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Frequency of vocalization before and after cochlear implantation: Dynamic effect of auditory feedback on infant behavior

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Abstract

The motivation for infants' non-word vocalizations in the second half of the first year and later is unclear. This study of hearing infants and infants with profound hearing loss with and without cochlear implants addressed the hypothesis that vocalizations are primarily motivated by auditory feedback. Early access to cochlear implants has created unique conditions of auditory manipulation that permit empirical tests of relations between auditory perception and infant behavior. Evidence from two separate tests of the research hypothesis showed, before cochlear implantation, infants with profound hearing loss vocalized significantly less often than hearing infants; however, soon after cochlear implantation, they vocalized at levels commensurate with hearing peers. In contrast, vocal behaviors that are typically considered reflexive or emotion-based signals (e.g., crying) were infrequent overall and did not vary with auditory access. These results support the hypothesis that auditory feedback is a critical component motivating early vocalization frequency.

Keywords

cochlear implant; infant vocalization; auditory feedback; dynamic systems; hearing loss; self-generated feedback

Infant vocal development in the first year proceeds in predictable steps from reflexive behaviors (e.g., crying), non-distress vocalizations (e.g., cooing) and loosely shaped syllables in the first half of the year, to well-formed syllables and first words in the second half (e.g., Stark, 1980). Early progression (i.e., 0-6 months) is largely dependent on infants' improving articulatory motor control and loosening ties to affective states (Bowlby, 1969; Stark, 1978; Keller & Scholmerich, 1987). The resulting production flexibility is essential

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for varied phonetic content and eventual word use in the second half of the year (Papaeliou, Minadakis, & Cavouras, 2002).

Despite broad agreement regarding vocal stage progression, the underlying motivation and function of non-word vocalizations from 6 to 12 months and later is not entirely clear. For example, substantial numbers of these vocalizations occurred independent of social interactions, without eye contact, and without apparent communicative intent (Anderson, Vietze, & Doeckei, 1977; Stark, 1980; Stark, Bernstein, & Demorest, 1993). In fact, throughout the first year, infants were more likely to vocalize alone than when in the presence of mothers (Delack, 1976). Additionally, Moeller et al. (2007b) found that 40% of hearing¹ infants' vocalizations at 16 months, and almost 60% of the vocalizations of infants with hearing loss were not directed toward an adult. These non-social productions may be motivated in large part by infants' interest in auditory-vocal exploration; however, if that were the case, which has been speculated (e.g., Locke, 1993; Stark, 1980), vocal production would be expected to decline in the absence of auditory feedback—an expectation that, as you will see, is not widely accepted.

The goal of this study, therefore, was to test the proposal that vocalizations are motivated in large part by auditory-vocal exploration by measuring vocalization quantity in hearing infants and infants with profound hearing loss with and without cochlear implants. The increasing use of cochlear implants (devices that stimulate the auditory nerve, allowing users to perceive auditory stimuli) has created unique conditions of auditory manipulation that permit empirical tests of relations between auditory perception and infant behavior. Understanding the effects of auditory perception on vocalization frequency is of considerable importance in understanding both the theoretical and sensory foundations of this fundamental infant behavior. Potentially, defining relations between auditory perception and vocalization frequency may further allow the theoretical integration of vocalizations with other developmental behaviors shaped by self-generated auditory feedback (e.g., object exploration; Palmer, 1989).

Using an approach based on principles of dynamic systems theory, investigating vocalizations from a perceptual-motor perspective is expected to identify auditory feedback as an influential component in vocalization frequency, similar in importance to influential components affecting other dynamic infant behaviors such as stepping (Thelen & Ulrich, 1991), reaching (Smith, Thelen, Titzer, & McLin, 1999; Spencer, Smith, & Thelen, 2001), and object manipulation (Palmer, 1989). In fact, from a dynamic systems perspective, while it is true that focal systems typically improved in quality over time, that improvement was often directly related to frequency of given behavioral occurrence. For example, number of weeks spent walking and crawling influenced navigational judgments (Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008) and number of preceding reaches influenced performance on A-not-B tasks (Smith et al., 1999; Spencer et al., 2006; Spencer et al., 2001). Although vocalization frequency has received little attention compared to stages of vocal development, until functional and motivational questions underlying vocalization

¹Individuals with normal hearing.

frequency are resolved, infant vocalizations and their role in development will remain inadequately understood developmental phenomena.

Although the focus in this study is vocalization quantity, first, relevant arguments regarding both quality and quantity will be considered in turn in order to facilitate critical analysis of conflicting reports regarding auditory feedback and infant vocal behavior.

Vocalization Quality

Currently, there is broad general agreement that hearing loss impacts the quality of vocalizations infants produce in the second half of the first year and beyond. This has not always been so. Less than fifty years ago, infant vocal behaviors were thought to emerge in universal patterns on a maturational timeline independent of infants' hearing ability and irrespective of variations in input associated with maternal hearing status (Lenneberg, 1967; Lenneberg, Rebelsky, & Nichols, 1965). Lenneberg et al. (1965), for example, reported the vocalizations of hearing infants, whether of deaf or hearing parents, were similar despite the fact that deaf parents vocalized less often and thus provided less input than hearing parents did. Lenneberg (1967) additionally argued that deaf and hearing infants were similar in producing both the early vocalizations (distress and non-distress) of the first few months, and the consonant-vowel (CV) strings of babbling at six months and beyond. Thus, in the past, the vocal behaviors of infants with hearing loss were thought to be indistinguishable in quality from the vocal behaviors of hearing infants.

However, several transformational studies have since provided clear evidence that this is not the case. Rather, the quality of many vocal behaviors does in fact depend on auditory perceptual ability (Kent, Osberger, Netsell, & Hustedde, 1987; Oller & Eilers, 1988; Stoel-Gammon & Otomo, 1986; von Hapsburg & Davis, 2006). Stoel-Gammon & Otomo (1986) showed, for example, that 4- to 28-month-old infants with moderate to profound hearing loss produced a smaller variety of consonant vocalizations than hearing infants did. Oller and Eilers (1988) found, moreover, that infants with hearing loss were delayed in producing well-formed (i.e., canonical) CV syllables, essentially syllables executed with relatively rapid articulatory transitions. Whereas hearing infants consistently produced well-formed syllables between 6 and 10 months of age, such syllables were not produced by infants with hearing loss until 11 to 25 months. Therefore, auditory perception affected both the shape (i.e., canonical vs. non-canonical) and content of key vocalization types, with profound hearing loss having greater impact than mild hearing loss (Stoel-Gammon & Otomo, 1986; von Hapsburg & Davis, 2006). Together, this research led to a major shift in thinking regarding the universal nature of vocal emergence and supported the role of auditory perception in qualitative vocal development.

Vocalization Quantity

Over time, however, a new question has arisen regarding auditory perception and an additional aspect of infant vocal behavior—vocalization quantity. The question concerns how often infants with hearing loss produce vocal behaviors, of any type, as well as the potential motivation for vocalizations they produce but cannot hear. Unlike prevailing theories of vocalization quality, which now embrace the role of auditory perception,

arguments about vocalization quantity have moved in the opposite direction. In the past, that is, hearing loss was thought to reduce vocalization quantity, but more recent research appears to reject that thinking.

In 1967, Lenneberg noted that, after three months of age, deaf infants were much less vocal than hearing infants—despite his belief that the *quality* of their vocalizations was no different. Around the same time, Mowrer (1960) similarly noted that deaf infants produced few vocalizations. Mowrer's proffered explanation for diminished vocalization frequency was that deaf infants heard neither the vocalizations of their caregivers nor the auditory feedback generated by their own vocalizations. Mowrer's argument, although not clearly tested at the time, was consistent with his thinking, and that of others more recently as well, that production and control of all voluntary behavior was contingent upon sensory feedback (e.g., Adolph & Joh, 2009; Thelen, 1989; Thelen & Smith, 1994). An early, small empirical study of vocalization quantity in deaf ($n = 1$) and hearing ($n = 4$) infants confirmed that only the vocal productions of the single infant with hearing loss failed to increase from 2 to 7 months (Maskarinec, Cairns, Butterfield, & Weamer, 1981). The early consensus, therefore, was that infants with hearing loss produced few vocalizations when compared to hearing infants.

In contrast, studies that have addressed vocalization frequency more recently have reported instead that regardless of age, infants with hearing loss vocalized as frequently as hearing infants did (Koester, Brooks, & Karkowski, 1998; Iyer & Oller, 2008; Moeller et al., 2007a; Nathani, Oller, & Neal, 2007). Even when infants were matched on vocal development (i.e., canonical syllable production) rather than age, no differences in vocalization quantity were reported (Iyer & Oller, 2008).

Studies reporting similarities in number of vocalizations have several limitations, however. The central limitation concerns variability in actual levels of infant hearing loss. By definition, profound hearing loss is remarkable in that it is the most severe form of hearing loss. Individuals with profound hearing loss (typically considered *deaf*) do not perceive most acoustic stimuli, including their own vocalizations, and seldom benefit to an appreciable degree from hearing aids. Although some individuals with profound hearing loss may have very limited access to a narrow range of acoustic signals, they typically do not have sufficient access, even with amplification, to develop spoken language as hearing infants do. In contrast, individuals with mild or moderate to severe hearing loss (typically considered *hard-of-hearing*) have substantially greater access to acoustic stimuli and benefit from hearing amplification (Northern & Downs, 2002). Thus, research participants with mild to moderate hearing loss likely inflated performance results when infants with hearing loss were considered as an undifferentiated group (Nathani et al., 2007; Stoel-Gammon & Otomo, 1986). That is, as with vocalization quality (Stoel-Gammon & Otomo, 1986; von Hapsburg & Davis, 2006), mild hearing loss may have less impact on vocalization numbers than profound hearing loss.

Nonetheless, in studies reporting similar numbers of vocalizations, levels of hearing loss have varied widely from mild to profound (Koester et al., 1998; Moeller et al., 2007a). For example, in a study of 9-month-old deaf and hearing infants, more than one third of the 33

infants considered deaf either did not have profound hearing loss (2 had mild to moderate, and 6 had moderate to severe loss) or hearing results were not obtained (i.e., 4 infants' results were unavailable; Koester et al., 1998). In another study that reported no evidence of diminished vocalization frequency in four infants with hearing loss, participants had moderate to severe rather than profound hearing loss and hearing controls were not included (Nathani et al., 2007).

A second limitation of studies of vocalization frequency concerns sampling variation—both variations in length of sampling sessions, and variations in inclusion criteria for counted vocalizations. First, in efforts to secure targeted vocalization sample sizes from infants with hearing loss, data collection periods have been extended for infants with few vocalizations, sometimes including data collected over a month or more (Iyer & Oller, 2008; von Hapsburg & Davis, 2006). To obtain equivalent samples, for example, Von Hapsburg and Davis recorded infants with severe-to-profound hearing loss nearly twice as long as hearing infants. Even with prolonged or supplemental recording sessions, however, infants with hearing loss sometimes failed to produce targeted numbers of vocalization (Iyer & Oller, 2008; Moeller et al., 2007a), in which case, they were sometimes considered outliers and eliminated from mean analyses. Both methods—excluding infants with few vocalizations, and extending efforts to gather minimum numbers of vocalizations—potentially overestimated vocalization frequency in infants with hearing loss. The second sampling issue concerned differences in criteria for counting vocalizations. Vocalization totals, for example, have variously excluded or included squeals (Nathani et al., 2007), laughing, raspberry sounds, and crying (Koester et al., 1998). Nathani et al. (2007) counted squeals as canonical syllables, acknowledging this exception to typical practices and its effect in increasing vocalization totals.

Given these limitations, relations between hearing loss and vocalization frequency remain uncertain, confounding efforts to fully explain vocal behavior, its motivation, and its role in infant development. Theoretically, if infants with profound hearing loss do vocalize as often as hearing infants—despite little if any access to auditory feedback—potential effects of non-auditory sensory feedback generated while vocalizing (e.g., vibro-tactile), as well as arguments regarding biologically motivated (e.g., reflexive) vocalization tendencies must be considered.

By contrast, if vocalization quantity is influenced by auditory feedback, as vocalization quality is, then vocalization numbers should decline in its absence. Diminished vocalization frequency in infants with profound hearing loss would support this hypothesis, as would increased vocalization after cochlear implantation. Infants with profound hearing loss, with and without cochlear implants, both under represented populations in developmental research, present unique opportunities to test dynamic relations between auditory perception and infant behavior. This study aims to test these relations before and after cochlear implantation in relation to hearing controls. Moreover, this study aims to address limitations of earlier investigations by limiting participation to infants with profound hearing loss, using a standard method of data collection with equal observation periods, and providing an accounting of all vocal behavior.

Method

Participants

Participants included 16 infants with profound hearing loss and 27 hearing infants. Infants with profound hearing loss (13 boys, 3 girls) were identified during newborn hearing screenings and participated in auditory-oral intervention programs that included use of hearing aids as part of the accepted protocol for determining cochlear implant candidacy (Cosetti & Roland, 2010; Heman-Ackah, Roland, Haynes, & Waltzman, 2012). They had no known diagnoses other than hearing loss. Hearing infants (11 boys, 16 girls) passed newborn hearing tests and did not have a history of chronic otitis media or known developmental concerns.

All infants participated at one of two time points (i.e., Time 1 or Time 2) and a subset of infants provided data at both time points. Table 1 shows number of infants tested at each time point. For infants with profound hearing loss, Time 1 was scheduled to take place in the second half of the first year shortly before cochlear implantation (Pre-CI); Time 2 was scheduled 4.2 months ($SD = 2.6$, range = 1-8 months) after cochlear implant activation (Post-CI) in order to observe proximate changes in behavior. Mean age at cochlear implant surgery (11 unilateral, 2 simultaneous bilateral) was 12.9 months ($SD = 2.3$, range = 8-16 months); mean age at cochlear implant activation was 14.0 months ($SD = 2.2$, range = 10-17 months). Data collection for hearing infants (H1 and H2) recruited from the local community was scheduled in the same age range as infants with hearing loss. At Time 1, all infants (H1 and Pre-CI) were 7 to 11 months old ($M = 9.9$ months, $SD = 1.3$, range = 7.8 – 11.9), a focal age range in many studies of vocal development; mean age at Time 2 was 17.7 months ($SD = 2.9$; range = 13-22 months).

Because study funding was time-limited, data were collected simultaneously for hearing and deaf infants. Participation for infants with cochlear implants was constrained by the timing of surgical procedures within the study window. Thus, infants who already had cochlear implants at the start of the study participated only Post-CI. Infants who had not yet received cochlear implants before the end of the study were seen only Pre-CI. Thus, in this relatively low-incidence clinical population with profound hearing loss and early access to cochlear implants (i.e., 12.9 months), some participated only Pre- and others only Post-CI (Table 1). Although hearing infants were typically easier to enroll, two age-matched hearing controls failed to keep Time 2 appointments and thus did not contribute data to both time points as planned. Differences in vocalization frequency between infants who contributed data at one ($M = 60.3$ vocalizations, $SD = 39.9$) versus two ($M = 57.6$, $SD = 51.3$) time points were not significant, $t(55) = .22$, $p = .82$.

All infants were born to hearing parents who primarily used spoken English to communicate with their infants. All participants scored within the normal range on the Motor Skills domain of the Vineland Adaptive Behavior Scales, Second Edition (Sparrow, Cicchetti, & Balla, 2005), administered at the first study visit ($M_{SS} = 101.0$, $SD = 8.3$). Two infants with hearing loss (1 Pre-CI, and 1 Post-CI) were premature (born at 28 and 33 weeks, respectively). Statistical analyses computed with and without data from these participants did not differ. Therefore, they were retained in the analyses. Mean years of education for

mothers of infants with profound hearing loss was 14.3 years ($SD = 2.9$); mean years of education for mothers of hearing infants was 14.8 years ($SD = 2.8$). Four infants were bi-racial, 6 were African American, and 33 were Caucasian.

Procedure

Two sets of 12 objects appropriate for infant play and manipulation (e.g., rattle, car, ball) were presented to infants one at a time for 30 seconds each (i.e., 12 minutes total). Infants, seated on the lap of a caregiver facing a table, were free to manipulate objects and vocalize at will. Following object presentation, parents were asked to engage with infants for two additional minutes of unstructured social interaction.

In deference to travel demands, parents of Pre-CI and Post-CI infants, many of whom lived 1 to 3 hours from the laboratory, were offered the option to participate in home or laboratory sessions. The experimental protocol was identical in either case; infants were seated at a table in a quiet environment in the home (58%) or laboratory (42%). Preliminary analyses showed vocalization frequency did not differ significantly for home ($M = 47.7$, $SD = 55.0$) vs. laboratory ($M = 46.4$, $SD = 41.3$) visits, $t(22) = .06$, $p = .95$.

During video-recording, infants wore a vest containing a small microphone and transmitter with wireless connection to a camera-mounted receiver. All audible infant vocal behaviors were identified from the 14-minute videotaped records by four trained coders (undergraduate and graduate students) unfamiliar with the purpose of the study. Identified behaviors were categorized as *vocalizations* or *vocal behaviors*. Vocalizations contained one or more consonant- or vowel-like sounds (e.g., [a, ba, baba]). Vocal behaviors included all other vocal sounds in eight exhaustive and mutually exclusive categories: *cry*, *laugh*, *growl*, *effortful grunt*, *raspberry* (bilabial, or tongue between lips), *squeal* (unarticulated high pitched screech), *vegetative* (e.g., cough, hiccup, burp), and *other* (i.e., rare tongue clicks). Vocalizations were also analyzed for temporal duration using acoustic analysis software (Praat; Boersma, 2001). Vocalizations were separated by a breath or brief silence, confirmed in Praat.

To assess reliability, 13 randomly selected videotaped records (23%) were independently coded by a second trained coder. The intra-class correlation coefficient (ICC) for number of vocalizations identified was .97. Point by point percent agreement for specific vocal classification type (i.e., category assignment) was 89.5%.

Results

Preliminary Analyses

Vocalization quantity did not differ significantly by Object Set, $t(56) = .38$, $p = .70$, or by Task ($M = 5.7$ vocalizations/minute, $SD = 3.9$, for object play; $M = 5.0$ vocalizations/minute, $SD = 4.5$, in unstructured interactions), $t(56) = 1.25$, $p = .21$. Males were over represented among infants with hearing loss; however, vocalization quantity did not differ by gender in infants with hearing loss, $t(4.2) = .95$, $p = .38$, or hearing infants, $t(31) = 1.20$, $p = .23$. Therefore, data were combined across Gender, Object Set, and Task for additional analyses.

Vocalization Quantity

At Time 1, infants with profound hearing loss (Pre-CI) produced significantly fewer vocalizations than hearing infants did (H1), independent samples $t(24) = 2.25, p < .05, d = .93$. The Pre-CI group produced fewer than half as many vocalizations as hearing peers ($M = 23.0, SD = 26.5$ vs. $M = 56.8, SD = 44.1$, respectively). One individual with profound hearing loss produced no vocalizations at all and another vocalized only once in 14 minutes. In all, five of the 11 Pre-CI infants (i.e., 45%) produced fewer than six vocalizations, whereas, none of the hearing infants produced so few. Individual vocalization totals for Pre-CI and H1 infants are shown in Figure 1. Word vocalizations did not factor significantly into Time 1 vocalization counts, as only a single (H1) word vocalization occurred. Figure 2 shows mean number of word and non-word vocalizations by Group and Time.

At Time 2, the significant difference in overall vocalization quantity observed before cochlear implantation was no longer evident. That is, vocalization numbers for Post-CI and H2 infants were not significantly different, $t(29) = .53, p = .59, d = .18$. Thus, Post-CI infants matched their hearing peers in vocalization frequency relatively soon after gaining access to auditory feedback through their cochlear implants. The rapidity and degree of behavioral change in relation to auditory access was highlighted by four infants who had used their implants for the least amount of time at Time 2, only 42.75 days on average (range = 38-53 days). For these infants, vocalizations tripled in quantity, compared to Time 1, within just 43 days of implant activation.

Infant age was not significantly correlated with number of vocalizations among typically developing hearing infants, $r = .16, p = .35$. Age was also not significantly correlated with number of vocalizations in infants with hearing loss, $r = .36, p = .08$. This second correlation, for infants with hearing loss, appears to show a trend toward significance; however, in this group, age was also associated with cochlear implant status. That is, *all* infants >12 months old with hearing loss had cochlear implants. Further analysis of age effects further showed age was not significantly correlated with vocalization frequency within either subgroup with hearing loss, Pre-CI, $r = .25, p = .44$, or Post-CI, $r = -.17, p = .56$; nor was age significantly correlated with number of vocalizations within combined groups of infants (Pre, H1) at Time 1, $r = -.03, p = .87$, or Time 2 (Post-CI, H2), $r = -.13, p = .47$. Thus, number of vocalizations in infants with hearing loss increased significantly with cochlear implantation but not (in any group) in conjunction with age alone.

Next, Time 2 word and non-word vocalizations were considered separately. Whereas word production was still quite infrequent among Post-CI infants ($M = .62, SD = 1.3$), H2 infants produced word vocalizations in significantly greater numbers than Post-CI infants ($M = 21.6, SD = 24.8$), $t(29) = 3.03, p < .01, d = 1.19$. Despite this difference in word production, both groups (Post-CI, H2) produced *non-word* vocalizations in similar numbers ($M = 67.0, SD = 54.6$ vs. $M = 54.9, SD = 33.7$, respectively), $t(29) = .75, p = .45, d = .26$. In fact, non-word vocalizations significantly exceeded word vocalizations not only among Post-CI infants, who produced few words (Figure 2), $t(12) = 4.37, p < .01, d = 1.71$, but also among H2 infants, $t(17) = 3.13, p < .01, d = 1.12$. Moreover, given that hearing infants (H2) produced non-word vocalizations in numbers nearly identical to Time 1 (H1) non-word

values ($M = 54.9$ and $M = 56.7$, respectively), H2 infants added word vocalizations to established non-word totals, rather than decreasing non-word vocalizations as words use grew.

Temporal Duration

Additional analyses indicated between group differences in mean temporal duration were not significant at Time 1, $t(23) = .41$, $p = .68$, $d = .16$, or Time 2, $t(29) = 1.72$, $p = .09$, $d = .62$. Overall, infant vocalizations were relatively brief ($M = .651$ ms, $SD = .31$). Thus, temporal duration was not a significant factor in accounting for differences in vocalization frequency. Pre-CI infants, for example, did not produce fewer but longer vocalizations. Table 2 presents mean duration by Group and Time.

Together, the vocalization data are consistent with the hypothesis that vocalization quantity is significantly influenced by auditory perception, in that Pre-CI infants vocalized significantly less often than hearing infants (H1), and Post-CI infants' vocalizations were similar in number to hearing peers (H2).

Vocal Behaviors

Analyses for number of vocal behaviors (e.g., cry, raspberries, squeals) showed no significant differences between groups at Time 1, $t(24) = .84$, $p = .40$, or Time 2, $t(29) = .05$, $p = .95$. Raspberry sounds, for example, were produced with similar frequency by hearing infants and infants with hearing loss at each time point, Time 1, $t(24) = .33$, $p = .74$, and Time 2, $t(29) = .63$, $p = .52$. Figure 3 presents mean numbers for each behavior by Group and Time. Together, these behaviors occurred significantly less frequently overall than did infant vocalizations ($M = 11.3$, $SD = 12.9$ vs. $M = 58.9$, $SD = 45.5$, respectively), $t(56) = 8.16$, $p < .001$, $d = 1.42$. Thus, vocal behaviors were relatively infrequent and there was no evidence that they were motivated predominately by auditory feedback as Pre-CI and H1 infants produced them with equal frequency at Time 1, as did Post-CI and H2 infants at Time 2.

Discussion

This study, designed to test hypothesized relations between vocalization quantity and auditory feedback, investigated vocalization frequency in hearing infants and infants with profound hearing loss with and without cochlear implants. Before cochlear implantation, 9-month-old infants with profound hearing loss produced significantly fewer vocalizations than hearing infants. However, with access to cochlear implants, vocalizations more than doubled in quantity, roughly matching numbers produced by hearing peers within just four months on average of cochlear implant activation. Both diminished vocalization frequency before cochlear implantation and increased vocalization frequency after cochlear implantation support the hypothesis that auditory feedback is a critical component motivating infant vocalizations. In contrast, the data showed vocal behaviors (e.g., raspberries, laughs, cries) did not vary significantly in accordance with auditory access. Similar numbers of vocal behavior across hearing status suggest they were not motivated by

auditory feedback and highlighted the unique status of vocalizations with regard to auditory feedback.

In addition to addressing theoretical and sensory foundations of early infant vocalizations, these results also extend research on infant behavior in the second year by showing the non-word vocalizations of hearing infants continued unabated from Time 1 to Time 2 even as word production increased. As Palmer (1989) has noted, infant behavior reveals the focus of their attention and interest. Therefore, the predominance and stability of non-word vocalizations, together with dynamic relations between vocalization quantity and auditory feedback, reveal infants interest in vocalizing and exploring the perceptual-motor relationships generated by vocalizing. Certainly, other factors including social communication can influence vocalization quantity as well; however, results from this study suggest that vocalizations depend to a large extent on auditory feedback nonetheless.

Auditory access permits infants to hear both their own vocal productions and the vocalizations of caregivers. In this study, the relative contribution of infants' access to self-generated feedback and/or caregiver input was not tested. However, questions regarding the relative importance of perceiving caregiver input and/or infants' own auditory-vocal feedback has been addressed in comparative research, as well as research with hearing infants of Deaf parents. For instance, despite evidence that Deaf mothers who communicated primarily with sign language produced fewer than half as many vocalizations as hearing mothers did, their infants with normal hearing nevertheless vocalized as often as infants of hearing parents did (Rea, Bonvillian, & Richards, 1988; see also Koester et al., 1998). The fact that vocalizations of infants of Deaf parents did not decline under conditions of diminished input, that vocalizations have regularly occurred without social or communicative intent (Anderson et al., 1977; Delack, 1976; Moeller et al., 2007b; Stark, 1980; Stark et al., 1993), and that vocalization numbers changed rapidly and significantly in conjunction with cochlear implantation in this study suggests caregiver input alone can neither explain vocalization motivation nor obviate perceptual-motor exploration and auditory feedback as viable sources of motivation.

In comparative research, white-crowned sparrows exposed to conspecific bird song, but deafened before they themselves began to sing, failed to produce the songs to which they had been exposed prior to deafening (Konishi, 1965). Thus, in addition to the importance of exposure to conspecific song during development, Konishi found that sparrows must hear their own vocalizations in order to replicate conspecific songs experienced earlier. Furthermore, in adult songbirds, sparrows' song production decreased nearly eightfold after surgical deafening (Brenowitz, Lent, & Rubel, 2007) and deafened Australian parrots vocalized less frequently than non-deafened parrots (Heaton, Dooling, & Farabaugh, 1999). Together, these human and comparative studies found auditory feedback from self-generated vocalizations affected vocalization frequency at least as much, if not more than auditory perception of input from others.

Recent research has focused attention on the importance of self-generated actions and perceptual-motor representations in early social-cognitive development (Daum, Prinz, & Aschersleben, 2011; Gerson & Woodward, 2014). For example, infants' experience with

self-produced actions, but not observational experience, helped infants assign intentional goals to the actions of others (Gerson & Woodward, 2014). Moreover, 6-month-old infants formed expectations about adults' grasp intention only in relation to their own skilled grasp experience (Daum et al., 2011). Similarly, infants' experience with self-generated vocalization may help them assign intention to caregiver speech. As Smith and colleagues (Smith, 2006; Thelen & Smith, 1994) have noted, infants need not know vocalizations will become words in order to establish perception-action representations and discover associations between explored sounds and meaning. That is, infants can discover both the task to be learned and the solution through exploration (Smith, 2006, p. 88).

In this study, infants with profound hearing loss vocalized before access to auditory feedback, albeit in quite limited numbers. Non-auditory feedback mechanisms (e.g., vibrotactile, proprioceptive) likely motivated at least some of those vocalizations, and the vocalizations of hearing infants, as well. However, although alternative sensory feedback generated during vocalizing likely motivated some vocalizations, such sensory feedback alone (i.e., in the absence of auditory feedback), was not sufficient to support Time 1 productivity levels equivalent to that of hearing peers. If non-auditory feedback (and/or social feedback) had been sufficient, Pre-CI vocalization numbers would have approximated those of hearing infants.

Additional Pre-CI vocalizations, particularly the structurally simple and common vowel vocalizations predominant in the first year (e.g., Fagan, 2009), may have emerged in part as the product of naturally occurring variations in respiration and laryngeal tension—similar to the vowel-like expressions uttered by adults when exasperated. Thelen (1991) proposed similar dynamics for the vocal characteristics of crying, which she described as the outcome of respiratory and vocal fold tension under heightened distress. Her view was that structurally constrained and dynamically assembled components of sound production were biologically variable but not innately determined.

Limitations of the current study include the gender imbalance among infants with hearing loss; however, gender differences in vocalization quantity were not evident. Additionally, the age range at Time 2 was larger than at Time 1, although infant age was not correlated with number of vocalizations in either group. The participants were otherwise relatively homogeneous with regard to age at cochlear implantation, duration of cochlear implant use, and degree of hearing loss (i.e., profound hearing loss only). Questions still to be addressed include how differences in early vocalization frequency and sensory experience influence later learning and development.

In summary, this study of infants with and without cochlear implants identified auditory feedback as a critical component in vocalization quantity. In the absence of auditory feedback, 9-month-old infants with profound hearing loss (Pre-CI) vocalized significantly less often than hearing peers. However, infants quickly produced numbers of vocalization similar to hearing peers relatively soon after cochlear implantation, thus providing theoretically consistent results from two tests of the dynamic effect of auditory feedback on infant behavior. These results, together with evidence that hearing infants produced substantial numbers of non-word vocalizations after the emergence of word production,

support the hypothesis that auditory feedback is a critical component motivating early vocalization frequency. These results, obtained by controlling methodological variations in earlier studies, challenge and extend previous reports by showing hearing loss affected vocalization quantity, as has been shown for vocalization quality in the past.

References

- Adolph, KE.; Joh, AS. Multiple learning mechanisms in the development of action. In: Woodward, A.; Needham, A., editors. *Learning and the infant mind*. Oxford University Press; New York: 2009. p. 172-207.
- Adolph KE, Tamis-LeMonda CS, Ishak S, Karasik LB, Lobo SA. Locomotor experience and use of social information are posture specific. *Developmental Psychology*. 2008; 44:1705–1714. [PubMed: 18999332]
- Anderson BJ, Vietze P, Dokecki PR. Reciprocity in vocal interactions of mothers and infants. *Child Development*. 1977; 48:1676–1681. [PubMed: 608379]
- Boersma P. Praat: A system for doing phonetics by computer. *Glott International*. 2001; 5:341–345.
- Bowlby, J. *Attachment*. Vol. 1. Basic Books; New York: 1969. Attachment and loss.
- Brenowitz EA, Lent K, Rubel EW. Auditory feedback and song production do not regulate seasonal growth of song control circuits in adult white-crowned sparrows. *Journal of Neuroscience*. 2007; 27:6810–6814. [PubMed: 17581968]
- Cosetti M, Roland JT Jr. Cochlear implantation in the very young child: Issues unique to the under-1 population. *Trends in Amplification*. 2010; 14:46–57. [PubMed: 20483813]
- Daum MM, Prinz W, Aschersleben G. Perception and production of object-related grasping in 6-month-olds. *Journal of Experimental Child Psychology*. 2011; 108:810–818. [PubMed: 21092981]
- Delack JB. Aspects of infant speech development in the first year of life. *Canadian Journal of Linguistics*. 1976; 21:17–37.
- Fagan MK. Mean length of utterance before words and grammar: Longitudinal trends and developmental implications of infant vocalizations. *Journal of Child Language*. 2009; 36:495–527. [PubMed: 18922207]
- Gerson SA, Woodward AL. Learning from their own actions: The unique effect of producing actions on infants' action understanding. *Child Development*. 2014; 85:264–277. [PubMed: 23647241]
- Heaton JT, Dooling RJ, Farabaugh SM. Effects of deafening on the calls and warble song of adult budgerigars (*Melopsittacus undulatus*). *Journal of the Acoustical Society of America*. 1999; 105:2010–2019. [PubMed: 10089618]
- Heman-Ackah SE, Roland JT Jr, Haynes DS, Waltzman SB. Pediatric cochlear implantation: Candidacy evaluation, medical and surgical considerations, and expanding criteria. *Otolaryngologic Clinics of North America*. 2012; 45:41–67. [PubMed: 22115681]
- Iyer SN, Oller DK. Prelinguistic vocal development in infants with typical hearing and infants with severe-to-profound hearing loss. *Volta Review*. 2008; 108:115–138. [PubMed: 21499444]
- Keller H, Scholmerich A. Infant vocalizations and parental reactions during the first 4 months of life. *Developmental Psychology*. 1987; 23:62–67.
- Kent RD, Osberger MJ, Netsell R, Hustedde CG. Phonetic development in identical twins differing in auditory function. *Journal of Speech and Hearing Disorders*. 1987; 52:64–75. [PubMed: 3807347]
- Koester LS, Brooks LR, Karkowski AM. A comparison of the vocal patterns of deaf and hearing mother-infant dyads during face-to-face interactions. *Journal of Deaf Studies and Deaf Education*. 1998; 3:290–301. [PubMed: 15579869]
- Konishi M. The role of auditory feedback in the control of vocalization in the White-crowned sparrow. *Zeitschrift fur Tierpsychologie*. 1965; 22:770–783. [PubMed: 5874921]
- Lenneberg, EH. *Biological foundations of language*. John Wiley & Sons; New York: 1967.
- Lenneberg EH, Rebersky FG, Nichols IA. The vocalizations of infants born to deaf and to hearing parents. *Human Development*. 1965; 8:23–37. [PubMed: 14308324]
- Locke, JL. *The child's path to spoken language*. Harvard University Press; Cambridge, MA: 1993.

- Maskarinec AS, Cairns GF, Butterfield EC, Weamer DK. Longitudinal observations of individual infant's vocalizations. *Journal of Speech and Hearing Disorders*. 1981; 46:267–273. [PubMed: 7278170]
- Moeller MP, Hoover B, Putman C, Arbataitis K, Bohnenkamp G, Peterson B, Stelmachowicz P. Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I – Phonetic development. *Ear & Hearing*. 2007a; 28:605–627. [PubMed: 17804976]
- Moeller MP, Hoover B, Putman C, Arbataitis K, Bohnenkamp G, Peterson B, Stelmachowicz P. Vocalizations of infants with hearing loss compared with infants with normal hearing: Part II – Transition to words. *Ear & Hearing*. 2007b; 28:628–642. [PubMed: 17804977]
- Mowrer, OH. *Learning theory and the symbolic processes*. John Wiley & Sons; New York: 1960.
- Nathani S, Oller DK, Neal AR. On the robustness of vocal development: An examination of infants with moderate-to-severe hearing loss and additional risk factors. *Journal of Speech, Language, and Hearing Research*. 2007; 50:1425–1444.
- Northern, JL.; Downs, MP. *Hearing in Children*. Lippincott Williams & Wilkins; Philadelphia: 2002.
- Oller DK, Eilers RE. The role of audition in infant babbling. *Child Development*. 1988; 59:441–449. [PubMed: 3359864]
- Palmer CF. The discriminating nature of infants' exploratory actions. *Developmental Psychology*. 1989; 25:885–893.
- Papaeliou C, Minadakis G, Cavouras D. Acoustic patterns of infant vocalizations expressing emotions and communicative functions. *Journal of Speech, Language, and Hearing Research*. 2002; 45:311–317.
- Rea CA, Bonvillian JD, Richards HC. Mother-infant interactive behaviors: Impact of maternal deafness. *American Annals of the Deaf*. 1988; 133:317–324. [PubMed: 3251417]
- Smith LB. Movement matters: The contributions of Esther Thelen. *Biological Theory*. 2006; 1:87–89.
- Smith LB, Thelen E, Titzer R, McLin D. Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review*. 1999; 106:235–260. [PubMed: 10378013]
- Sparrow, SS.; Cicchetti, DV.; Balla, DA. *Vineland Adaptive Behavior Scales*. Second Edition. American Guidance Service; Circle Pines, MN: 2005.
- Spencer JP, Clearfield M, Corbetta D, Ulrich B, Buchanan P, Schoner G. Moving toward a grand theory of development: In memory of Esther Thelen. *Child Development*. 2006; 77:1521–1538. [PubMed: 17107442]
- Spencer JP, Smith LB, Thelen E. Tests of a dynamic systems account of the A-not-B error: The influence of prior experience on the spatial memory abilities of two-year-olds. *Child Development*. 2001; 72:1327–1346. [PubMed: 11699674]
- Stark RE. Features of infant sounds: The emergence of cooing. *Journal of Child Language*. 1978; 5:379–390. [PubMed: 701415]
- Stark, RE. Stages of speech development in the first year of life. In: Yeni-Komshian, GH.; Kavanagh, JF.; Ferguson, CA., editors. *Child phonology: Vol. 1. Production*. Academic Press; New York: 1980. p. 73-90.
- Stark RE, Bernstein LE, Demorest ME. Vocal communication in the first 18 months of life. *Journal of Speech and Hearing Research*. 1993; 36:548–558. [PubMed: 8331912]
- Stoel-Gammon C, Otomo K. Babbling development of hearing-impaired and normally hearing subjects. *Journal of Speech and Hearing Disorders*. 1986; 51:33–41. [PubMed: 3945058]
- Thelen E. The (re)discovery of motor development: Learning new things from an old field. *Developmental Psychology*. 1989; 25:946–949.
- Thelen, E. Motor aspects of emergent speech: A dynamic approach. In: Krasnegor, N., editor. *Biobehavioral foundations of language*. Erlbaum; Hillsdale, NJ: 1991. p. 339-363.
- Thelen, E.; Smith, LB. *A dynamic systems approach to the development of cognition and action*. MIT Press; Cambridge, MA: 1994.
- Thelen E, Ulrich BD. Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development*. 1991; 56(1) Serial No. 223.
- von Hapsburg D, Davis BL. Auditory sensitivity and the prelinguistic vocalizations of early-amplified infants. *Journal of Speech, Language, and Hearing Research*. 2006; 49:809–822.

Highlights

Infants with profound hearing loss did not vocalize as often as hearing peers

Soon after cochlear implantation, vocalization numbers equaled hearing peers

Cochlear implants quickly influenced changes in behavior

Vocal behavior often linked with emotion expression did not vary with auditory access

Figure 1.

Time 1 vocalization totals for individual infants by group. Pre = infants with profound hearing loss; H1 = hearing infants.

Figure 2.

Mean number of word and non-word vocalizations by Group and Time. Pre-CI = before cochlear implantation; H1 = hearing infants at Time 1; Post-CI = after cochlear implantation; H2 = hearing infants at Time 2.

Figure 3.

Mean number of vocal behaviors by Group and Time. Pre-CI = before cochlear implantation; H1 = hearing infants at Time 1; Post-CI = after cochlear implantation; H2 = hearing infants at Time 2.

Table 1

Number of Participants by Time and Group

Group	Time 1 Only	Time 2 Only	Time 1 and 2	Total
Profound Hearing Loss	3	5	8	16
Hearing	9	12	6	27

Table 2

Vocalization Duration in Milliseconds by Group and Time

Duration	Time 1		Time 2	
	Pre-CI	H1	Post-CI	H2
Mean (<i>SD</i>)	0.633 (.44)	0.573 (.29)	0.791 (.31)	0.623 (.23)
Range	0.157-1.569	0.169-1.239	0.251-1.311	0.187-1.079

Note. Pre-CI = before cochlear implantation; H1 = hearing infants at Time 1; Post-CI = after cochlear implantation; H2 = hearing infants at Time 2.