Journal of Communication Disorders 54 (2015) 32–42

Contents lists available at ScienceDirect

Journal of Communication Disorders

# Reliance on auditory feedback in children with childhood apraxia of speech

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ARTICLE INFO

*Article history:*
Received 6 February 2014
Received in revised form 7 November 2014
Accepted 8 January 2015
Available online 19 January 2015

*Keywords:*
Childhood apraxia of speech
Feedforward programs
Auditory feedback
Voice onset time
Vowels
Acoustical analyses

ABSTRACT

Children with childhood apraxia of speech (CAS) have been hypothesized to continuously monitor their speech through auditory feedback to minimize speech errors. We used an auditory masking paradigm to determine the effect of attenuating auditory feedback on speech in 30 children: 9 with CAS, 10 with speech delay, and 11 with typical development. The masking only affected the speech of children with CAS as measured by voice onset time and vowel space area. These findings provide preliminary support for greater reliance on auditory feedback among children with CAS.

**Learning outcomes**: Readers of this article should be able to (i) describe the motivation for investigating the role of auditory feedback in children with CAS; (ii) report the effects of feedback attenuation on speech production in children with CAS, speech delay, and typical development, and (iii) understand how the current findings may support a feedforward program deficit in children with CAS.

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## 1. Introduction

Childhood apraxia of speech is a pediatric speech disorder characterized by a broad range of features that includes inconsistent speech sound production (ASHA, 2007; Iuzzini, 2012), voicing errors (Iuzzini, 2012; Lewis, Freebairn, Hansen, Iyengar, & Taylor, 2004), disrupted prosody (Shriberg, Aram, & Kwiatkowski, 1997), and disrupted coarticulatory transitions (Maassen, Nijland, & Van Der Meulen, 2001; Nijland et al., 2002). The neurologic basis of these speech difficulties is unknown, but a recent proposal implicates an impairment of the feedforward motor control system (Terband & Maassen, 2010). Feedforward programs putatively contain articulatory motor commands for acoustic (Guenther, 2006) or vocal tract goals (Browman & Goldstein, 1989), and it is posited that weak feedforward programs result in the imprecise and inconsistent speech errors that are associated with CAS (Terband & Maassen, 2010).

Children's dependence on sensory feedback is purported to decline as they master motor skills (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991; Guenther, 2006; Haas, Diener, Rapp, & Dichgans, 1989). During the early stages of speech development, for example, auditory and somatosensory feedback is used to establish robust neural programs that encode the acoustic consequences of articulator movements (Guenther, 2006). Computational models of speech have simulated how that talkers refine these feedforward programs over time by resolving discrepancies between intended speech goals and actual speech output (Guenther, 2006; Haruno, Wolpert, & Kawato, 2001; Houde & Nagarajan, 2011). Once

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http://dx.doi.org/10.1016/j.jcomdis.2015.01.002
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these feedforward programs are established, sensory feedback is used only intermittently for (1) making online corrections in speech and (2) adjusting articulator movements in response to changing speaking conditions (Houde & Jordan, 1998; Jones & Munhall, 2000; Lane & Tranel, 1971). This shift from feedback dependency to feedforward-dominant control presumably permits talkers to efficiently produce speech at an average rapid rate of 160 words per minute (Picheny, Durlach, & Braida, 1986).

In contrast to typically developing children, the reliance on auditory feedback control may persist into later stages of development in children with CAS, a pattern that could be an adaptive response to weak feedforward programs. Terband and Maassen (2009, 2010) proposed that, in children with CAS, the formation of robust feedforward programs may be hindered by excessive neural noise or by reduced oral somatosensation. Poorly formed feedforward programs would provide a parsimonious explanation for many features that are associated with CAS such as speech sound inconsistency, and vowel and voicing distortions (ASHA, 2007). The poor treatment outcomes and limited generalization exhibited by children with CAS (e.g., Forrest, 2003) could also be explained by a difficulty establishing robust feedforward programs. In contrast, it is unlikely that a feedforward control deficit would underlie speech impairment in children with speech delay (SD), whose errors are characterized by consistent substitutions and the use of phonological processes, and who typically show evidence of learning and generalization following treatment (e.g., Gierut, 1998).

In the absence of robust feedforward programs, children with CAS may adapt by continuously monitoring their speech to preempt, minimize, or repair speech errors (Terband, Maassen, Guenther, & Brumberg, 2009; Terband & Maassen, 2010). The continuous reliance on auditory feedback is, however, inefficient and is predicted to have several negative consequences on speech. For example, the online processing of one's speech is purported to take up to 100 ms (Houde & Nagarajan, 2011), which is probably too long to allow for rapid and accurate speech. Moreover, feedback has been evoked as a causal mechanism for stuttering. Disfluencies have been attributed to an over-reliance on feedback among stutterers, and interventions that delay or attenuate feedback often increase fluency in this population (e.g., Van Borsel, Reunes, & Van den Bergh, 2003).

Lastly, Terband, van Brenk, & van Doornik-van der Zee (2014) investigated effects of real-time formant-frequency perturbation in 17 typically developing children, and 11 children with speech sound disorders including 5 with CAS. Previous studies showed that most talkers produce a compensatory adaptation to the perturbation (e.g., Cai, Ghosh, Gunether, & Perkell, 2010; Houde & Jordan, 2002). Terband et al. found that typically developing controls tended to compensate for the perturbation where children with speech sound disorders tended to follow and exaggerate the frequency shift. These authors suggested that children with speech sound disorders perceived the formant-shift but did not compensate appropriately, which they attributed to impaired feedforward and feedback models.

In this study, we test the integrity of speech feedforward programs in children with CAS using an auditory masking paradigm. In this paradigm, calibrated levels of noise are used to disrupt the talkers' access to auditory feedback. It is hypothesized that well-established programs are relatively resistant to the perturbing effects of masking noise whereas weak programs will become disrupted as indicated by acoustic changes to speech. To test the weak feedforward program hypothesis, we addressed the following experimental questions: (1) Do school-aged children with CAS evidence comparable VOTs, vowel durations, and vowel space areas relative to those with SD and typical development (TD) in unmasked and masked speech, and (2) Do children with CAS, SD, and TD evidence an effect of noise-masking on VOT, vowel durations, vowel space areas, and speech intensity? Whereas previous research (Iuzzini & Forrest, 2008; Iuzzini, 2012) showed that preschool-aged children with CAS evidenced shorter VOTs and smaller vowel space areas relative to those with TD and SD, it is unknown whether school-aged children with CAS will also perform differently than their peers on these measures. It is posited that children with SD and TD will have intact feedforward control systems and will show an adaptive response to noise masking. In contrast, we hypothesize that children with CAS have a feedforward control deficit and therefore, will not adapt to noise masking.

VOT is a speech target of interest because Iuzzini (2012) showed that children with CAS are delayed in acquisition of the voicing contrast. Specifically, compared to children with SD, children with CAS produced shorter VOTs for voiceless plosives (e.g., /t/), which often overlapped with the VOTs for voiced cognates (e.g., /d/). The overlapping voicing categories may explain why children with CAS are often perceived to produce voicing errors or voicing distortions (Lewis et al., 2004). In contrast, typically developing children produce adult-like voicing categories by 3 years of age (Macken & Barton, 1980). Based on these findings, we predicted that school-aged children with CAS would have a vulnerability for this contrast, and therefore might evidence a regression to shorter VOTs in the presence of a perturbation—in this case, masking.

Examining masking effects on vowel production was also of interest because children with CAS have difficulty producing clear vowel contrasts (Lewis et al., 2004), which may reflect weak feedforward programs for these phonemes. Previous research by Iuzzini and Forrest (2008) showed that preschool-aged children with CAS evidenced smaller vowel space area relative to age-matched children with SD and TD, consistent with the percept of vowel neutralization for children with CAS. We posit that children with CAS will evidence smaller vowel space areas relative to those with SD and TD, and that these differences will be larger in the masked speech condition.

The current research also tests the effect of masking on vowel durations and speech intensity of vowels. Previous research showed that masking can induce an increase in speech intensity, which can in-turn lengthen vowel durations and alter vowel formant frequencies (Maas, Mailend, & Guenther, 2013; Rogers, Eyraud, Strand, & Storkel, 1996; Van Summers, Pisoni, Bernacki, Pedlow, & Stokes, 1988). This phenomenon, known as the Lombard effect, is considered an adaptive response for maximizing speech intelligibility in the presence of noise. We hypothesize that children with CAS may have difficulty making adaptive changes to speech in response to masking due to impaired control over segmental and suprasegmental aspects of speech.

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