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Overreliance on auditory feedback may lead to sound/syllable repetitions: Simulations of stuttering and fluency-inducing conditions with a neural model of speech production

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Abstract

This paper investigates the hypothesis that stuttering may result in part from impaired readout of feedforward control of speech, which forces persons who stutter (PWS) to produce speech with a motor strategy that is weighted too much toward auditory feedback control. Over-reliance on feedback control leads to production errors which if they grow large enough, can cause the motor system to "reset" and repeat the current syllable. This hypothesis is investigated using computer simulations of a "neurally impaired" version of the DIVA model, a neural network model of speech acquisition and production. The model's outputs are compared to published acoustic data from PWS' fluent speech, and to combined acoustic and articulatory movement data collected from the dysfluent speech of one PWS. The simulations mimic the errors observed in the PWS subject's speech, as well as the repairs of these errors. Additional simulations were able to account for enhancements of fluency gained by slowed/prolonged speech and masking noise. Together these results support the hypothesis that many dysfluencies in stuttering are due to a bias away from feedforward control and toward feedback control.

Educational objectives: The reader will be able to (a) describe the contribution of auditory feedback control and feedforward control to normal and stuttered speech production, (b) summarize the neural modeling approach to speech production and its application to stuttering, and (c) explain how the DIVA model accounts for enhancements of fluency gained by slowed/prolonged speech and masking noise.

Keywords: Stuttering; Auditory feedback; Fluency enhancement; Error monitoring

1. Introduction

In his classic book "The Nature of Stuttering," Van Riper (1982) describes a person that stopped stuttering "after an incident in which he became completely deafened. The cessation of stuttering occurred within three hours of the trauma and shortly after he began to speak" (p. 383). What is the relationship between sensory feedback (in this case, hearing

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oneself speak) and stuttering? Although many investigations have attempted to account for the effect altered sensory feedback has in enhancing fluency (e.g., Fairbanks, 1954; Hutchinson & Ringel, 1975; Loucks & De Nil, 2006a; Mysak, 1960; Neilson & Neilson, 1987, 1991; Webster & Lubker, 1968; Wingate, 1970), no account has received overwhelming support. The obstacle may lie in the classic experimental devices typically used to study stuttering rather than the theoretical models themselves.

Most researchers have used psychophysical experiments to investigate sensory feedback in speech, but the results are often difficult to interpret because several feedback channels are simultaneously active during a typical experiment. In addition, experimental blockage of proprioceptive feedback channels is unfeasible (Scott & Ringel, 1971, p. 806), and auditory blockage is usually incomplete (e.g., Adams & Moore, 1972; but cf. Namasivayam, van Lieshout, McIlroy, & De Nil, 2009). Alternatively, sensory feedback can be studied by using computational models of speech production where feedback channels can be systematically blocked or altered.

In this paper we use the DIVA model (see Guenther, Ghosh, & Tourville, 2006), which is a biologically plausible model of speech production that mimics the computational and time constraints of the central nervous system (CNS), to test our hypothesis regarding the involvement of sensory feedback in stuttering. The DIVA model differs from other computational models applied to stuttering (e.g., Kalveram, 1991, 1993; Neilson & Neilson, 1987; Toyomura & Omori, 2004) in its ability to simulate the articulatory kinematic and acoustic features of both normal and disordered speech (for DIVA simulations of normal speech see Guenther, 1995, 2006; Guenther et al., 2006; Guenther, Hampson, & Johnson, 1998; Nieto-Castanon, Guenther, Perkell, & Curtin, 2005; for simulations of childhood apraxia of speech, or CAS, see Terband & Maassen, 2010; Terband, Maassen, Guenther, & Brumberg, 2009), which makes it possible to compare the simulations to a much larger set of data than permitted by other models.

Many authors have suggested that stuttering may be due in part or whole to an aberrant sensory feedback system. Some have hypothesized that persons who stutter (PWS) differ from those who do not stutter (PNS) by relying too heavily on sensory feedback (Hutchinson & Ringel, 1975; Tourville, Reilly, & Guenther, 2008, p. 1441; van Lieshout, Peters, Starkweather, & Hulstijn, 1993), while others have claimed that PWS actually benefit from reliance on sensory feedback (Max, 2004, p. 375; Max, Guenther, Gracco, Ghosh, & Wallace, 2004, p. 113; Namasivayam, van Lieshout, & De Nil, 2008; van Lieshout, Hulstijn, & Peters, 1996a, 1996b; Zebrowski, Moon, & Robin, 1997). Our hypothesis is that due to an impaired feedforward (open-loop) control system,[1] PWS rely more heavily on a feedback-based (closed-loop) motor control strategy (cf. De Nil, Kroll, & Houle, 2001; Jäncke, 1991; Kalveram, 1991; Kalveram & Jäncke, 1989; Lane & Tranel, 1971; Stromsta, 1972, 1986, p. 204; Toyomura & Omori, 2004; Van Riper, 1982, pp. 387, 442; Zimmermann, 1980c). Such an impairment in the feedforward control system is compatible with the general notion of stuttering arising out of diminished motor skill (Peters, Hulstijn, & van Lieshout, 2000; van Lieshout, Hulstijn, & Peters, 2004) because motor skill, in part, involves a transition from feedback to feedforward control (see Schmidt & Lee, 2005).

The hypothesized impairment in feedforward control and the resulting over-reliance on feedback control increase the frequency of production errors. The feedforward commands – stored detailed instructions of how to move the articulators – are read out directly from memory, which in our model occurs via projections from the premotor to the motor cortex. Feedback control, on the other hand, requires the detection and correction of production errors (e.g., incorrect tongue position or unexpected formant pattern). Since a feedback-based strategy is relatively slow to detect and correct errors (e.g., Guenther et al., 2006), it is our contention that over-reliance on feedback control leads to error accumulation, and eventually, to a motor "reset" in which the system attempts to repair the error by restarting the current syllable. Such a reset would constitute a sound/syllable repetition (or simply *repetition*), a term we use to refer to any audible repetition of a syllable or part of it, without regard to phonemic boundaries, i.e., the cut-off can be within or between phonemes (cf. Conture, 2001, p. 6; Wingate, 1964). We also contend that an impaired feedforward control system may lead to other common types of dysfluency (Civier, 2010; Civier, Bullock, Max, & Guenther, 2009). However, to limit the scope of the paper, we will focus solely on sound/syllable repetitions (for further discussion see Section 7.2).

[1] The current investigation does not speak directly to the cause of the feedforward impairment (possibly, a dysfunction of the basal ganglia, see Alm, 2004, 2005, p. 30; Smits-Bandstra & De Nil, 2007) or to its exact nature (Civier, 2010; Civier et al., 2009); instead the focus is on the consequences of biasing away from feedforward control and toward feedback control.