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Why volubility can predict the success of cochlear implantation: A last decade review

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REVIEW

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ABSTRACT

Background

We sought to identify potential communication markers predicting the success of cochlear implantation, that might be observed within the first year of life. According the last ten years literature review volubility can be considered as a potentially important vocal measure predicting later language development.

Aims

The present review aims to review existing evidence related with: (i) why volubility posits a plausible marker of cochlear implantation success in infancy, and (ii) presents the clinical usefulness of volubility data in predicting later language trajectory.

Methods

Rate of vocalization or volubility measured in terms of frequency of syllable production and it is clearly affected by parental interactivity. A low percentage of volubility can be predictive of significant communication impairment. Vocalization growth during the first year of life, as demonstrated in publications examining sound production characteristics of normally hearing (NH) and hearing impaired (HI) infants fitted with CI, were reviewed.

Results

Literature results revealed differences in linguistic performance among NH and CI infants which are typically attributed to auditory deprivation. Infants received late CI, produce fewer syllables (low volubility) and exhibit late-onset babbling, especially those who underwent the procedure as late as the age of 12 months or thereafter. Early recipients (implanted before the age of 12-months) related with more vocalizations, which is thought to stem from CI-initiated auditory feedback. In sum, total syllables produced (volubility) demonstrate the developmental trajectory of language acquisition which in turn is a crucial factor related with the success of cochlear implantation.

Conclusion

Contemporary findings collectively endorse volubility as a plausible criterion of differentiation between successful and non-successful early CI. It is argued that volubility measures predict language development and, in doing so, carry vast implications on designing efficient clinical assessment and intervention practices.

Key Words

Volubility, cochlear implantation, language development, infants, auditory perception, early vocalization

What this review adds:

1. What is known about this subject?

Recent research suggests that early differences in the quantity of vocalizations has the potential to differentiate infants. Volubility is a potential early indicator for a deviant trajectory of language development.

2. What new information is offered in this review?

This review adds a new contribution upon existing evidence by proposing that post-implementation vocalization frequency predicts early CI success and later language growth.

3. What are the implications for research, policy, or practice?

The development of a cost-effective marker for earlier diagnosis for the success of cochlear implantation.

Introduction

One of the limitations of conducting research in the field of pre-speech development, involves the difficulty in discerning the variables that sit beneath various forms of expressive sound output during infancy. One of the merits of securing early access to CI, is that the empirical manipulation of auditory input is facilitated, allowing more straightforward interpretations and reducing any contaminating effects that may arise from confounding variables. The present paper sets out to examine usefulness of a particular source of data, namely vocalization frequency or volubility, as a measure of CI success, and as a prognostic criterion of later linguistic performance.

Precursors to speech: Early vocal development

During the months preceding word use, early aspects of language appear to evolve in a universal and predictable pattern of vocalizations and babbling, which seems to play an important role in later language development.[1-4] Although several existing models had been proposed to describe early linguistic growth in the past, not much detail was available on prelinguistic vocal development until relatively recently.[5] Nowadays, theoretical and conceptual advancements in this area of exploration are suggestive as to why early sound production is a fairly robust phenomenon during infancy.

Before we proceed to review the existing literature regarding sound production in early CI recipients, it is important to clarify the underlying concept at the heart of vocal development; namely, infant vocalizations. Amongst the multitude of precursors to speech, beginning from loosely-shaped, partially-intelligible utterances and followed by well-formed syllables and word production (which typically occurs during the later second half of the first year of life[4]) vocalizations include “all types of non-vegetative sounds” (Clement 2004, p. 137), excluding reflexive behaviours (e.g., crying) as well as those tied to affective states (e.g., laughing and crying).[2,4] Infant vocalizations constitute a developmental milestone in language development, and progressively decrease in frequency as speech-sound vocalizations emerge.[3]

A potentially clinically significant aspect of early speech sound development is that of volubility, which can be defined as the quantity of infant vocalizations[6] (i.e., amount or frequency sound production[7]), regardless of the type of vocalization or utterance. In other words, the measure of volubility signifies a prelinguistic marker of vocal ability, whose development has been associated with biological[8] and environmental[6] factors and, more recently, with neuroconstructivist or experience-driven processes.[9]

The motivation behind pre-speech sound production is as yet unclear.[4,10] Traditionally, volubility has been investigated in small-scale studies, most commonly of a descriptive nature.[11] This observation may be attributed to the inherent methodological limitations associated with the process of recording early markers of speech-sound production. In addition to being time-consuming, measurements on volubility data require longitudinal naturalistic language recordings,[12] whereas the resulting quantification of pre-speech vocalizations is often susceptible to performance variability (i.e., performance fluctuations related to socioeconomic status [SES][6,13] and caregiver interaction,[7,9,10] diverse and interdependent factors associated with neurodevelopmental complexity,[9] etc.).

At a descriptive level, reports of lower volubility among children from deprived SES[13] households are suggestive pointers as to how environmental factors may influence the trajectories of vocalization development. Oftentimes infants from socioeconomically disadvantaged homes receive less caregiver communication[7] and produce vocalizations less frequently as a result of their reduced interaction with parents or other primary caregivers. Notably, however, a number of researchers[1,9] emphasize the importance of experiential interplay, stressing the fact that, by the same token, parental input varies in accordance with the child’s existing language performance, making it difficult to set a clear direction of causality between these co-existing environmental factors.

Despite the aforementioned methodological shortcomings, the quantification of pre-speech development into low and high volubility has proven to be particularly informative in the context of specific population subgroups, amongst which Down[14] and Fragile X Syndromes,[6] autism spectrum disorder,[12,15] childhood apraxia of speech,[11] congenital cleft palate,[8,16] and hearing impairment.[3,4,17,18] More specifically, volubility data provide a valid and valuable measure for setting a point of departure between important aspects of typical and divergent language acquisition, thus enabling the clinical differentiation between children who exhibit typical speech sound development and those who present a greater risk for developing language disorders.

Methodological approaches to studying volubility

When assessing volubility data, protophones arise as the principle vocal unit of interest. Commonly utilized for coding infant vocalizations, protophones represent a class of sound units characterized by their primitive (prelinguistic) properties. Accordingly, protophone volubility refers to the number of protophones produced per unit time.[5] Fundamentally distinctive from mature speech along phonatory and articulatory/acoustic parameters,[19] protophonic structures form part of an infant's infraphonological repertoire (the infrastructural realm of the human speech sound system), which involves the capacity for an entire class of vocalizations during the first year of life, as shown in Table 1 below.

Table 1: Hierarchy of early vocalization development classified by mastery of protophone unit structures

Note. Adapted from D. K. Oller (2000, p. 15)[19]

Stages	Onset Age (in months)	Class of Protophone Units Mastered
Phonation	0-2	quasivowels
Primitive articulation	2-4	gooing
Expansion	4-6	marginal babbling/ full vowels
Canonical	6-7	canonical babbling

The infraphonological properties of protophones establish a natural hierarchy of vocalizations, amongst which canonical babbling typifies higher levels of developmental advancement. Canonical syllables, which synthesize this homonymous class of babbling structures, represent "phonetic building blocks of words",[20] and approximate mature speech systems of Consonant-Vowel (C-V) transitions. Mastery of these early structures is important for achieving the necessary phonetic content flexibility and diversity leading up to word generation at the second half of the first year of life.[4]

Although these global designations appear to be relatively straightforward, trying to build a comprehensive picture of an infant's expressive phonology requires several sources of protophone coding, for which no universal consensus exists. For instance, Oller favours protophone coding based on auditory impressions. Yet, a combination of a pure acoustic with an auditory analysis method, akin to that conducted by speech-analysis software programs (i.e., Praat[21]) can prove to be particularly helpful, as they reveal an enriched array of evidence underlying speech production mechanisms. Stoel-Gammon,[22] on the other hand, classifies all consonants except glottals and glides as true consonants, whereas Chapman and colleagues[16] prefer to include glottals as consonants in their work. The authors also proposed the true canonical babbling ratio (TCBR; the number of true canonical syllables divided by the total number of syllables), as an improved version of the canonical babbling ratio (CBR; number of canonical syllables divided by total number of syllables) that had been previously proposed by Oller and colleagues.

How does hearing impairment affect volubility?

As we described in the previous sections, volubility can be operationally defined as "the number of utterances vocalized by an infant per minute".[18] Hence, it connotes pre-speech development and, as we will see in the upcoming discussion, is considered a valid indicator of further linguistic progression. Normally hearing (NH) infants undergo universal vocalization development stages at similar points in time,[2] exhibiting a mean volubility ranging between 1.3 and 11.3 vocalizations per minute at the age of six months,[8] although these frequency ratings have been known to fluctuate, depending on a number of confounding factors.

A quick scan of the existing literature reveals controversial assumptions regarding volubility performance and whether it can be used as a measure of NH versus HI group membership identification. Past studies contain disparities, which limit our ability to fully operationalize the construct of volubility within the context of hearing impairment. For example, early theories widely assumed that vocal sounds such as babbling, were mainly reflexive and, thus, vocalizations produced by NH and HI infants were expected to be similar throughout their first year of life.[19] Comparable volubility rates among infants with hearing loss and those of NH have been confirmed in recent research, covering a non-variant chronological spectrum of 2.5 to 18 months of age.[2,23] Subsequent reports,[24,25] recognized lack of hearing as a factor that either caused a notable developmental delay (of up to a year, according to Oller[19]), or a vocalization decline in severely-to-profound HI infants after the age of 6 months, which signifies the onset of a less conspicuous protophone category, namely canonical babbling.

These observations brought auditory perception to the forefront of interest, as an essential feature of prelinguistic development. Whilst there is no shortage of investigations postulating that HI infants produce a decreased amount of utterances, there are also those that have documented equivalent levels of volubility between deaf and NH groups. Papers reporting inverse differences –who endorse, in other words, the view that deaf infants exhibit "hypervocal" tendencies in comparison to their NH counterparts[2]- have not gone amiss either.

Notwithstanding the lack of detailed explanatory research on the relationship between early infant vocalizations and linguistic development and growth, evidence increasingly seems to suggest that early aspects of vocal sound production constitute plausible predictors of later language-related cognitive achievements. For instance, increased vocabulary acquisition has been directly linked to more frequent vocalizations during infancy.[1]

Hearing impairment and early cochlear implantation

The compelling upsurge in the number of infants and children fitted with CIs in recent years (estimated to be in excess of 80.000 worldwide and currently on the rise[4,26]) speaks volumes of the high sophistication of contemporary molecular-genetic[26,27] and newborn audiometric[2,28,29] testing procedures, which enable the timely screening and detection of congenital deafness, as early as the first few weeks of life. At the moment, reports on the prevalence of congenital deafness range between 0.2 and 3 cases per 1,000 live births in industrialised –and even greater in developing– countries.[26,27,29]

A description of the design and function of CIs has been presented elsewhere in the literature (e.g., for extensive reviews see: Dorman & Wilson;[30] Kral & O'Donoghue[28]), therefore will be outlined briefly below. CIs are devices of aided hearing designed to stimulate otoacoustic emissions, with the intent of enabling the amplification of sound energy to be delivered in the auditory nerve, and onwards to cortical areas. CIs channel direct stimulation to the auditory nerve, bypassing the (non-functional) legion site at any transmission point between the outer ear and the auditory nerve, so as to provide substitute electrical stimulation for further processing by the auditory cortex. Although this electrical stimulation carries properties that are different than those of acoustic stimulation, these remain true to the coding principles of typical cochlear functioning[4]. Cochlear implantation facilitates the compensation of conductive or sensorineural types of hearing loss, typically encountered in the middle (i.e., ossicles) and/or inner (i.e., "dead regions" in the cochlea[27,28]) ear, circumventing the impaired channel and targeting the auditory nerve directly instead, hence creating a sound energy reception point for the artificially-induced stimulation.

It is safe to assume that disturbed auditory experience can adequately account for any observed differences in linguistic performance between HI and NH groups. By considerable empirical agreement, the prognosis for spoken language development –both in terms of comprehension and production— is significantly more favourable when CI occurs early, rather than late during childhood.[26,31,32] Therefore, an evidence-based window of opportunity exists, during which CI is expected to yield the most beneficial longitudinal outcomes. These outcomes include the perceptual understanding of complex speech sounds and the phonatory/articulatory structures that formulate and coordinate early vocalizations.[33] The dynamic character of auditory input and auditory self-feedback has only recently resurfaced as a field of exploration,[4,32,33] and may hold the key towards a deeper understanding of the motivation behind the course of vocalization development for NH and HI infants.

With such high stakes and vast implications, ensuring that early assessment practices are in place and that post-CI intervention is applied with immediacy and accuracy, is of utmost importance and cannot be undermined. At this point, the main pre-implementation objectives are revisited: diagnosis, prognosis, intervention. With these in mind, Pediatric Ear, Nose, and Throat (ENT) interdisciplinary teams enter the new era of the post-implementation experience.

Cochlear Implanted Infants and Vocalization Frequency

Once CIs have been fitted, ENT teams focus on following-up the recipient's CI experience; this endeavor presents a unique set of evaluation difficulties (e.g., expressive limitations of infancy). Applying valid and reliable criteria CI fitting success is rendered particularly crucial at this point, and the stakes for future language growth or failure are high, given the noted benefits of early CI on vocal acquisition.[26,34] During post-surgical recovery and rehabilitation, prognostic tools that will assist with the identification of receptive and expressive language development are essential for the timely and accurate intervention of CI & ENT teams.

The value of volubility as a clinical tool to be applied CI and ENT team settings has been recognized in a growing number of studies demonstrating auditory-guided speech-sound development following early CI. Warner-Czyz, Davis and

Morrison,[34] who examined lexical accuracy following CI, reported a dramatic increase in phonetic volubility, rising from 65 to 334 vowels from pre- to post-implantation sessions. The authors attributed the observed expansion of the phonetic inventory to the children's improved auditory acuity. Similar findings were reported by Dettman and colleagues,[31] where positive volubility (positive outcomes in comparison with normal hearing peers) emerged even in recipients who had been fitted at less than 12 months of age. In a series of studies conducted by Ertmer and colleagues,[3,17] post-implementation volubility reached comparable levels to NH peers, especially in cases where the child had been fitted before the age of 3 years, and had participated in oral habilitation programs.

More recently, Fagan[4] addressed the hypothesis that auditory feedback constitutes a primary motivation behind the production of early vocalizations, in a sample of NH and profoundly HI infants. To that effect, she compared pre- and post-implantation vocalization frequency, thereby confirming the act of CI fitting as a critical linguistic landmark for HI infants, differentiating their vocal performance progression from poor towards one resembling that of their NH peers.

According to Fagan,[4] CI benefits HI infants in two ways; by providing auditory access (i) to their own voice (self-generated vocalizations) and (ii) to the vocalizations of their caregivers. The former reinforce the latter, by attracting attention from their environment, hence enabling the attribution of meaning to the sounds produces, accelerating closure of the pre-existing developmental gap between HI and NH peers.[35]

Figure 1 traces volubility as a developmental milestone in infancy, leading to future academic achievement. Studying volubility through protophone production provides an evidenced-based practice for the acquisition of canonical syllable control which is an essential linguistic component for higher expressive vocabulary skills and low reading levels can be explained by poor expressive vocabulary. In contrast, poor results lead to deviant speech production and later language disorders with latter low reading levels and overall academic failure.

Collectively, these studies suggest that volubility can serve as a developmental point of reference during infancy, which ENT teams can use to assess the success of a CI procedure, and to predict linguistic development thereafter.

Conclusion

All data and recent studies presented above emphasized the critical role that auditory feedback has for triggering early vocalization frequency or volubility. This role has been assigned to cochlear implants and the group of young recipients is the focus of this review. Vocalization frequency has been found below than hearing infants during pre-implantation period, while the access to cochlear implants was especially beneficiary to quantity of vocalizations. The post-implantation results revealed comparable speech production skills to hearing peers. This finding has been recorded within 4 months on average of CI activation which is very important for the immediate start of oral habilitation programs implemented by speech pathologists.

The present paper contributes towards a growing body of literature which affirms the plausibility of sound production quantification methods (volubility) as prognostic markers of speech-language development, by setting the focus on CI infants and their post-operative linguistic success. The validity of volubility as an index of CI performance outcomes and, ultimately, as a prodromal marker of adult/mature expressive language production, is endorsed.

Furthermore, it describes a new protocol for the assessment and optimization of CI success, by clarifying post-implementation goal-setting and efficiency criteria, offering a renewed outlook on monitoring the progress of communication and continuity of care, and ensuring that the infant-recipient gets the most out of the CI during the recovery phase and throughout the early CI experience.

References

1. Morgan L, Wren YE. A systematic review of the literature on early vocalizations and babbling patterns in young children. Commun Disord Q. 2018.
2. Clement CJ. Development of vocalizations in deaf and normally hearing infants. Amsterdam: Netherlands Graduate School of Linguistics; 2004.
3. Ertmer DJ, Jung J. Prelinguistic vocal development in young cochlear implant recipients and typically developing infants: Year 1 of robust hearing experience. J Deaf Stud Deaf Educ. 2011;17:116–32.
4. Fagan MK. Frequency of vocalization before and after cochlear implantation: Dynamic effect of auditory feedback on infant behavior. J Exp Child Psychol [Internet]. 2014;126:328–38. Available from: http://dx.doi.org/10.1016/j.jecp.2014.05.005
5. Oller DK, Griebel U, Warlaumont AS. Vocal development as a guide to modeling the evolution of language face-to-face. Top Cogn Sci. 2016;8:382–92.

6. Belardi K, Watson LR, Faldowski RA, et al. A retrospective video analysis of canonical babbling and volubility in infants with Fragile X syndrome at 9 - 12 months of age. J Autism Dev Disord. 2017;47(4):1193–206.
7. Iyer SN, Denson H, Lazar N, et al. Volubility of the human infant: Effects of parental interaction (or lack of it). Clin Linguist Phonetics. 2016;30(6):470–88.
8. Nathani S, Oller KD, Neal AR. On the robustness of vocal development: An examination of infants with moderate-to-severe hearing loss and additional risk factors. J Speech, Lang Hear Res. 2007;50:1425–44.
9. D’Souza D, D’Souza H, Karmiloff-Smith A. Precursors to language development in typically and atypically developing infants and toddlers : the importance of embracing complexity. J Child Lang. 2017;44(3):591–627.
10. Franklin B, Warlaumont AS, Messinger D, et al. Effects of parental interaction on infant vocalization rate, variability and vocal type. Lang Learn Dev. 2013;10(3):279–96.
11. Overby M, Caspari SS. Volubility, consonant, and syllable characteristics in infants and toddlers later diagnosed with childhood apraxia of speech: A pilot study. J Commun Disord. 2015;55:44–62.
12. Swanson MR, Shen MD, Wolff JJ, et al. Naturalistic language recordings reveal “hypervocal” infants at high familial risk for autism. Child Dev. 2018;89(2):e60–73.
13. Eilers RE, Oller DK, Levine S, et al. The role of prematurity and socioeconomic status in the onset of canonical babbling in infants. Infant Behav Dev. 1993;16(3):297–315.
14. Smith BL, Oller DK. A comparative study of pre-meaningful vocalizations produced by normally developing and Down’s syndrome infants. J Speech H. 1981;46:46–51.
15. Patten E, Belardi K, Baranek GT, et al. Vocal patterns in infants with Autism Spectrum Disorder: Canonical babbling status and vocalization frequency. J Autism Dev Disord. 2014;44(10):2413–28.
16. Chapman KL, Hardin-jones M, Schulte J, et al. Vocal development of 9-month-old babies with cleft palate. J Speech, Lang Hear Res. 2001;44:1268–83.
17. Ertmer DJ, Young NM, Nathani S. Profiles of vocal development in young cochlear implant recipients. J Speech, Lang Hear Res. 2007;50:393–408.
18. Nathani S. Oller DK. Prelinguistic vocal development in infants with typical hearing and infants with severe-to-profound hearing loss. Volta Rev. 2008;108(2):115–38.
19. Oller DK. The emergence of the speech capacity. Mahwah, NJ: Lawrence Erlbaum; 2000.
20. Oller DK, Eilers RE. The role of audition in infant babbling. Child Dev. 1988;59(2):441–9.
21. Boersma P, Weenink D. Praat: doing phonetics by computer [Internet]. 2010. Available from: http://www.fon.hum.uva.nl/praat/download_win.html
22. Stoel-Gammon C. Prespeech and early speech development of two late talkers. First Lang. 1989;9:207–224.
23. Moeller MP, Hoover B, Putman C, et al. Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I - Phonetic development. Ear Hear. 2007;28(5):605–27.
24. Lenneberg EH, Rebelsky G, Nichols IA. The vocalizations of infants born to deaf and hearing parents. Vita Humana (Human Dev). 1965;8:23–37.
25. Maskarinec AS, Cairns GF, Butterfield EC, et al. Longitudinal observations of individual infant’s vocalizations. J Speech Hear Disord. 1981;46:267–73.
26. Kral A, Sharma A. Developmental neuroplasticity after cochlear implantation. Trends Neurosci [Internet]. 2012;35(2):111–22. Available from: http://dx.doi.org/10.1016/j.tins.2011.09.004
27. Luo J, Bai X, Zhang F, et al. Prevalence of mutations in deafness-causing genes in cochlear implanted patients with profound nonsyndromic sensorineural hearing loss in Shandong Province, China. Ann Hum Genet. 2017;81(6):258–66.
28. Kral A, O’Donoghue GM. Profound deafness in childhood. N Engl J Med. 2010;363(15):1438–50.
29. Gürtler N, Gysin C, Schmid N, et al. Bilateral congenital deafness: What investigations should be performed? A qualitative descriptive review. Swiss Med Wkly. 2017;147:1–12.
30. Dorman MF, Wilson BS. The design and function of cochlear implants. Am Sci. 2004;92:436–45.
31. Dettman SJ, Dowell RC, Choo D, et al. Long-term communication outcomes for children receiving cochlear implants younger than 12 months: A multicenter study. Otol Neurol. 2016;37:e82–95.
32. von Hapsburg D, Davis BL. Auditory sensitivity and the prelinguistic vocalizations of early-amplified infants. J Speech, Lang Hear Res. 2006;49:809–23.
33. Koopmans-van Beinum FJ, Clement CJ, et al. Babbling and the lack of auditory speech perception: a matter of coordination? Dev Sci. 2001;4(1):61–70.
34. Warner-Czyz AD, Davis BL, Morrison HM. Production accuracy in a young cochlear implant recipient. Volta Rev. 2003;105(2):151–73.
35. Smith LB. Movement matters: The contributions of Esther Thelen. Biol Theory. 2006;1(1):87–9.

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Figure 1: Infant vocalizations and their relationship to linguistic development

Note *canonical aspects of early vocalization; †vocabulary growth, morphology and syntax acquisition, mean length of utterance, narrative