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Research report

Stuttering adults' lack of pre-speech auditory modulation normalizes when speaking with delayed auditory feedback

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Auditory modulation during speech movement planning is limited in adults who stutter (AWS), but the functional relevance of the phenomenon itself remains unknown. We investigated for AWS and adults who do not stutter (AWNS) (a) a potential relationship between pre-speech auditory modulation and auditory feedback contributions to speech motor learning and (b) the effect on pre-speech auditory modulation of real-time versus delayed auditory feedback. Experiment I used a sensorimotor adaptation paradigm to estimate auditory-motor speech learning. Using acoustic speech recordings, we quantified subjects' formant frequency adjustments across trials when continually exposed to formant-shifted auditory feedback. In Experiment II, we used electroencephalography to determine the same subjects' extent of pre-speech auditory modulation (reductions in auditory evoked potential N1 amplitude) when probe tones were delivered prior to speaking versus not speaking. To manipulate subjects' ability to monitor real-time feedback, we included speaking conditions with non-altered auditory feedback (NAF) and delayed auditory feedback (DAF). Experiment I showed that auditory-motor learning was limited for AWS versus AWNS, and the extent of learning was negatively correlated with stuttering frequency. Experiment II yielded several key findings: (a) our prior finding of limited pre-speech auditory modulation in AWS was replicated; (b) DAF caused a decrease in auditory modulation for most AWNS but an increase for most AWS; and (c) for AWS, the amount of auditory modulation when speaking with DAF was positively correlated with stuttering frequency. Lastly, AWNS showed no correlation between pre-speech auditory modulation (Experiment II) and extent of auditory-motor learning (Experiment I) whereas AWS showed a *negative* correlation between these measures. Thus, findings suggest that AWS show deficits in both pre-speech auditory modulation and auditory-motor learning; however, limited pre-speech modulation is not directly related to limited auditory-motor adaptation; and in AWS, DAF paradoxically tends to normalize their otherwise limited pre-speech auditory modulation.

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1. Introduction

Structural neuroimaging studies of stuttering have revealed abnormalities in various fronto-parieto-temporal pathways (Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Chang, Horwitz, Ostuni, Reynolds, & Ludlow, 2011; Cykowski, Fox, Ingham, Ingham, & Robin, 2010; Kronfeld-Duenias, Amir, Ezrati-Vinacour, Civier, & Ben-Shachar, 2016; Sommer, Koch, Paulus, Weiller, & Buchel, 2002; Watkins, Smith, Davis, & Howell, 2008). Although the exact assignment of functional processes to the affected tracts is still open to debate (see for example Kronfeld-Duenias, Amir, Ezrati-Vinacour, Civier, & Ben-Shachar, 2017; Neef, Anwander, & Friederici, 2017), it appears that at least some of the pathways may impair the connectivity between speech (pre-)motor regions and auditory regions. This interpretation is consistent with behavioral studies demonstrating that stuttering individuals, as compared with nonstuttering individuals, show reduced compensatory motor responses to unexpected auditory feedback perturbations (Cai, Beal, Ghosh, Guenther, & Perkell, 2014, 2012; Daliri, Wieland, Cai, Guenther, & Chang, 2017; Loucks, Chon, & Han, 2012). Together, these lines of neuroimaging and behavioral research provide substantial support for the idea that stuttering is associated with deficits in the integration of auditory and motor information for speech production.

One aspect of sensorimotor integration involves predicting the sensory consequences of planned control signals (Kawato, 1999; Shadmehr, Smith, & Krakauer, 2010; Wolpert, Diedrichsen, & Flanagan, 2011; Wolpert, Miall, & Kawato, 1998). Predictions are used to optimize motor commands and to prepare task-relevant sensory systems for their subsequent roles in processing the sensory outcomes of those motor commands. In this context, we have recently investigated in adults who stutter (AWS) and adults who do not stutter (AWNS) a modulation of the auditory system that occurs during speech movement planning prior to the initiation of muscle activity (Daliri & Max, 2015b). We recorded long-latency auditory evoked potentials (LLAEPs) in response to probe tones delivered during the speech movement planning phase as compared with no-speaking control conditions. Nonstuttering speakers showed a clear modulation of the auditory system (i.e., reduced amplitude of the N1 component in the LLAEP) during speech movement planning whereas stuttering speakers showed limited or no modulation of their auditory system (Daliri & Max, 2015b). These findings (later replicated, extended, and further interpreted in (Daliri & Max, 2015a) strongly suggest that stuttering is associated with deficits in using sensory prediction mechanisms to prime the auditory system for its role in processing upcoming auditory feedback. In other words, it is possible that neural activity in stuttering speakers' pre-motor and/or motor systems involved in speech movement planning does not result in a correct, or complete, pre-setting of the auditory system for feedback monitoring once execution actually starts. As we have hypothesized elsewhere (Daliri & Max, 2015b; Max, 2004; but see also McClean, 1996; Zimmermann, 1980 for related hypotheses), an insufficient pre-movement priming of sensory systems (to ensure appropriate responses to self-generated sensory input) may trigger interfering motor responses that disrupt, rather than correctly update, ongoing movements.

However, the functional relevance of the pre-speech auditory modulation phenomenon itself is unknown at this time. It is particularly noteworthy that a reduction in the amplitude of a given LLAEP component (i.e., the scalp-recorded sum of electrical potentials from multiple intracranial sources and processes) does not necessarily indicate an actual suppression of the cognitive processes of interest (see, among others, Luck, 2014). Hence, it remains to be determined whether the neurophysiological processes underlying pre-speech auditory modulation serve to merely implement a *suppression* of auditory input (leading to a reduction in this sensory channel's contributions to error correction) versus a more complex *optimization* of auditory processing (leading to precise contributions to error correction based on, for example, an adjustment in the excitation-suppression balance of auditory neurons with specific tuning characteristics—see Eliades & Wang, 2017). This is an absolutely critical question to start addressing if we are to understand if and how stuttering individuals' lack of pre-speech auditory modulation relates to their demonstrated deficiencies in using the subsequent auditory feedback signal during speech production (Cai et al., 2014, 2012; Daliri et al., 2017; Loucks et al., 2012).

Thus, one purpose of the present study was to examine the relationship between individuals' pre-speech auditory modulation and auditory feedback contributions to auditory-motor speech motor learning. In a first experiment, we used a sensorimotor adaptation paradigm to quantify, on an individual basis, the contributions of auditory feedback to speech motor learning. In this paradigm, the speakers' auditory feedback was digitally altered in real time (i.e., the formant frequencies in the heard speech signal were shifted up during all trials in the perturbation phase of the experiment) while they produced monosyllabic words. We used the extent of auditory-motor adaptation (i.e., the speakers' lowering of formant frequencies in their produced speech) as an estimate of learning. In a second experiment, we then recorded the same speakers' LLAEPs in response to probe tones presented during speech movement planning in three conditions: (a) a speaking condition with typical auditory feedback (non-altered auditory feedback, NAF), (b) a speaking condition in which the usefulness of the auditory feedback signal for online monitoring was experimentally degraded (delayed auditory feedback, DAF), and (c) a no-speaking control condition (silent reading). DAF was included to provide additional insights into the possible relationship between pre-speech auditory modulation and contributions of the auditory feedback signal in speech production: we hypothesized that if this type of auditory modulation serves to optimize auditory processing for feedback monitoring, then reducing the usefulness of auditory feedback would lead to a reduction in pre-speech auditory modulation.

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