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# EFFECTS OF DIGITAL VIBROTACTILE SPEECH FEEDBACK ON OVERT STUTTERING FREQUENCY[1]

GREGORY J. SNYDER

*The Laboratory for Stuttering Research*
*Department of Communication Sciences & Disorders*
*University of Mississippi*

PAUL BLANCHET

*Department of Speech Pathology and Audiology*
*State University of New York at Fredonia*

DWIGHT WADDELL

*Department of Health, Exercise Science & Recreation Management*
*University of Mississippi*

LENNETTE J. IVY

*Department of Communication Sciences & Disorders*
*University of Mississippi*

*Summary.*—Fluency-enhancing speech feedback, originating from internally or externally generated sources via auditory or visual sensory modalities is not restricted to a specific sensory modality or signal origination. Research suggests that externally generated digital vibrotactile speech feedback serves as an effective fluency enhancer. The present purpose was to test the fluency-enhancing effects of self-generated digital vibrotactile speech feedback on stuttering frequency. Adults who stutter read passages aloud over the telephone, both with and without digital vibrotactile speech feedback. Digital vibrotactile speech feedback was operationally defined as feeling the vibrations of the thyroid cartilage with the thumb and index finger while speaking. Analysis indicated that self-generated digital vibrotactile speech feedback reduced overt stuttering frequency by an average of 72%. As the specific neural mechanisms associated with stuttering and fluency enhancement from tactile speech feedback remain unknown, theoretical implications and clinical applications were discussed.

Developmental stuttering is generally considered a speech disorder usually surfacing between 2 and 4 years of age (Starkweather, 1987; Bloodstein & Bernstein-Ratner, 2008) and is characterized by part- and whole-word repetitions, prolongations, and inaudible postural fixations (Guitar, 2006; Bloodstein & Bernstien-Ratner, 2008). While the nature and etiology of stuttering remains unknown, substantial evidence suggests that persistent developmental stuttering has a neurological genesis (Wu, Maguire, Riley, Fallon, LaCasse, Chin, Klein, Tang, & Caldwell, 1995; Ambrose, Cox, & Yairi, 1997; Braun, Varga, Stager, Schulz, Selbie, Maisog, Carson, & Ludlow, 1997; Fox, Ingham, Ingham, Zamarripa, Xiong, & Lancaster, 2000; Salmelin, Schnitzler, Schmitz, & Freund, 2000) and is documented as projecting a distinct neurophysiological signature, including overactivation of the right hemi-

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[1] Address correspondence to Greg Snyder, Ph.D., The Laboratory for Stuttering Research, Department of Communication Sciences & Disorders, University of Mississippi, 310 George Hall, University, MS 38677 or e-mail (GSnyder@OleMiss.edu).

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sphere during speech and language production (Fox, Ingham, Ingham, Hirsch, Downs, Martin, Jerabek, Glass, & Lancaster, 1996; Fox, *et al.*, 2000), decreased glucose metabolic activity in the left frontal and limbic regions (Wu, *et al.*, 1995), increased dopaminergic activity in the left frontal and limbic regions (Wu, Maguire, Riley, Lee, Keator, Tang, Fallon, & Najafi, 1997), overactivation of the motor systems in both the cerebrum and cerebellum (Fox, *et al.*, 2000), underactivation of the temporal cortices (Salmelin, Schnitzler, Schmitz, Jancke, Witte, & Freund, 1998), and a reversed speech-related sequential activation pattern between the left inferior frontal cortex and the dorsal premotor cortices (Salmelin, *et al.*, 2000) during speech production. Despite these data, researchers remain unable to agree upon any single scientific theory accounting for stuttering. As a result, there are numerous competing theories on the nature of stuttering and fluency enhancement (Bloodstein & Bernstein-Ratner, 2008).

Observable stuttering behaviors are dramatically, albeit transiently, reduced by as much as 80 to 100% with the use of specified forms of speech feedback (e.g., masking noise, delayed auditory feedback, frequency-altered feedback), many of which employ the choral speech phenomenon (Andrews, Howie, Dozsa, & Guitar, 1982; Hargrave, Kalinowski, Stuart, Armson, & Jones, 1994). Moreover, exposure to auditory choral speech during speech production is associated with many functional corrections (i.e., relative normalization) to the distinctly deviant neurophysiological activation patterns associated with stuttering (Wu, *et al.*, 1997; Fox, *et al.*, 2000; Salmelin, *et al.*, 2000) to resemble better the speech-related neurological processing patterns of fluent speech produced by a normally fluent speaker. Researchers have suggested that the most efficient form of induced fluency enhancement utilizes a "second speech signal" (Cherry & Sayers, 1956; Kalinowski, Stuart, Rastatter, Snyder, & Dayalu, 2000), which is a speech signal presented concurrently with the speaker's primary speech signal, and contains speech gestures similar to those used in primary speech.

For optimal fluency enhancement, a second speech signal should be presented in parallel with the speaker's primary speech signal, so both the speaker and the speech feedback are in choral unison (Andrews, *et al.*, 1982). For example, this effect can be achieved when a second speech signal originates from another speaker (e.g., choral speech) or from electronic alterations of the speaker's (audible) primary speech signal, which are then reintroduced to the speaker's auditory system by way of headphones (e.g., delayed auditory feedback or frequency-shifted feedback, also known as frequency-altered feedback). Both auditory and visual second speech signals have been observed to enhance fluency in people who stutter (Andrews, Craig, Feyer, Hoddinott, Howie, & Neilson, 1983; Kalinowski, *et al.*, 2000; Snyder, Strauss Hough, Blanchet, Ivy, & Waddell, 2008).

Moreover, research suggests that externally generated digital vibrotactile speech feedback (sensed by the speaker's middle fingers) also enhances fluency in those who stutter (Kuniszyk-Jozkowiak & Adamczyk, 1989; Kuniszyk-Jozkowiak, Smolka, & Adamczyk, 1996, 1997). The methodology employed by these studies measured the effects of synchronous, echo (i.e., delayed), and reverberated (i.e., prolonged) visual, auditory or tactile speech feedback on stuttering frequency and (speech) articulatory rate. Tactile feedback was presented at 230 Hz, with a 0.05-mm maximum amplitude of oscillation, to the participants' middle fingers. Data collected from these studies suggest that externally generated digital vibrotactile speech feedback served as an effective fluency enhancer regardless of experimental presentation, i.e., synchronous, echo, or reverberation (Kuniszyk-Jozkowiak & Adamczyk, 1989; Kuniszyk-Jozkowiak, *et al.*, 1996, 1997).

Until relatively recently, it was generally assumed that fluency enhancement via a second speech signal was a function of the auditory sensory modality and, therefore, largely interpreted as an auditory phenomenon (Starkweather, 1987; Kalinowski, *et al.*, 2000; Bloodstein & Bernstein-Ratner, 2008). This interpretation may have led researchers to associate the etiology of stuttering with functional errors in auditory processing (Postma & Kolk, 1992a, 1992b) or to associate the second speech signal with the masking effect (Andrews, *et al.*, 1983). However, relatively recent research has documented fluency enhancement in those who stutter via an externally generated visual second speech signal (in the form of visual choral speech), thereby implicating fluency enhancement via a second speech signal as a multisensory, rather than solely an auditory, phenomenon (Kalinowski, *et al.*, 2000). This notion was further tested and supported with evidence that synchronous and asynchronous self-generated visual second speech signals also significantly enhance the fluent speech of those who stutter (e.g., the use of a mirror or delayed visual feedback; Snyder, *et al.*, 2008). These data led to the hypothesis that synchronous self-generated digital vibrotactile speech feedback would likewise enhance fluency in those who stutter. Therefore, the purpose of the present study was to test the effects of self-generated vibrotactile feedback on stuttering frequency of adults who stutter.

## METHOD

### *Participants*

Eight adults who stutter (2 women, 6 men; age range = 22–55 years; *M* age = 39.6, *SD* = 11.8; median = 39.0) participated. Participants reported no other diagnosed medical conditions, such as speech, language, hearing, neurological or attentional disorders; only self-reported right-handed people who stutter were included. All participants were college graduates or currently registered as full-time college students. Although all had a history of speech therapy, they also reported therapeutic relapse. Only one participant was currently enrolled in stuttering therapy.

### *Design and Procedure*

Participants read passages aloud over the telephone in two different speaking conditions. Reading passages were adopted from previous research (see Kalinowski, *et al.*, 2000). In the control condition, participants were instructed to read a passage aloud without using any treatment techniques or controls which might alter their speech fluency. In the experimental condition, participants were asked to read a passage aloud while feeling the thyroid cartilage vibrate (secondary to phonation) with their thumb and index finger. Specifically, participants were instructed to extend the index finger at a 90° angle from the thumb and gently to place the distal end of the proximal phalanx of the index finger on the thyroid notch, thereby allowing the thumb and the side of the index finger to sense vibrotactile feedback from the thyroid cartilage during phonation. Participants were specifically instructed to apply as little (if any) pressure as possible to the thyroid cartilage while still sensing its vibration. Participants were given the choice of using either the right or left hand during the experimental speaking condition. The two reading passages and the speaking conditions were counterbalanced using a Latin square design, thereby controlling order effects.

All telephone calls were made using Skype (Version 3.6.0.216), which is a voice-over-internet protocol computer program, allowing calls to be made from a computer to plain old telephone service (POTS). All calls were recorded as an uncompressed digital audio file (.wav) using HotRecorder for VoIP (Version 2.1.4). These recordings were later analyzed; the number of overtly stuttered syllables was counted.

### *Data Collection and Analysis*

For the purposes of this study, moments of overt stuttering were operationally defined as whole- and part-word repetitions, sound or syllable prolongations, or inaudible postural fixations (Bloodstein & Bernstein-Ratner, 2008). Stuttered syllables were counted from the first 300 syllables of each speaking condition by the primary author of the study. Intrajudge syllable-by-syllable agreement for 25% of the data, as indexed by *kappa* Cohen (1960) was .95. A trained stuttering research assistant, blind to the purpose of the study, randomly selected and independently analyzed 25% of the data, yielding an interjudge syllable-by-syllable agreement of .87, which represents excellent agreement (Fleiss, 1981).

## RESULTS

The distributions of stuttering frequency as a function of speaking condition are presented in Fig. 1. Specifically, the mean stuttering frequency was 11.0 stuttered syllables ($SD = 6.63$) for the control speaking condition

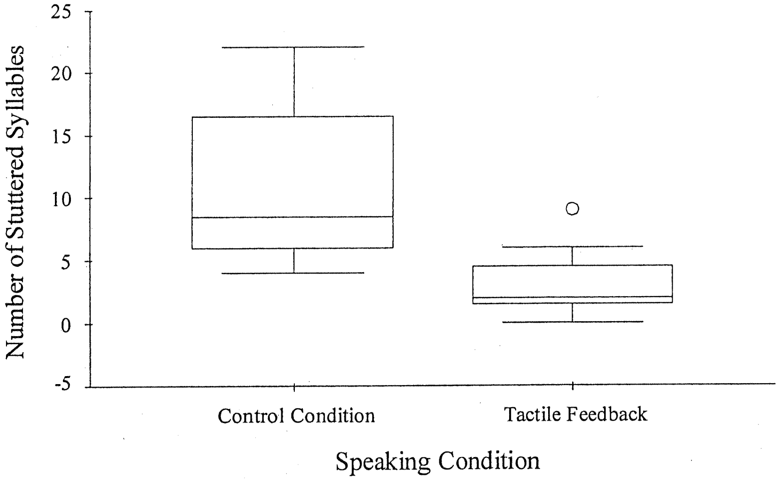

FIG. 1. The minimum, maximum, interquartile range, and median values as a function of the control and digital vibrotactile speech-feedback speaking conditions with Ns=8 ( o : outlier in the tactile feedback speaking condition)

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and 3.1 stuttered syllables (*SD*=2.9) for the tactile feedback speaking condition. This represents an approximate 72% reduction in stuttering frequency as a function of digital vibrotactile speech feedback. Reductions for individual participants' stuttering frequency as a function of digital vibrotactile speech feedback are presented in Fig. 2. Given the relatively small sample tested (i.e., <20 participants), a square root transformation was performed on the data prior to analysis, resulting in a more symmetrical (transformed) distribution (Jones, Onslow, Packman, & Gebski, 2006). A repeated-measures analysis of variance yielded a main effect for digital vibrotactile speech feedback ($F_{1,7}=95.79$, $p=.001$, $\eta_p^2=.932$).

## DISCUSSION

As hypothesized, self-generated digital vibrotactile speech feedback resulted in reliable and powerful fluency enhancement. As a consequence, data from current and previous research suggest that digital vibrotactile speech feedback enhances fluency of those who stutter in either self- or externally generated forms (Kuniszyk-Jozkowiak & Adamczyk, 1989; Kuniszyk-Jozkowiak, *et al.*, 1996, 1997). Although this fluency-enhancing phenomenon is both reliable and powerful, the question of why digital vibrotactile speech feedback enhances fluency in those who stutter remains unknown.

One possible interpretation of this phenomenon would come from the "distraction hypothesis", suggesting that self-generated digital vibrotactile speech feedback provided a sufficient "distraction" from stuttering, thereby

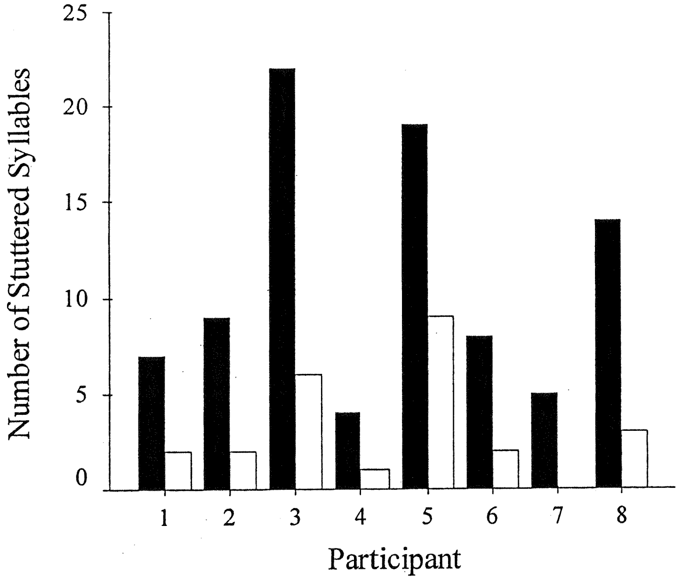

FIG. 2. The frequency of overt stuttered syllables, detailed per participant as a function of the Control ( ■ ) and digital vibrotactile ( □ ) speech feedback speaking conditions

enhancing fluency in those who stutter (Wingate, 1976; Bloodstein, 1999; Bloodstein & Bernstein-Ratner, 2008). Although this perspective may be enticing to some, the scientific rigor and validity of the distraction hypothesis has been challenged (Beech & Fransella, 1968) and deemed an inadequate theoretical model for predicting and accounting for fluency enhancement within the stuttering phenomenon (Stuart, 1999).

Another interpretation of these data, from a "speech-motor" stuttering perspective, suggests that (even the slightest) pressure on the larynx could alter laryngeal functioning (Freeman & Ushijima, 1975, 1978), which has been suggested as causal in the stuttering phenomenon (Wingate, 1970). However, this perspective also has been challenged for insufficient scientific rigor, as it is difficult to support the notion that errors in laryngeal functioning are causal to stuttering (Bloodstein & Bernstein-Ratner, 2008) rather than merely symptoms of stuttering (Armson & Kalinowski, 1994). Also, present participants were specifically instructed to apply small amounts of (if any) pressure on the larynx. Therefore, attributing these results, which are consistent and robust across all eight participants, as "a laryngeal movement artifact", seems inappropriate. Moreover, data from this study are consistent with externally generated digital vibrotactile speech feedback (Kuniszyk-Jozkowiak & Adamczyk, 1989; Kuniszyk-Jozkowiak, *et al.*, 1996, 1997); this suggests it is unlikely that laryngeal displacement would be responsible for the fluency enhancement reported.

An additional theoretical perspective which integrates these data while accounting for the nature of stuttering and fluency enhancement is the EXPLAN model. In essence, this model suggests that failures in speech fluency result from asynchrony between cognitive-linguistic formulation of a speech plan and the motor execution of the plan (Howell, 2002, 2004; Howell & Sackin, 2002). Moments of stuttering are theorized as occurring when the linguistic plan is not fully formed in time for (fluent) motor execution (Howell, 2002, 2004; Howell & Sackin, 2002). From this perspective, speech feedback is hypothesized to enhance fluency by offering a second source of rhythm, which affects the global or local speech rate relative to (speech) motor execution. These alterations (i.e., reductions) in either global or local speech rate allow increased time relative to cognitive-linguistic speech planning, thereby increasing the chances of fluently executing a fully formed speech plan. Consequently, the EXPLAN model would predict (1) that the perception of self-generated digital vibrotactile speech feedback actively influences the peripheral nervous system, (2) which results in a (global or local) reduced rate of speech, (3) thereby allowing more time for cognitive-linguistic formulation, (4) resulting in increased fluent speech-motor execution of fully formed cognitive-linguistic speech plans (Howell, 2002, 2004; Howell & Sackin, 2002).

An alternative perspective on the fluency enhancement via speech feedback phenomenon suggests that the digital vibrotactile speech feedback utilized in this study qualifies as a "second speech signal" (Kalinowski, *et al.*, 2000; Kalinowski & Dayalu, 2002; Guntupalli, Kalinowski, Saltuklaroglu, & Nanjundeswaran, 2005). Research indicates that the sensory perception of a second speech signal may passively activate mirror neuron networks embedded within the central nervous system (Kalinowski & Saltuklaroglu, 2003b). In essence, exposure to a second speech signal passively activates (speech-related) mirror neuron networks which are hypothesized to innervate fluent speech production (Kalinowski & Saltuklaroglu, 2003a; Saltuklaroglu, Kalinowski, & Guntupalli, 2004). Consequently, this perspective would suggest that exposure to second speech signals (including a self-generated visual second speech signal), regardless of the sensory modality in which it was perceived, passively influences the central nervous system to activate mirror neuron networks that would innervate fluent speech production.

Finally, Goldberg and Bloom's hypothesis of a dual premotor system (1990) could also account for these data by differentiating the roles of the medial and lateral premotor systems (Goldberg, 1985, 1992). This hypothesis identifies a medial premotor system, thought to be responsible for initiating self-generated (speech) motor plans (Goldberg & Bloom, 1990; MacNeilage, 1998). Tests of the hypothesis also provided evidence for a lateral premotor system (Goldberg & Bloom, 1990), which utilizes a multitude of multisensory afferent connections (Pandya, 1987) to activate externally generated (speech) motor plans (Schubotz, von Cramon, & Lohmann, 2003). It has been hypothesized that the concept of activating an alternate (e.g., lateral) premotor system during speech production may be an essential component in fluency enhancement via speech feedback (Alm, 2004, 2005; Snyder, 2004). Subsequently, one may hypothesize that exposure to digital vibrotactile speech feedback activates an alternate (i.e., lateral) premotor system, which then innervates fluent speech production.

Regardless of how these data are interpreted, additional research relative to the effects of self- and externally generated digital vibrotactile feedback is warranted. For example, the immediacy and carryover of digital vibrotactile speech-feedback fluency enhancement could be tested using a single-subject design, although the design is expected to provide the same immediate, yet transient, fluency enhancement found in speech feedback from the auditory and visual sensory modalities. Additional testing may include the efficacy of externally generated synchronous and asynchronous digital vibrotactile speech feedback or even initiating digital vibrotactile stimulation (prior to speech gesture initiation) on stuttering frequency. These latter research issues might lead to the development of a discrete prosthetic device for management of stuttering.

Clinical implications of these data are immediate and straightforward. In the literature is evidence that stuttering has the potential to hinder the quality of life, including social, educational, and vocational opportunities and performance (Klein & Hood, 2004; Klompas & Ross, 2004). Use of the telephone, in particular, has been documented to be difficult for many people who stutter (James, Brumfit, & Cuud, 1999) and is certainly an important tool in social and vocational interaction. Present data suggest that overt stuttering frequency may be reduced by approximately 72% simply by speakers' sensing vibrotactile speech feedback from their own thyroid cartilage during phonation with the index finger and thumb. This finding also suggests the possibility of new forms of prosthetic management of overt stuttering frequency.

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