel word is ambiguous, children are more likely to check speaker gaze to determine the correct referent than when the referent of a novel word is not ambiguous (Baldwin, Bill, & Ontai, 1996). Older infants use eye gaze to label boring objects even when they would prefer to look at other interesting objects (Pruden *et al.*, 2006).

When adults are contingently responsive to children, their responses are reliable and timely (Beebe *et al.*, 2011; Catmur, 2011), appropriate in content (Bornstein, Tamis-LeMonda, Hahn, & Ha, 2008) and matched in intensity (Gergely & Watson, 1996). These responses establish the "conversational duet" which is characterized by back-and-forth turn taking (Hirsh-Pasek *et al.*, 2015). Contingency is a powerful social cue that has recently garnered attention for its role in the social interactions that facilitate language learning. Infants are drawn to contingent responses from others very early in life. As early as four months, for example, infants prefer an adult who responds contingently to their behaviors to an adult who does not (Bigelow, MacLean, & MacDonald, 1996; Hains & Muir, 1996). Children's preference for contingent interactions extends into toddlerhood (Bloom *et al.*, 1975; Brand & Tapscott, 2007; Goldstein, King, & West, 2003) and to word learning (e.g., Tamis-LeMonda, Bornstein, Baumwell, & Damast, 1996). Moreover, as we have reviewed above, contingency may be the critical social cue that transforms machines into social vehicles for word-learning children, as is the case in video chats (Roseberry *et al.*, 2014) and social robots (Movellan *et al.*, 2009).

One of the most studied social cues is joint attention, in which both partners focus their attention on a common object or event (Adamson, Bakeman, & Deckner, 2004; Baldwin, 1991; Moll & Tomasello, 2007; Mundy, Block, Delgado, Pomares, VanHecke, & Parlade, 2007; Tomasello & Farrar, 1986). Naturalistic observations find that both children and parents talk more during episodes of joint attention (Tomasello & Farrar, 1986), and that children show increased word learning during joint attention (Adamson *et al.*, 2004; Mundy & Gomes, 1998; Smith & Ulvund, 2003; Tomasello & Todd, 1983). Baldwin (1991), for example, asked adults to label an object either when the 16- to 19-month-old infant was attending to it or when the infant was attending to another object. Infants were much more successful at mapping labels onto objects when they were already attending to the labeled object (see also Dunham, Dunham, & Curwin, 1993; Pruden *et al.*, 2006; Tomasello & Farrar, 1986).

Although each of these social cues contributes to children's language learning, there have been relatively few efforts to specify the underlying mechanisms. Kuhl (2007) hypothesizes two broad mechanisms that would help explain why social interaction could support language learning. Social interaction increases motivation and information: social interactions between adults and infants increase infant attention and heighten social arousal, and moreover, social interaction increases the amount of information children have from which to learn.

With respect to the role of motivation, social interactions increase children's attention to the communicative learning situation. A live speaker may alert children to pay attention because the information being presented is directed to them. This possibility is supported by data from the Mandarin phonemic discrimination study described earlier (Kuhl *et al.*, 2003), in which children exposed to a live Mandarin speaker were more attentive and visibly excited than children in the non-social exposure conditions. In terms of social cues, both contingency and child directed speech captures and maintains young children's attention (Fernald & Kuhl, 1987; Landry, Smith & Swank, 2006; Ratner, 1984). Infants produce more vocalizations when their parent responds contingently to them, as compared to parents who are directed to respond only on a fixed schedule (Goldstein *et al.*, 2003; Ramirez-Esparza *et al.*, 2014). Also, focusing the child on important aspects of their environment through CDS may help children learn language by directing their attention to the referent. Indeed, children who hear more CDS at 12 months of age have larger receptive vocabularies at 24 months of age (Ramirez-Esparza *et al.*, 2014).

Social interaction may also prove motivational to children through the mere presence of a social partner, as some data suggests that even minimal social connections to another person increase young children's motivation to learn (Walton *et al.*, 2012). Recent evidence from our laboratory indicates that baby peers may increase motivation, or social arousal, in the context of social interactions (Lytle, Garcia-Sierra, & Kuhl, in preparation). Nine month olds' phoneme learning was tested after exposure to a foreign language via contingent touch screen video, in which infants controlled video presentations by touching the screen. Infants were either exposed individually or in pairs. Both groups learned when videos were contingent on infants' screen touches, but infants tested in pairs showed better learning and produced greater numbers of vocalizations. In this study, the only difference between the two groups was the presence of the second baby in the paired condition. Across groups, children demonstrated equal mobility, equal screen touches to activate the video, and equal amounts of joint attention. The mere presence of the social partner appeared to motivate infants' learning.

In addition to motivational cues, social interactions may also provide children with the precise information they need to learn language. Children may gain information about the referents of novel words through social interactions with adults. Eye gaze and joint attention align with this informational hypothesis, as children look to these social cues to gather relevant information. In a sense, social cues like eye gaze and joint attention serve as spotlights for children learning words, narrowing children's focus to a small subset of possible referents (Baldwin, 1993; Dunham *et al.*, 1993).

Occasionally, the same social cues provide motivation as well as additional information about language to children. For example, contingent interactions have been shown to increase children's attention to adults (Brand & Tapscott, 2007; Goldstein *et al.*, 2003), but one recent study suggests that another form of contingency, contingent touch, may provide critical information for children's word learning. Seidl and colleagues (2015) played a stream of artificial language

for four month olds, similar to the classic design of infant statistical learning studies (e.g., Aslin, Saffran, & Newport, 1998). While infants listen to this artificial language, an experimenter touched either the elbow or the knee each time a particular target "word" appeared in the language. The experimenter also touched the infant on the other body part, either the knee or the elbow, once for every grouping of non-target "words" in the language. Thus, the infant experienced equal touches to the knee and to the elbow, always contingent to words in the artificial language, though only touches to one body part could be reliably associated with a particular word. At test, infants responded differently to target words, than they did to non-target words and non-words, or rearrangements of syllables into patterns that never appeared in the language. Interestingly, there was no differentiation between test items when an experimenter touched her own elbow or knee. The authors suggest that contingent touch may be a powerful mechanism that calls attention and provides information for word-learning children.

Taken together, there is evidence that social interactions with adults promotes language learning, perhaps because it increases motivation and confers more information to the child. Yet, the behavioral evidence only tells part of the story. There is a growing body of research on the candidate brain systems that might explain the existing results as well as new approaches to these questions. In the following section, we examine these systems as well as neuroscience studies using magnetoencephalography (MEG) brain imaging conducted in our laboratory, which may provide breakthrough data.

Candidate brain mechanisms

As reviewed above, the increase in attention and the increase in information that is provided by interaction with another human may help explain social learning effects for language. However, it is also possible that social interaction is connected to language through even more fundamental mechanisms. Social interaction may activate brain mechanisms that invoke a sense of relationship between the self and other, as well as activating social understanding systems that link perception and action (Hari & Kujala, 2009). Neuroscience research focused on shared neural systems for perception and action have a long tradition in speech research (Liberman & Mattingly, 1985). Recent interest in "mirroring systems" specifically and the "social brain" more generally have re-invigorated this tradition (Kuhl & Meltzoff, 1996; Meltzoff & Decety, 2003; Pulvermuller, 2005; Rizzolatti, 2005; Rizzolatti & Craighero, 2004).

There is tantalizing evidence from the Spanish exposure experiment suggesting that exposure to Spanish not only changes speech perception but also changes speech production. The English-learning infants who were exposed to 12 sessions of Spanish (Conboy & Kuhl, 2011) showed subsequent changes in their patterns of babbling after experience with Spanish; interestingly, babbling was language-specific after exposure (Ward, Sundara, Conboy, & Kuhl, 2009). After the 12

exposure sessions were complete infants were brought back into the laboratory for play sessions with a Spanish speaker and with an English speaker. When the children interacted with a Spanish speaker, a new pattern of infant vocalizations occurred, one that reflected the prosodic patterns of Spanish, rather than English, with longer utterance duration and more multi-syllabic utterances occurring in response to Spanish as opposed to English, consistent with the characteristics of those languages. The fact that this new pattern of vocalization only occurred in response to Spanish speech, not English, suggests that the learning that occurs in the language exposure experiments not only involves perceptual learning, but also may affect motor systems in the brain. Future language exposure experiments are needed to examine how babbling changes as a function of perceptual experience in these studies.

Thus, social exposure to language may alter both the sensory mechanisms and the motor systems underlying speech—in essence, *hearing* speech creates *motor* learning. This kind of audio-motor coupling may be activated in social settings in which we listen to others and expect to talk back reciprocally. This speculation would be enhanced by brain studies (see below) showing that listening to speech activates not only auditory sensory areas but also the motor areas underlying speech.

A neurobiological view

Recent advances in neuroscience allow us to test the hypothesis that the pure perception of speech activates motor brain systems. Two infant studies provide intriguing data. Imada and colleagues (2006) used MEG to study newborns, 6-month-old infants, and 12-month-old infants while they listened to nonspeech, harmonics, and syllables. Dehaene-Lambertz and colleagues (2006) used fMRI to scan three-month-old infants while they listened to sentences. Both studies show activation in brain areas responsible for speech production (the inferior frontal region, Broca's area) in response to auditorily presented speech. Imada and colleagues reported synchronized activation in response to speech in auditory and motor areas at 6 and 12 months, and Dehaene and colleagues reported activation in motor speech areas in response to sentences in 3 month olds. Newborns showed no activation in motor speech areas for any signals (Imada *et al.*, 2006), whereas auditory areas responded robustly to all signals, suggesting the possibility that perception-action linkages for speech develop by three months of age as infants begin to produce vowel-like sounds.

Previous studies demonstrated activation in motor brain areas in response to speech but did not explain the role played by these areas in perceptual processing. A new study goes further in that regard. In two experiments using MEG, we investigated motor and auditory brain activation during perceptual processing of native and non-native syllables in infants at two ages that straddle the developmental transition from language-universal to language-specific speech perception (Kuhl,

Ramirez, Bosseler, Lin, & Imada, 2014). MEG data revealed that seven-month-old infants activate auditory (superior temporal) as well as motor brain areas (Broca's area, cerebellum) in response to speech, and equivalently for native and non-native syllables. However, in 11- and 12-month-old infants, *native* speech activated auditory brain areas to a greater degree than non-native, while *non-native* speech activated motor brain areas to a greater degree than native speech. This double dissociation in 12-month-old infants matched the pattern of results obtained in adult listeners. The data were interpreted in the context of two historical theories from the 1950s and 1960s that dealt with the nature of the interaction between perceptual and motor representations of speech, *The Motor Theory* (MT) (Liberman *et al.*, 1967) and *Analysis by Synthesis* (AxS) (Stevens & Halle, 1967), a framework derived from artificial intelligence. Both MT and AxS hold that speech perception involves access to motor representations of speech in adults, but differ with regard to the role of development. A tenet of MT is that knowledge of speech production is innate (Liberman & Mattingly, 1985), whereas AxS holds that perception involves access to stored representations that result from the learning of motor patterns—analysis of incoming speech uses a kind of synthesis of the motor patterns of speech to assist perception.

Kuhl *et al.*'s experiment posed the question using MEG technology in infants for the first time. At seven months of age, infants activate both auditory and motor brain areas equally to both native and non-native syllables, and 11 month olds show greater activation in motor areas to non-native syllables. These results were interpreted in the framework of *Analysis by Synthesis* arguing that infants coupled auditory *analysis* of speech with approximations of the motor plans necessary to produce the speech signal gleaned from their own nascent abilities to produce speech (a form of *synthesis*). In other words, Kuhl *et al.* argued that infants are engaged in a kind of crude motor rehearsal of the patterns needed for speech well before they can articulate the sounds they are listening to. This form of motor activation is not seen for non-speech (Imada *et al.*, 2006). We suggest that this brain activation may underpin infants' differential babbling to English and Spanish after exposure to Spanish (Ward *et al.*, 2009), and also that motor brain activation plays a role in the developmental transition in infant perception (Kuhl *et al.*, 2014). Further support for connections between sensory and motor interactions in speech perception derive from a recent study reporting that infants' perception of speech is disrupted by a prosthetic device inserted in the baby's mouth—a device disrupting the lips, for example, impeded discrimination of bilabial sounds (ba-pa) but not dental (da-ta) sounds (Bruderer *et al.*, 2015). Taken together, these studies prompt us to revisit the original theories of speech perception, which argued that deep connections exist between sensory and motor representations of speech.

Action-perception linkages early in development could play a role in supporting social reciprocity in humans. The fact that the infant's motor brain systems respond to the speech actions of others is a step toward social communication. What the existing data do not reveal is whether joint activation of the perception-action systems is evoked especially when language is presented socially, and not

when language is presented through a disembodied source such as a television set. In the recent Kuhl *et al.* (2014) study, infants heard synthetic adult-directed speech, not motherese in face-to-face interchanges, and yet motor activation was observed in the brain. We expect that if infants viewed a social stimulus (e.g., a human face speaking parentese) motor brain activation would be enhanced. Experiments are currently underway with infants using MEG in our laboratory to address this question. These tests may provide tangible evidence that speech occurring in a social face-to-face setting is especially effective in activating motor brain systems.

Conclusions

In both animals and humans, the idea that a social context is critical to communicative learning is gaining traction. In the case of humans, language learning has been suggested as grounded in a rich social setting. Researchers testing this claim in the laboratory have provided ample evidence showing that social contexts provide both *motivation* in the form of increased attention and social arousal, as well as *information*, such as eye-gaze following, that provides added information about speakers' intentions and goals. These features of social contexts are not present to the same degree in non-social contexts. New depth regarding theoretical explanations of the effects of social contexts on communicative learning are expected from studies now underway using the tools of modern neuroscience. These studies directly investigate how communicative signals and social settings alter the brain's responses. It is hoped that these studies will eventually provide a full neurobiological account that explains how and why human language learning is fundamentally imbedded in social interaction.

Acknowledgments

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FURTHER READING

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R. M., Gray, J. M., Robb, M. B., & Kaufman, J. (2015). Putting education in "educational" apps: Lessons from the science of learning. *Psychological Science in the Public Interest*, 16, 3–34. doi: 10.1177/1529100615569721

This paper provides an excellent theoretical structure for how to think about children's media, specifically apps. The framework proposed by this paper can be used to guide decision-making about which types of screen media might be a useful tool for children's learning.

Hoff, E. (2006). How social contexts support and shape language development. *Developmental Review*, 26, 55–88. doi: 10.1016/j.dr.2005.11.002

This is a fantastic review about how children learn language in their environments and the social cues in those environments that they recruit for language acquisition.

Kuhl, P. K. & Rivera-Gaxiola, M. (2008). Neural substrates of language acquisition. *Annual Reviews of Neuroscience*, 31, 511–534.

This paper provides an excellent review of the neuroscience techniques used to study infant language learning and provides a thorough discussion of the questions researchers can ask with such techniques.

Institute for Learning & Brain Sciences (producer). (2014) Online Training Modules [online modules]. Available at: http://modules.ilabs.uw.edu/outreach-modules/

These free online resources offer the latest science of child development, presented in a way that is relevant, accessible, and useable. Each module takes 20-25 minutes to complete, and discusses a specific topic in child development.