JSLHR

Review Article

A Perceptual Learning Approach for Dysarthria Remediation: An Updated Review

Stephanie A. Borrie[a] and Kaitlin L. Lansford[b]

Purpose: Early studies of perceptual learning of dysarthric speech, those summarized in Borrie, McAuliffe, and Liss (2012), yielded preliminary evidence that listeners could *learn* to better understand the speech of a person with dysarthria, revealing a potentially promising avenue for future intelligibility interventions. Since then, a programmatic body of research grounded in models of perceptual processing has unfolded. The current review provides an updated account of the state of the evidence in this area and offers direction for moving this work toward clinical implementation.
Method: The studies that have investigated perceptual learning of dysarthric speech (N = 24) are summarized and synthesized first according to the proposed learning source and then by highlighting the parameters that appear to mediate learning, culminating with additional learning outcomes.
Results: The recent literature has established strong empirical evidence of intelligibility improvements following familiarization with dysarthric speech and a theoretical account of the mechanisms that facilitate improved processing of the neurologically degraded acoustic signal.
Conclusions: There are no existing intelligibility interventions for individuals with dysarthria who cannot behaviorally modify their speech. However, there is now robust support for the development of an approach that shifts the weight of behavioral change from speaker to listener, exploiting perceptual learning to ease the intelligibility burden of dysarthria. To move this work from bench to bedside, recommendations for translational studies that establish best practices and candidacy for listener-targeted dysarthria remediation, perceptual training, are provided.

There exist few effective treatments that ease the intelligibility burden of dysarthria, and all of these require cognitive and physical effort on the part of the speaker to achieve and maintain gains (Herd et al., 2012; Mitchell et al., 2017). Therefore, individuals with intelligibility deficits who cannot behaviorally modify their speech are not viable candidates for current intelligibility interventions. This constitutes a significant health disparity that disproportionately affects those with developmental, cognitive, or significant neuromuscular impairment. While prevalence data are not fully known, dysarthria is frequent in a number of common neurological disorders that are accompanied by such co-occurring impairments (e.g., Parkinson's disease [PD], amyotrophic lateral sclerosis [ALS]), stroke, cerebral palsy, and multiple sclerosis). The dearth of intervention options is not an inconsequential problem. The intelligibility impairments that characterize dysarthria have been described as "the most clinically and socially important aspects of dysarthria" (Ansel & Kent, 1992), tracking with reduced participation in situations that involve communicating with others (Barnish et al., 2017; Sixt Börjesson et al., 2020; Spencer et al., 2020). As such, interventions that target intelligibility are critical for not only improved communication outcomes but also quality of life.

The definition of intelligibility, "the accuracy with which a message is conveyed by a speaker and recovered by a listener" (Yorkston et al., 1988), highlights contributions from both speaker (i.e., production) and listener (i.e., perception). With speaker–listener contributions in mind, it was proposed that the intelligibility impairments exhibited by individuals with dysarthria may benefit from interventions that focus on the listener (Liss, 2007; McAuliffe et al., 2010). While listener-targeted treatment of the intelligibility impairments in dysarthria was, at the time, conceptually novel, the notion of training a listener to better understand

[a]Department of Communicative Disorders and Deaf Education, Utah State University, Logan
[b]Department of Communication Science and Disorders, Florida State University, Tallahassee
Correspondence to Stephanie A. Borrie: stephanie.borrie@usu.edu
Editor-in-Chief: Katherine C. Hustad
Editor: Jessica E. Huber
Received January 7, 2021
Revision received March 15, 2021
Accepted March 29, 2021
https://doi.org/10.1044/2021_JSLHR-21-00012

Disclosure: The authors have declared that no competing interests existed at the time of publication.

 Copyright © 2021 American Speech-Language-Hearing Association

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

the neurologically degraded acoustic signal is firmly grounded in theoretical models of perceptual learning of speech (e.g., Clayards et al., 2008; Feldman et al., 2009; Kleinschmidt & Jaeger, 2015) and a large body of literature evidencing the malleability of the listeners' speech perception system (e.g., Bradlow & Bent, 2008; Clarke & Garrett, 2004; Davis et al., 2005; Eisner & McQueen, 2005; see also Bieber & Gordon-Salant, 2021, and Samuel & Kraljic, 2009, for reviews).

In early 2012, a review article titled "Perceptual Learning of Dysarthric Speech: A Review of Experimental Studies" was published (Borrie, McAuliffe, & Liss, 2012). In addition to reviewing perceptual learning of noncanonical speech more generally, the article reviewed the small body of literature that had examined perceptual learning of dysarthric speech (n = 8), established the rationale for further investigation in this area, and offered direction for advancing this line of scientific inquiry in a systematic way. In response to this, a programmatic body of work has unfolded over the last decade (n = 16), calling for an updated review of experimental studies of perceptual learning of dysarthric speech. The purpose of this current review is threefold. First, we explain perceptual learning and the theoretical models that support listener adaptation to a degraded speech signal. We then summarize and synthesize the literature investigating perceptual learning of dysarthric speech according to key themes that have emerged regarding how listeners adapt to the neurologically degraded acoustic signal. Equipped with foundational evidence and a theoretical framework to support a perceptual learning approach for dysarthria remediation, we conclude by providing direction for the next steps in this area of inquiry: arguing for translational studies that move this work from bench to bedside, establishing best practice and candidacy for perceptual training programs that ease the intelligibility burden of dysarthria.

Perceptual Learning

Successful speech perception requires listeners to accurately parse the continuous, incoming signal into word-sized frames and map them onto discrete meanings. In familiar listening situations, this process occurs with no apparent effort. However, when listeners encounter a speaker with a novel way of talking, the speech perception system must rapidly and flexibly adapt to map the noncanonical acoustic cues onto linguistic categories stored in memory. This experience-induced adaptation is known as perceptual learning. According to theoretical models of perceptual learning, experience with the novel speech signal allows the listener to acquire knowledge of how linguistic units (e.g., words, syllables, phonetic categories) are realized by different distributions of acoustic cues (e.g., Clayards et al., 2008; Feldman et al., 2009; Kleinschmidt & Jaeger, 2015). Fundamental to acquiring this knowledge is acoustic regularity in the speech signal, arising from segmental and suprasegmental information. The statistical predictability of these regularities then drives listeners' acquisition of category-specific cue distributions. Thus, perceptual learning can be conceptualized as a form of statistical inference: Listeners build linguistic generative models for novel speakers based on knowledge about the distribution of acoustic cues associated with each linguistic category (Kleinschmidt & Jaeger, 2015). These generative models can then be leveraged to more successfully decipher the speaker's productions in future encounters (e.g., Eisner & McQueen, 2005; Kraljic & Samuel, 2007). The phenomenon of perceptual learning of speech has been extensively studied in experimental paradigms in which listeners are given a structured *familiarization* experience with laboratory-modified speech, including synthetic (e.g., Francis et al., 2007; Greenspan et al., 1988), noise-vocoded (e.g., Davis & Johnsrude, 2007; Loebach et al., 2008), and time-compressed (e.g., Dupoux & Green, 1997; Golomb et al., 2007) signals or naturally occurring speech variants such as accented speech (e.g., Clarke & Garrett, 2004; Sidaras et al., 2009) and, importantly, dysarthric speech (e.g., Borrie, McAuliffe, Liss, Kirk, et al., 2012; Lansford et al., 2016; but see also Table 1).

Perceptual Learning of Dysarthric Speech

Since the first study in 1983, 24 studies have investigated perceptual learning of dysarthric speech. These studies are reported in chronological order in Table 1. The early works, the eight studies summarized in the initial review article by Borrie, McAuliffe, and Liss (2012), were largely descriptive, and their findings were somewhat equivocal, although substantial methodological differences and an absence of rigorous control confounded meaningful comparisons across those studies. Since then, a programmatic body of research grounded in models of perceptual processing has investigated learning and learning mechanisms for listeners familiarized with neurologically degraded speech. This work has collectively enabled us to reach the following overarching conclusion: *Familiarization with dysarthric speech facilitates improvements in a listener's ability to understand the neurologically degraded acoustic signal*. To date, the line of investigation following the 2012 review article has chiefly targeted theory; however, robust intelligibility (percent words correct) improvements across the studies, sometimes up to 20%, have been observed (Borrie et al., 2017a, 2017b; Borrie, McAuliffe, Liss, Kirk, et al., 2012; Lansford et al., 2018). Intelligibility improvements of 5%–12% are considered a guideline for clinically significant change in dysarthria management (Stipancic et al., 2016, 2018; Van Nuffelen et al., 2010). Thus, the intelligibility improvements observed following listener familiarization are not only statistically significant but also likely clinically meaningful in terms of improved communication outcomes. Table 1 highlights that the large majority of studies investigating perceptual learning of dysarthric speech have evidenced significant intelligibility improvements. In the following section, we summarize and synthesize the body of research presented in Table 1 first according to the proposed source of learning and then by highlighting the theoretically grounded parameters that appear to mediate learning of neurologically degraded speech, culminating with a discussion of additional perceptual learning outcomes.

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Table 1. Summary of previously published studies on perceptual learning of dysarthric speech (*N* = 24).

Study	Speakers	Listeners	Setting	Familiarization conditions	Familiarization stimuli	Testing stimuli	Primary findings
Yorkston & Beukelman (1983)	Nine speakers with dysarthria: three mild, three moderate, and three severe	Nine experienced listeners: SLPs and SLP students; (age and hearing status not provided)	Lab	Passive or explicit	Sentences	Sentences	**No intelligibility improvement for listeners familiarized with dysarthric speech[a]**
Tjaden & Liss (1995a)	One speaker with moderate–severe spastic–ataxic dysarthria	30 naive listeners, college students (age not provided), normal hearing	Lab	Explicit	Phrases	Phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[a]**
Tjaden & Liss (1995b)	One speaker with moderate–severe spastic–ataxic dysarthria	30 naive listeners, college students (age not provided), normal hearing	Lab	Explicit	Word list or passage	Phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[a]** Equivalent intelligibility improvement for word list vs. passage familiarization stimuli.
Garcia & Cannito (1996)	One speaker with severe flaccid dysarthria	96 naive listeners, aged 18–30 years, normal hearing	Lab	Passive	Conversational speech sample	Phrases	**No intelligibility improvement for listeners familiarized with dysarthric speech[a]**
Spitzer et al. (2000)	Six speakers with moderate–severe hypokinetic dysarthria or six speakers with moderate–severe ataxic dysarthria	34 naive listeners, aged 18–50 years, normal hearing	Lab	Explicit	SA phrases	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[a]** Improved segmental processing for listeners familiarized with ataxic but not hypokinetic speech.
Liss et al. (2002)	Six speakers with moderate–severe hypokinetic dysarthria or six speakers with moderate–severe ataxic dysarthria	120 naive listeners, aged 18–50 years, normal hearing	Lab	Explicit	SA phrases	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[a]** Intelligibility improvement generalized to untrained speakers. No changes in suprasegmental processing for listeners familiarized with dysarthric speech.
Hustad & Cahill (2003)	One of five speakers with mild or severe dysarthria: three spastic, one hyperkinetic, and one spastic–hyperkinetic	100 naive listeners, aged 18–30 years, normal hearing	Lab	Passive	Phrases	Phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[b]** Time course of intelligibility improvement faster for mild vs. severe dysarthrias.
D'Innocenzo et al. (2006)	One speaker with moderate spastic–flaccid dysarthria	120 naive listeners, aged 18–60 years, normal hearing	Lab	Explicit	Word list or passage	Sentences	**Intelligibility improvement for listeners familiarized with dysarthric speech[a]** Equivalent intelligibility improvement for word list vs. passage familiarization stimuli.
Borrie, McAuliffe, Liss, Kirk, et al. (2012)	Three speakers with moderate hypokinetic dysarthria or three control speakers	60 naive listeners, aged 19–40 years, normal hearing	Lab	Passive or explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[c]** Superior intelligibility improvement, in magnitude and maintenance (1 week), for explicit vs. passive familiarization. Improved segmental and suprasegmental processing for listeners familiarized with dysarthric speech.

(*table continues*)

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Table 1. *(Continued).*

Study	Speakers	Listeners	Setting	Familiarization conditions	Familiarization stimuli	Testing stimuli	Primary findings
Borrie, McAuliffe, Liss, O'Beirne, & Anderson (2012)[1]	Three speakers with moderate hypokinetic dysarthria	40 naive listeners, aged 19–40 years, normal hearing	Lab	Passive or explicit	SA phrases	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[c]** Superior intelligibility improvement for explicit vs. passive familiarization and for passage vs. SA phrase stimuli. Improved suprasegmental processing for listeners familiarized with dysarthric speech.
Borrie et al. (2013)	Three speakers with moderate hypokinetic dysarthria	60 naive listeners, aged 19–40 years, normal hearing	Lab	Speaker (indexical) or word (linguistic) identification task	Passage and SA phrases	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[a]** Equivalent intelligibility improvement for listeners trained on indexical or linguistic properties of the signal. Improved suprasegmental processing for listeners familiarized with dysarthric speech.
Kim & Nanney (2014)	One of four speakers with moderate spastic dysarthria	120 naive listeners, aged 18–40 years, normal hearing	Lab	Passive or explicit	Single words	Single words	**Intelligibility improvement for listeners familiarized with dysarthric speech[a,b]** Superior intelligibility improvement, in magnitude and maintenance (1 month), for explicit vs. passive familiarization.
Kim (2015)	One of four speakers with moderate dysarthria: three spastic and one athetoid	120 naive listeners, aged 18–40 years, normal hearing	Lab	Passive or explicit	Single words	Consonant productions	**Consonant identification improvement for listeners familiarized with dysarthric speech[a,b]** Superior consonant improvement, in magnitude and time course, for explicit vs. passive familiarization.
Borrie & Schäfer (2015)	One speaker with moderate spastic dysarthria	100 naive listeners, aged 19–37 years, normal hearing	Lab	Passive, explicit, imitation, or explicit + imitation	Phrases	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[b,c]** Equivalent intelligibility improvement for explicit vs. imitation familiarization. Superior intelligibility improvement for explicit + imitation familiarization.
Lansford et al. (2016)	Three speakers with moderate hypokinetic dysarthria or three control speakers	91 naive listeners, aged 19–55 years, normal hearing	Lab and remote	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[c]** Equivalent intelligibility improvement for lab vs. remote setting.
Borrie & Schäfer (2017)	One speaker with moderate ataxic dysarthria or one control speaker	60 naive listeners, aged 19–33 years, normal hearing	Lab	Explicit or imitation	Phrases	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[a,b]** Equivalent intelligibility improvement for explicit vs. imitation familiarization. Superior maintenance of intelligibility improvement for imitation familiarization.

(*table continues*)

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Table 1. *(Continued).*

Study	Speakers	Listeners	Setting	Familiarization conditions	Familiarization stimuli	Testing stimuli	Primary findings
Borrie et al. (2017b)	One speaker with moderate ataxic dysarthria	50 naive listeners, aged 18–29 years, normal hearing	Lab	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech**[b] Rhythm perception scores predicted magnitude of intelligibility improvement.
Borrie et al. (2017a)	Test speaker: one speaker with moderate ataxic dysarthria Familiarization speakers: one of seven speakers with dysarthria of systematically varied presentations or one control speaker	160 naive listeners, aged 19–45 years, normal hearing	Remote	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech**[b,c,] Intelligibility improvement generalized to untrained speaker. Magnitude of improvement tracked with level of perceptual similarity between familiarization speaker and test speaker and was reduced when familiarization speakers had lower intelligibility.
Borrie et al. (2018)	One speaker with moderate hypokinetic dysarthria or one speaker with moderate hyperkinetic dysarthria	98 naive listeners, aged 22–62 years, normal hearing	Remote	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with hypokinetic but not hyperkinetic speech**[b] Rhythm perception scores predicted magnitude of intelligibility improvement.
Lansford et al. (2018)[2]	One speaker with moderate ataxic dysarthria	19 naive listeners, aged 60–95 years, with or without HL	Lab	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech**[b] Baseline intelligibility scores of older listeners with HL were lower than scores of younger and older listeners without HL, but there was no difference in magnitude of intelligibility improvement between listener groups.
Lansford et al. (2019)[3]	One of two additional speakers with moderate or severe hyperkinetic dysarthria	40 naive listeners, aged 18–62 years, normal hearing	Remote	Explicit	Passage	SA phrases	**No or negligible intelligibility improvement for listeners familiarized with dysarthric speech**[b]
Lansford et al. (2020)	One speaker with moderate hyperkinetic dysarthria	89 naive listeners, aged 18–59 years, normal hearing	Lab and remote	Explicit, imitation, or explicit + imitation	Passage	SA phrases	**No intelligibility improvement for listeners familiarized with dysarthric speech**[b] Neither familiarization manipulation (more/different) facilitated intelligibility improvement.

(*table continues*)

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Table 1. *(Continued).*

Study	Speakers	Listeners	Setting	Familiarization conditions	Familiarization stimuli	Testing stimuli	Primary findings
Hirsch et al. (2021)[4]	Test speaker: one speaker with moderate ataxic dysarthria Familiarization speakers: one of two speakers with dysarthria	40 naive listeners, aged 19–66 years, normal hearing	Remote	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[b,c]** Intelligibility improvement generalized to untrained speakers of different sexes. Magnitude of improvement tracked with level of perceptual similarity between familiarization speaker and test speaker.
Borrie et al. (2021)[4]	One speaker with moderate ataxic dysarthria	47 experienced listeners: SLPs, aged 26–62 years, normal hearing	Remote	Explicit	Passage	SA phrases	**Intelligibility improvement for listeners familiarized with dysarthric speech[b,c]** Baseline intelligibility scores of SLPs with more dysarthria experience were higher than those of SLPs with less dysarthria experience, but there was no difference in magnitude of intelligibility improvement between listener groups.

Note. Passive = dysarthric signal; explicit = dysarthric signal and orthographic transcripts; imitation = imitate dysarthric signal. “Passage” is used to denote stimuli that authors termed passage or paragraph. SLP(s) = speech-language pathologist(s); SA = semantically anomalous; HL = hearing loss. Numerical superscripts indicate studies that included historical data to address research questions: [1]Borrie, McAuliffe, Liss, Kirk, et al. (2012); [2]Borrie et al. (2017b); [3]Borrie et al. (2018); [4]Borrie et al. (2017a). Bolded text highlights whether or not intelligibility improvement was observed. Intelligibility is measured as percent words correct. Alphabetical superscripts are used to denote improvement established relative to [a]nonfamiliarized listener group, [b]listener’s own baseline intelligibility scores, or [c]listener group familiarized with neurotypical speech. The reader is directed to the original articles for additional study details, including the data on the magnitude of intelligibility improvement.

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Learning Source

Studies have documented changes in perceptual processing following familiarization with dysarthric speech that point to the source of the intelligibility improvements. As above, theoretical models posit that perceptual learning of speech, and the critical cue-to-category mapping process, is fostered by acoustic regularities in segmental and suprasegmental information. Collectively, the literature has revealed that the intelligibility improvements following familiarization with dysarthric speech are accompanied by improved processing of both types of information. At the segmental level, studies have reported improvements in percent syllable resemblance, a metric of segmental goodness reflecting whether syllables perceived in error resemble their intended target (Borrie, McAuliffe, Liss, Kirk, et al., 2012; Borrie, McAuliffe, Liss, O'Beirne, & Anderson, 2012; Borrie et al., 2013), substitution errors (Spitzer et al., 2000), and consonant identification (Kim, 2015). To document changes to processing at the suprasegmental level, Liss et al. (2002) developed a lexical boundary error (LBE) paradigm that quantifies and qualifies listener reliance on syllabic stress cues to segment connected speech. While the study by Liss and colleagues, wherein listeners were familiarized with speakers with either ataxic or hypokinetic dysarthria, did not observe differences in the LBE patterns of familiarized versus nonfamiliarized listeners, it was speculated that the familiarization protocol, just 18 short phrases, may have been too brief to facilitate detectable changes to the processes involved in lexical segmentation. To follow up, Borrie, McAuliffe, Liss, Kirk, et al. (2012) employed a more extensive familiarization procedure, three readings of the Rainbow Passage (Fairbanks, 1960) elicited from speakers with hypokinetic dysarthria, and found that, in addition to intelligibility improvements, listeners were better able to utilize the syllabic stress cues to segment connected speech. This finding of improved processing of syllabic stress for listeners familiarized with dysarthric speech, established relative to a control group familiarized with the same speech stimuli elicited from neurotypical speakers, was replicated in subsequent studies (Borrie, McAuliffe, Liss, O'Beirne, & Anderson, 2012; Borrie et al., 2013). Thus, there is evidence that both the segmental and suprasegmental cues that characterize dysarthric speech contain learnable and useful regularities requisite for improved processing of the neurologically degraded speech signal.

Task Parameters

Explicit Familiarization

Hypothesis-driven manipulations of the familiarization task have revealed that perceptual learning of dysarthric speech is superior, in both magnitude of immediate intelligibility improvement and maintenance of improvements, when the stimuli produced by a speaker with dysarthria, the acoustic signal, are paired with lexical feedback in the form of orthographic transcripts of the intended targets. Lexical feedback is thought to promote mapping of the ambiguous acoustic realizations onto meaningful internal representations of speech by revealing the discrepancies between the input predicted by the lexical information and the degraded speech experienced (Guediche et al., 2014). In the seminal study of this task manipulation, Borrie, McAuliffe, Liss, Kirk, et al. (2012) observed that listeners familiarized with just the speech of speakers with hypokinetic dysarthria (passive familiarization) achieved intelligibility scores approximately 13% greater than listeners familiarized with control speech. However, listeners familiarized with the same dysarthric stimuli and lexical feedback (explicit familiarization) achieved intelligibility scores approximately 20% greater than those in the control condition. Furthermore, follow-up testing 1 week after the familiarization experience revealed that intelligibility scores for listeners who received passive familiarization had returned to levels comparable to the control. In contrast, intelligibility scores of listeners who received explicit familiarization remained significantly greater than those of the control. This suggests that lexical information disambiguates the neurologically degraded acoustics, fostering cue-to-category mapping of dysarthric speech. This finding that explicit familiarization, relative to passive familiarization, facilitates superior learning was replicated by others (Borrie, McAuliffe, Liss, O'Beirne, & Anderson, 2012; Borrie & Schäfer, 2015; Kim, 2015; Kim & Nanney, 2014). Together, this collection of studies established what we have come to know as the standard familiarization experience for perceptual learning of dysarthric speech: presenting listeners with dysarthric speech stimuli accompanied by lexical feedback regarding the intended targets. Explicit familiarization has subsequently been utilized in the large majority of studies in this area of inquiry (Borrie et al., 2017a, 2017b, 2018, 2021; Borrie & Schäfer, 2015, 2017; Hirsch et al., 2021; Lansford et al., 2016, 2018, 2019, 2020).

Vocal Imitation

Theoretically rooted in the Directions Into Velocities of Articulators (DIVA) model (Guenther et al., 1998), a computational model of speech acquisition and production, there is preliminary evidence that perceptual learning of dysarthric speech might be further optimized with somatosensory feedback established via a vocal imitation task. While the DIVA model itself does not explicitly account for improved perceptual processing of a teaching signal, the model specifies that both auditory and somatosensory information are required to guide learning of consistent mappings between a speech sound map and its corresponding reference frames (Golfinopoulos et al., 2010). Thus, imitation of the dysarthric speech signal, conceptualized as a teaching signal, may indirectly facilitate perceptual learning of the target sound by linking the acoustic target with the somatosensory information required to produce that sound, enabling accurate imitation and recognition of the target sound (see Borrie & Schäfer, 2015, for more details of how DIVA predictions might apply to perceptual learning of dysarthric speech). In the first study to examine the

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

role of somatosensory feedback in perceptual learning of dysarthric speech, Borrie and Schäfer (2015) observed that a familiarization experience that instructed listeners to imitate the dysarthric stimuli (imitation familiarization) resulted in comparable intelligibility improvements as the standard explicit familiarization experience involving dysarthric stimuli and lexical feedback. Although, the largest improvements were realized when the dysarthric stimuli were accompanied by both lexical and somatosensory feedback. Furthermore, the study identified a positive relationship between intelligibility improvement and imitation accuracy (measured acoustically), corroborating a mechanistic role for somatosensory feedback in perceptual learning of spastic dysarthria. The comparable intelligibility benefit of lexical or somatosensory feedback immediately following familiarization was replicated in a follow-up study with ataxic dysarthria, which further revealed that listeners who received imitation familiarization more successfully maintained improvements 1 week and 1 month following the familiarization experience (Borrie & Schäfer, 2017). This would suggest that ties to existing mental representations of speech are strengthened by way of a somatosensory motor trace. While not yet studied, it seems highly plausible that superior learning maintenance, like superior immediate benefits, would be achieved by a familiarization experience that includes both lexical and somatosensory feedback.

Listener Parameters

Rhythm Perception

In recent years, studies have begun to acknowledge and investigate individual differences in perceiving dysarthric speech. It is now well established that substantial variability exists, suggesting that some listeners are better equipped to navigate the complex task of deciphering the degraded speech signal (Bent et al., 2016; Borrie, Baese-Berk, et al., 2017; Ingvalson et al., 2017; McAuliffe et al., 2013). In recognition of this individual variability and the import of rhythm cues in perceiving spoken language under challenging conditions (see Mattys et al., 2005), Borrie et al. (2017b) investigated the relationship between rhythm perception abilities and perceptual learning of dysarthric speech. The study found that individuals with expertise in rhythm perception, operationalized as a superior ability to perceive rhythm cues in the musical domain (and strongly correlated with musician status), had a significant advantage in learning to understand a speaker with ataxic dysarthria, reflected in a greater magnitude of intelligibility improvement following explicit familiarization. This finding—that rhythm perception abilities tracked with perceptual learning of dysarthric speech—was replicated in a subsequent study involving stimuli produced by a speaker with hypokinetic dysarthria (Borrie et al., 2018). As noted earlier, improved understanding of dysarthric speech is supported by improved processing of acoustic regularity in segmental and suprasegmental cues (e.g., Borrie, McAuliffe, Liss, Kirk, et al., 2012). Thus, the findings from Borrie et al. (2017b, 2018) suggest that listeners with expertise in rhythm perception can better exploit the familiarization experience, identifying underlying acoustic cue distributions in the neurologically degraded speech signal.

Age and Hearing Status

In an effort to build well-controlled models of how the communication partner, the listener, adapts to dysarthric speech, the large majority of studies carried out thus far have recruited younger adults with normal hearing (e.g., Borrie, McAuliffe, Liss, Kirk, et al., 2012; Kim, 2015; Liss et al., 2002). However, etiologies of dysarthria (e.g., PD, ALS, stroke) typically onset later in life. Recognizing that the older adult population, namely, the aging spouses, friends, and caregivers of people with dysarthria, would particularly benefit from improved perceptual processing and that the prevalence of hearing loss increases substantially with age (e.g., Nash et al., 2011), Lansford et al. (2018) examined perceptual learning of dysarthric speech in a group of older adults, with and without hearing impairment. The study found that listener age and hearing status influenced baseline intelligibility levels of a speaker with ataxic dysarthria (i.e., pretest intelligibility scores of older listeners were lower than those of younger listeners with normal hearing) but, importantly, did not affect the magnitude of intelligibility improvement following explicit familiarization. That is, intelligibility benefits achieved by older listeners, regardless of hearing status, were comparable to the 20% intelligibility improvement achieved by younger adults with normal hearing who completed the same familiarization paradigm (Borrie et al., 2017a).

Listener Experience

In the first descriptive report of perceptual learning of dysarthric speech, Yorkston and Beukelman (1983) recruited nine listeners, five speech-language pathologists (SLPs) and four student clinicians, and assigned them to control, passive, or explicit familiarization. No difference in intelligibility scores among the three groups was observed—the assumption that these listeners, through their previous unstructured interactions, had already completely adapted to dysarthric speech. Since that first study, naive listeners, individuals with no or minimal previous experience with neurological speech disorders, have been used to investigate and advance models of perceptual learning of dysarthric speech (e.g., Borrie, McAuliffe, Liss, Kirk, et al., 2012; D'Innocenzo et al., 2006; Hustad & Cahill, 2003; Kim, 2015; Lansford et al., 2019; Liss et al., 2002; Spitzer et al., 2000; Tjaden & Liss, 1995a). However, motivated by theoretical models of listener adaptation that challenge the previously held assumption that SLPs have already fully adapted to dysarthric speech, Borrie et al. (2021) experimentally investigated the role of clinical experience in perceptual learning of dysarthric speech in a cohort of 47 SLPs. The study found that experience with dysarthria, not simply being an SLP, influenced baseline intelligibility levels of a speaker with ataxic dysarthria (i.e., pretest intelligibility scores of clinicians with greater than 40% dysarthria on their caseload

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

were higher than those of clinicians with less dysarthria on caseloads). Importantly, however, the study also found that SLPs, regardless of their level of dysarthria experience, benefited from familiarization with a novel speaker with dysarthria, achieving an average of 19% intelligibility improvement from pretest to posttest. These findings suggest that clinicians who regularly work with individuals with dysarthria acquire knowledge of dysarthric cue distributions more generally and can generalize this group-specific knowledge when encountering new speakers with dysarthria. However, despite any previous dysarthria experience, the opportunity to acquire knowledge of speaker-specific cue distributions is crucial for optimal adaptation to a particular speaker, consistent with ideal adaptor theories of learning (Kleinschmidt & Jaeger, 2015).

Speaker Parameters

Signal Predictability

Recall that signal predictability is the presumed driver of the perceptual learning phenomenon, such that noncanonical speech patterns that are rich in predictable acoustic information should be highly learnable. Empirical support for this theoretical account is emerging. Indeed, statistically and clinically significant intelligibility improvements have been consistently documented for listeners familiarized with hypokinetic (Borrie, McAuliffe, Liss, Kirk, et al., 2012; Borrie, McAuliffe, Liss, O'Beirne, & Anderson, 2012; Borrie et al., 2013, 2018; Lansford et al., 2016; Liss et al., 2002; Spitzer et al., 2000), ataxic (Borrie et al., 2017a, 2017b, 2021; Borrie & Schäfer, 2017; Hirsch et al., 2021; Lansford et al., 2018; Liss et al., 2002; Spitzer et al., 2000), spastic (Borrie & Schäfer, 2015; Hustad & Cahill, 2003; Kim, 2015; Kim & Nanney, 2014), and mixed (D'Innocenzo et al., 2006; Tjaden & Liss, 1995a, 1995b) dysarthrias. Recently, however, the seemingly robust benefit following perceptual training was not observed for listeners familiarized with hyperkinetic dysarthria (Borrie et al., 2018; Lansford et al., 2019, 2020). Unexpectedly encountered in a study that included a speaker with hyperkinetic dysarthria (Borrie et al., 2018), the authors replicated this finding of an absence of learning with two additional speakers with hyperkinetic dysarthria (Lansford et al., 2019). To further validate the finding, the authors followed up by providing listeners with a more robust familiarization experience (i.e., additional familiarization or a vocal imitation task) and still failed to find evidence of learning (Lansford et al., 2020). In contrast to the other dysarthria subtypes, which are characterized by *relatively* consistent segmental and suprasegmental degradations (e.g., slow rate, equal and even stress, reduced stress, monotone, monoloudness, harsh or breathy vocal quality, imprecise articulation, and reduced vowels), hyperkinetic dysarthria is produced upon a platform of involuntary and excessive movement patterns, causing speech production to break down in unpredictable ways. Phonemes produced adequately in one context may be distorted or omitted in the next word, speech may be inappropriately interrupted by silences, voicing may break or cease intermittently, and rate and rhythm may vary irregularly. Thus, these studies add to the mounting evidence that acoustic regularity, or statistically predictable degradation, drives perceptual learning of dysarthric speech. Clinically, these findings suggest that speakers with hyperkinetic dysarthria, or more accurately, speakers who present with unpredictable speech degradation, may not be suitable candidates for intelligibility interventions that hinge on improved signal processing.

Additional Perceptual Learning Outcomes

Learning Generalization

A primary goal of listener-targeted intervention would be to offset the intelligibility burden from the patient to their key communication partners, that is, spouse, caregiver, family, and friends. In such cases, where the listener needs only to understand one specific individual with dysarthria, perceptual learning needs only be speaker specific (also termed talker specific). To date, the large majority of studies in perceptual learning of dysarthric speech have targeted speaker-specific adaptation, whereby listeners are familiarized and tested on the same speaker or the same small group of speakers with relatively homogeneous patterns of degradation (e.g., Borrie, McAuliffe, Liss, Kirk, et al., 2012; Kim, 2015; Lansford et al., 2018; Spitzer et al., 2000; Tjaden & Liss, 1995a). However, another goal of listener-targeted remediation of dysarthria would be to train health care professionals, those who regularly interact with people with neurological speech disorders (e.g., physicians, nurses, physical therapists), to better understand speakers with dysarthria more generally. In these cases, learning would be most beneficial if it were speaker independent, meaning that training on one speaker(s) with dysarthria would generalize to improved understanding of a novel speaker(s) with dysarthria. In theory, the speech perception system is sensitive to distributional structure that unifies groups of speakers and can draw upon previously established generative models to support improved understanding of novel speakers with similar-sounding speech (Kleinschmidt & Jaeger, 2015). Preliminary evidence for learning generalization across the dysarthrias was first reported by Liss et al. (2002), whereby listeners were familiarized with speakers with either hypokinetic or ataxic dysarthria. Listeners were then tested on phrases produced by the same speakers encountered during familiarization and then a small subset of phrases produced by the untrained speaker group. The posttest intelligibility data revealed that listeners improved in understanding all speakers with dysarthria; however, intelligibility performance was superior for the speakers encountered during familiarization. To follow up, Borrie et al. (2017a) carried out a large-scale study involving 160 listeners and eight different familiarization conditions, each representing a different speaker with dysarthria or a control speaker with neurotypical speech. Following familiarization, all listeners were tested on the same speaker with ataxic dysarthria. The results showed that listeners familiarized with a speaker with dysarthria, regardless of speech characteristics, were better at understanding

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

the novel test speaker with dysarthria relative to the control condition. However, the magnitude of intelligibility benefit was predicted by the level of perceptual similarity between the test speaker and the familiarization speaker. The role of perceptual similarity in generalized adaptation to dysarthric speech was confirmed in a follow-up study by Hirsch et al. (2021), who further evidenced that learning generalized across speaker sex. Taken together, the results of these studies suggest that listeners are sensitive to shared structure across speakers with dysarthria (i.e., slow speaking rate, imprecise consonants, reduced vowel space; see Weismer & Kim, 2010) and can leverage these dysarthria-general cues when a new speaker with dysarthria is encountered. However, the findings also point to the utility of the speaker-specific experience; that is, the generative model established during the dysarthria familiarization experience will be most advantageous when applied to the same speaker. These theoretical assumptions and their application to dysarthria are further supported by the most recent study in this body of work: Borrie et al. (2021) found that while clinicians who regularly interact with patients with neurological speech disorders are better at understanding a novel speaker with dysarthria on initial encounter, they still derived a substantial perceptual benefit from a structured speaker-specific familiarization experience.

Ecological Validity

Finally, the literature has also confirmed that perceptual learning to improve listener understanding of dysarthria is ecologically valid. Early studies of perceptual learning of dysarthric speech were carried out in highly controlled laboratory environments, largely relying on convenience samples of college students (e.g., Borrie et al., 2013; Hustad & Cahill, 2003; Liss et al., 2002). However, Lansford et al. (2016) crowdsourced a perceptual learning study on Amazon Mechanical Turk (MTurk),[1] collecting data from 50 participants across the United States. These participants completed the perceptual learning protocol on their own devices via a web-based data collection program. While participants were instructed to use headphones, compliance was not monitored. The same experiment was also carried out on a dedicated computer in a research laboratory, a quiet room set up to minimize auditory and visual distractions, with participants recruited from the undergraduate student population. Participants who completed the study in the lab were fitted with sound-attenuating headphones, and the experimenter remained present throughout the experiment. Despite large differences in the experimental environments, the study found no difference between the learning achieved by MTurk participants versus that achieved by lab participants. That is, the intelligibility scores of listeners familiarized with dysarthric speech were significantly greater than those of listeners familiarized with control speech, yet the magnitude of benefit was not affected by the environment. That comparable perceptual gains could be elicited in more real-life settings, such as at home, in front of a personal computer or an iPad without supervision, provided important ecological validation for perceptual learning paradigms, particularly relevant given the rise of telepractice and computer-based home interventions in speech-language pathology. Furthermore, the study opened up a new avenue for data collection, remote online experiments, which allowed for efficient sampling of much more heterogeneous participants and was thus the data collection strategy for a number of subsequent studies (Borrie et al., 2017a, 2018, 2021; Hirsch et al., 2021; Lansford et al., 2019, 2020).

Next Steps: Listener-Targeted Perceptual Training

To date, the body of work investigating perceptual learning of dysarthric speech shows that listeners can be trained to better understand dysarthric speech, acquiring distributional knowledge about how the (initially) ambiguous acoustic realizations are mapped onto linguistic representations of speech. Thus, as called for in the initial review by Borrie, McAuliffe, and Liss (2012), rigorous evidence and a theoretical account supporting the extension of dysarthria management to listener-targeted remediation have now been established. While seemingly novel, training communication partners to better understand the speech of a person with dysarthria falls well within the World Health Organization's International Classification of Functioning, Disability and Health framework (World Health Organization, 2001), which advocates for clinical management that enables individuals with communication disorders to participate in meaningful life situations. Clinical utility of a perceptual learning approach has certainly been evidenced through statistically significant intelligibility improvements obtained both within and outside the laboratory; generalization of learning across dysarthrias; and demonstrations of the task, listener, and speaker parameters that mediate learning of the neurologically degraded speech signal. However, to move this work toward clinical implementation, translational studies establishing best practice and candidacy for listener-targeted perceptual training programs should ensue.

Optimal Perceptual Training Protocol

Like the development of any clinical intervention program, establishing the optimal perceptual training protocol will be essential. We see three key aspects of the existing familiarization paradigm that should receive initial attention—feedback, material, and dosage. As previously discussed, there are indications for using both lexical and somatosensory feedback during familiarization (Borrie & Schäfer, 2015, 2017). However, more studies in this area, guided by general learning principles, are needed, particularly regarding how type and amount of feedback could

[1]Amazon MTurk is an online labor market where requesters (e.g., researchers) can post jobs (e.g., experiments) and workers (e.g., participants) can self-select to complete them for monetary reimbursement.

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

be used to optimize performance gains. In terms of materials (i.e., familiarization stimuli), early studies reported no difference in the magnitude of intelligibility improvement when word list versus passage/paragraph-level productions were used to familiarize listeners with the degraded speech signal (D'Innocenzo et al., 2006; Tjaden & Liss, 1995b). However, findings from Borrie, McAuliffe, Liss, Kirk, et al. (2012) and Borrie, McAuliffe, Liss, O'Beirne, and Anderson (2012) revealed a substantial perceptual benefit for utilizing linguistically rich passage-level stimuli relative to semantically anomalous stimuli. One could also imagine that meaningful and functional materials relevant to the particular communication dyad may be advantageous. Thus, establishing the optimal familiarization paradigm also requires systematic attention to the potential differential value of familiarization materials. Additionally, while rigorous evidence and a theoretical account of perceptual learning of dysarthric speech have been documented using relatively brief familiarization experiences, it will be imperative to determine optimum dosage and frequency of perceptual training. Indeed, it may be the case that there is an upper limit of gain associated with this brief familiarization experience but that gains could be optimized with a more extensive perceptual training protocol.

A key outcome of any intervention approach is ensuring maintenance of learning over time. Accordingly, efforts to establish an optimal perceptual training protocol will need to consider both the magnitude of immediate improvement and the longevity of improvements. To date, maintenance of intelligibility benefits has been reported up to 1 month following an initial familiarization experience (Borrie & Schäfer, 2017; Kim & Nanney, 2014), suggesting that relatively long-lasting changes to the speech perceptual system can be realized for listeners familiarized with dysarthric speech. However, further examination of maintenance will be required as investigations target manipulations of the familiarization paradigm with the goal of optimizing performance outcomes.

Listener and Speaker Candidacy

In terms of candidacy for perceptual training, we can leverage previous studies that examined listener and speaker parameters that mediate learning outcomes. Although earlier studies examined how select listener parameters, including rhythm perception, age and hearing status, and prior experience, influence intelligibility following familiarization with dysarthria speech, these parameters have not been systematically examined within a large and diverse cohort of listeners across a heterogeneous corpus of speakers. Furthermore, cognitive factors (e.g., working memory, inhibitory control) revealed to interact with listener age and hearing status to support dysarthric speech perception (Ingvalson et al., 2017) have not been examined relative to the familiarization experience. Thus, to establish listener candidacy, studies should be conducted with a wide range of listeners, including spouses and caregivers of individuals with dysarthria, accounting for listener parameters that have already been shown to mediate intelligibility improvements and other unexamined parameters that likely implicate learning.

Regarding speaker candidacy, as outlined, recent findings suggest that a perceptual training approach may not be a viable option for individuals whose speech is primarily characterized by unpredictable speech degradations. While findings of negligible learning following familiarization were limited to speakers with hyperkinetic dysarthria (Borrie et al., 2018; Lansford et al., 2019, 2020), reduced signal predictability may be present in other forms of progressive neurological disease that result in motor instability, which may worsen as the disease progresses (e.g., cerebellar degeneration, PD). Candidacy decisions then may best be guided by the level of predictability available in the speech signal and not dysarthria subtype. Toward this end, measurement procedures that accurately quantify predictability in the speech signal will be essential for rigorous examination of this construct across speakers with dysarthria.

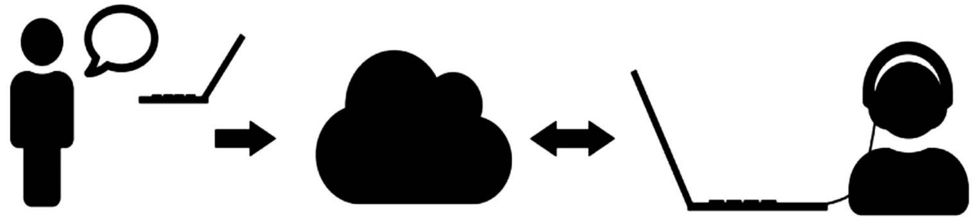
Additionally, it seems highly likely that intelligibility impairment or overall severity of dysarthria will inform decisions regarding speaker candidacy. This parameter has not been systematically addressed in the dysarthria literature to date. However, Borrie et al. (2017a) found reduced intelligibility improvement following familiarization with dysarthrias with lower levels of intelligibility, and an early study by Garcia and Cannito (1996) reported no intelligibility improvement following passive familiarization with a speaker with severe (flaccid) dysarthria. Indeed, studies with foreign-accented speech have observed that a more intelligible speech signal aids perceptual learning (e.g., Bradlow & Bent, 2008; Guediche et al., 2016). Ostensibly, severely degraded acoustic cues would challenge cue-to-category mappings. This hypothesis, particularly as it relates to candidacy decisions, must be thoroughly investigated with dysarthria.

Parameter Interactions and Clinical Realization

Importantly, understanding how task, listener, and speaker parameters may interact to optimize perceptual benefit is a critical piece of the puzzle. For example, one could imagine that intelligibility gains for dysarthria characterized by lower levels of signal predictability may be possible for listeners with expertise in rhythm perception, that severe dysarthria may require greater familiarization dosage, and that naive listeners may benefit from additional feedback during the familiarization experience. These examples of possible parameter interactions are, of course, not exhaustive but illustrate how particular combinations could inform both candidacy decisions and the subsequent intervention protocol. Figure 1 highlights how, with the additional studies outlined above, an online, customizable tool to deliver listener-targeted perceptual training for dysarthria remediation could eventually be realized. We envision both speakers and listeners access a web-enabled tool: The speaker would complete several speech production tasks. The uploaded stimuli would then be analyzed for speaker parameters (e.g., signal predictability, severity) and subsequently serve as training material. The listener would

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Figure 1. Envisioned tool for listener-targeted perceptual training for dysarthria remediation.



complete demographic details and tasks designed to estimate listener parameters (e.g., prior experience, rhythm perception). The obtained speaker and listener parameters would be modeled jointly to determine candidacy and generate an optimized familiarization experience. While this clinical scenario is, at present, hypothetical, it could be realized with translational studies that systematically investigate clinical implantation of listener-targeted perceptual training programs.

Primarily, the goal of a perceptual learning rehabilitation approach, listener-targeted perceptual training, would be to increase intelligibility through improved signal processing for the trained communication partner. As acknowledged by Borrie, McAuliffe, and Liss (2012), dysarthria interventions that facilitate improvements in universal verbal interactions are the ultimate goal; however, any approach that improves communication outcomes affords significant clinical application. A listener-targeted perceptual training approach to ease the intelligibility burden of dysarthria might be particularly applicable for speakers who cannot behaviorally modify their speech or when co-occurring deficits limit the utility of augmentative or alternative communication. However, a perceptual training approach could also be used alongside existing interventions to maximize communication outcomes with particular communication partners.

Conclusions

Early studies of perceptual learning of dysarthria speech, those summarized in the 2012 review, yielded preliminary evidence to suggest that listeners could learn to better understand a novel speaker with dysarthria, revealing a potentially promising avenue for future intelligibility interventions. Since then, a programmatic body of work grounded in models of perceptual processing has unfolded, establishing strong empirical evidence of intelligibility improvements following familiarization with dysarthric speech and a theoretical account of the mechanisms that facilitate improved processing of the neurologically degraded speech signal. Thus, there is now robust support for a perceptual learning approach for dysarthria remediation. To move toward clinical implementation, translational studies are needed to establish best practices for listener-targeted perceptual training programs.

Acknowledgments

This research was supported by National Institute on Deafness and Other Communication Disorders Grant R21DC018867, awarded to Stephanie A. Borrie and Kaitlin L. Lansford.

References

Ansel, B. M., & Kent, R. D. (1992). Acoustic–phonetic contrasts and intelligibility in the dysarthria associated with mixed cerebral palsy. *Journal of Speech and Hearing Research, 35*(2), 296–308. https://doi.org/10.1044/jshr.3502.296

Barnish, M. S., Horton, S. M. C., Butterfint, Z. R., Clark, A. B., Atkinson, R. A., & Deane, K. H. O. (2017). Speech and communication in Parkinson's disease: A cross-sectional exploratory study in the UK. *BMJ Open*, *7*(5), Article e014642. https://doi.org/10.1136/bmjopen-2016-014642

Bent, T., Baese-Berk, M., Borrie, S. A., & McKee, M. (2016). Individual differences in the perception of regional, nonnative, and disordered speech varieties. *The Journal of the Acoustical Society of America, 140*(5), 3775–3786. https://doi.org/10.1121/1.4966677

Bieber, R. E., & Gordon-Salant, S. (2021). Improving older adults' understanding of challenging speech: Auditory training, rapid adaptation and perceptual learning. *Hearing Research, 402,* 108054. https://doi.org/10.1016/j.heares.2020.108054

Borrie, S. A., Baese-Berk, M., Van Engen, K., & Bent, T. (2017). A relationship between processing speech in noise and dysarthric speech. *The Journal of the Acoustical Society of America, 141*(6), 4660–4667. https://doi.org/10.1121/1.4986746

Borrie, S. A., Lansford, K. L., & Barrett, T. S. (2017a). Generalized adaptation to dysarthric speech. *Journal of Speech, Language, and Hearing Research, 60*(11), 3110–3117. https://doi.org/10.1044/2017_JSLHR-S-17-0127

Borrie, S. A., Lansford, K. L., & Barrett, T. S. (2017b). Rhythm perception and its role in perception and learning of dysrhythmic speech. *Journal of Speech, Language, and Hearing Research, 60*(3), 561–570. https://doi.org/10.1044/2016_JSLHR-S-16-0094

Borrie, S. A., Lansford, K. L., & Barrett, T. S. (2018). Understanding dysrhythmic speech: When rhythm does not matter and learning does not happen. *The Journal of the Acoustical Society of America, 143*(5), EL379–EL385. https://doi.org/10.1121/1.5037620

Borrie, S. A., Lansford, K. L., & Barrett, T. S. (2021). A clinical advantage: Experience informs recognition and adaptation to a novel talker with dysarthria. *Journal of Speech, Language,*

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

and Hearing Research, 64(5), 1503–1514. https://doi.org/2021_JSLHR-20-00663

Borrie, S. A., McAuliffe, M. J., & Liss, J. M. (2012). Perceptual learning of dysarthric speech: A review of experimental studies. *Journal of Speech, Language, and Hearing Research, 55*(1), 290–305. https://doi.org/10.1044/1092-4388(2011/10-0349)

Borrie, S. A., McAuliffe, M. J., Liss, J. M., Kirk, C., O'Beirne, G. A., & Anderson, T. (2012). Familiarisation conditions and the mechanisms that underlie improved recognition of dysarthric speech. *Language and Cognitive Processes, 27*(7–8), 1039–1055. https://doi.org/10.1080/01690965.2011.610596

Borrie, S. A., McAuliffe, M. J., Liss, J. M., O'Beirne, G. A., & Anderson, T. J. (2012). A follow-up investigation into the mechanisms that underlie improved recognition of dysarthric speech. *The Journal of the Acoustical Society of America, 132*(2), EL102–EL108. https://doi.org/10.1121/1.4736952

Borrie, S. A., McAuliffe, M. J., Liss, J. M., O'Beirne, G. A., & Anderson, T. J. (2013). The role of linguistic and indexical information in improved recognition of dysarthric speech. *The Journal of the Acoustical Society of America, 133*(1), 474–482. https://doi.org/10.1121/1.4770239

Borrie, S. A., & Schäfer, M. C. M. (2015). The role of somatosensory information in speech perception: Imitation improves recognition of disordered speech. *Journal of Speech, Language, and Hearing Research, 58*(6), 1708–1716. https://doi.org/10.1044/2015_JSLHR-S-15-0163

Borrie, S. A., & Schäfer, M. C. M. (2017). Effects of lexical and somatosensory feedback on long-term improvements in intelligibility of dysarthric speech. *Journal of Speech, Language, and Hearing Research, 60*(8), 2151–2158. https://doi.org/10.1044/2017_JSLHR-S-16-0411

Bradlow, A. R., & Bent, T. (2008). Perceptual adaptation to non-native speech. *Cognition, 106*(2), 707–729. https://doi.org/10.1016/j.cognition.2007.04.005

Clarke, C. M., & Garrett, M. F. (2004). Rapid adaptation to foreign-accented English. *The Journal of the Acoustical Society of America, 116*(6), 3647–3658. https://doi.org/10.1121/1.1815131

Clayards, M., Tanenhaus, M. K., Aslin, R. N., & Jacobs, R. A. (2008). Perception of speech reflects optimal use of probabilistic speech cues. *Cognition, 108*(3), 804–809. https://doi.org/10.1016/j.cognition.2008.04.004

Davis, M. H., & Johnsrude, I. S. (2007). Hearing speech sounds: Top-down influences on the interface between audition and speech perception. *Hearing Research, 229*(1–2), 132–147. https://doi.org/10.1016/j.heares.2007.01.014

Davis, M. H., Johnsrude, I. S., Hervais-Adelman, A., Taylor, K., & McGettigan, C. (2005). Lexical information drives perceptual learning of distorted speech: Evidence from the comprehension of noise-vocoded sentences. *Journal of Experimental Psychology: General, 134*(2), 222–241. https://doi.org/10.1037/0096-3445.134.2.222

D'Innocenzo, J., Tjaden, K., & Greenman, G. (2006). Intelligibility in dysarthria: Effects of listener familiarity and speaking condition. *Clinical Linguistics & Phonetics, 20*(9), 659–675. https://doi.org/10.1080/02699200500224272

Dupoux, E., & Green, K. (1997). Perceptual adjustment to highly compressed speech: Effects of talker and rate changes. *Journal of Experimental Psychology: Human Perception and Performance, 23*(3), 914–927. https://doi.org/10.1037//0096-1523.23.3.914

Eisner, F., & McQueen, J. M. (2005). The specificity of perceptual learning in speech processing. *Perception & Psychophysics, 67*(2), 224–238. https://doi.org/10.3758/BF03206487

Fairbanks, G. (1960). Voice and articulation drillbook (2nd ed.). Harper & Row.

Feldman, N. H., Griffiths, T. L., & Morgan, J. L. (2009). The influence of categories on perception: Explaining the perceptual magnet effect as optimal statistical inference. *Psychological Review, 116*(4), 752–782. https://doi.org/10.1037/a0017196

Francis, A. L., Nusbaum, H. C., & Fenn, K. (2007). Effects of training on the acoustic–phonetic representation of synthetic speech. *Journal of Speech, Language, and Hearing Research, 50*(6), 1445–1465. https://doi.org/10.1044/1092-4388(2007/100)

Garcia, J. M., & Cannito, M. P. (1996). Influence of verbal and nonverbal contexts on the sentence intelligibility of a speaker with dysarthria. *Journal of Speech and Hearing Research, 39*(4), 750–760. https://doi.org/10.1044/jshr.3904.750

Golfinopoulos, E., Tourville, J. A., & Guenther, F. H. (2010). The integration of large-scale neural network modeling and functional brain imaging in speech motor control. *NeuroImage, 52*(3), 862–874. https://doi.org/10.1016/j.neuroimage.2009.10.023

Golomb, J. D., Peelle, J. E., & Wingfield, A. (2007). Effects of stimulus variability and adult aging on adaptation to time-compressed speech. *The Journal of the Acoustical Society of America, 121*(3), 1701–1708. https://doi.org/10.1121/1.2436635

Greenspan, S. L., Nusbaum, H. C., & Pisoni, D. B. (1988). Perceptual learning of synthetic speech produced by rule. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14*(3), 421–433. https://doi.org/10.1037/0278-7393.14.3.421

Guediche, S., Blumstein, S. E., Fiez, J. A., & Holt, L. L. (2014). Speech perception under adverse conditions: Insights from behavioral, computational, and neuroscience research. *Frontiers in Systems Neuroscience, 7,* 126. https://doi.org/10.3389/fnsys.2013.00126

Guediche, S., Fiez, J. A., & Holt, L. L. (2016). Adaptive plasticity in speech perception: Effects of external information and internal predictions. *Journal of Experimental Psychology: Human Perception and Performance, 42*(7), 1048–1059. https://doi.org/10.1037/xhp0000196

Guenther, F. H., Hampson, M., & Johnson, D. (1998). A theoretical investigation of reference frames for the planning of speech movements. *Psychological Review, 105*(4), 611–633. https://doi.org/10.1037/0033-295X.105.4.611-633

Herd, C. P., Tomlinson, C. L., Deane, K. H. O., Brady, M. C., Smith, C. H., Sackley, C. M., & Clarke, C. E. (2012). Comparison of speech and language therapy techniques for speech problems in Parkinson's disease. *Cochrane Database of Systematic Reviews, 2012*(8), CD002814. https://doi.org/10.1002/14651858.CD002814.pub2

Hirsch, M. E., Lansford, K. L., Barrett, T. S., & Borrie, S. A. (2021). Generalized learning of dysarthric speech between male and female talkers. *Journal of Speech, Language, and Hearing Research, 64*(2), 444–451. https://doi.org/10.1044/2020_JSLHR-20-00313

Hustad, K. C., & Cahill, M. A. (2003). Effects of presentation mode and repeated familiarization on intelligibility of dysarthric speech. *American Journal of Speech-Language Pathology, 12*(2), 198–208. https://doi.org/10.1044/1058-0360(2003/066)

Ingvalson, E. M., Lansford, K. L., Fedorova, V., & Fernandez, G. (2017). Cognitive factors as predictors of accented speech perception for younger and older adults. *The Journal of the Acoustical Society of America, 141*(6), 4652–4659. https://doi.org/10.1121/1.4986930

Kim, H. (2015). Familiarization effects on consonant intelligibility in dysarthric speech. *Folia Phoniatrica et Logopaedica, 67*(5), 245–252. https://doi.org/10.1159/000444255

Kim, H., & Nanney, S. (2014). Familiarization effects on word intelligibility in dysarthric speech. *Folia Phoniatrica et Logopaedica, 66*(6), 258–264. https://doi.org/10.1159/000369799

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions

Kleinschmidt, D. F., & Jaeger, T. F. (2015). Robust speech perception: Recognize the familiar, generalize to the similar, and adapt to the novel. *Psychological Review, 122*(2), 148–203. https://doi.org/10.1037/a0038695

Kraljic, T., & Samuel, A. G. (2007). Perceptual adjustments to multiple speakers. *Journal of Memory and Language, 56*(1), 1–15. https://doi.org/10.1016/j.jml.2006.07.010

Lansford, K. L., Borrie, S. A., & Barrett, T. S. (2019). Regularity matters: Unpredictable speech degradation inhibits adaptation to dysarthric speech. *Journal of Speech, Language, and Hearing Research, 62*(12), 4282–4290. https://doi.org/10.1044/2019_JSLHR-19-00055

Lansford, K. L., Borrie, S. A., Barrett, T. S., & Flechaus, C. (2020). When additional training isn't enough: Further evidence that unpredictable speech inhibits adaptation. *Journal of Speech, Language, and Hearing Research, 63*(3), 1700–1711. https://doi.org/10.1044/2020_JSLHR-19-00380

Lansford, K. L., Borrie, S. A., & Bystricky, L. (2016). Use of crowdsourcing to assess the ecological validity of perceptual-training paradigms in dysarthria. *American Journal of Speech-Language Pathology, 25*(2), 233–239. https://doi.org/10.1044/2015_AJSLP-15-0059

Lansford, K. L., Luhrsen, S., Ingvalson, E. M., & Borrie, S. A. (2018). Effects of familiarization on intelligibility of dysarthric speech in older adults with and without hearing loss. *American Journal of Speech-Language Pathology, 27*(1), 91–98. https://doi.org/10.1044/2017_AJSLP-17-0090

Liss, J. M. (2007). The role of speech perception in motor speech disorders. In G. Weismer (Ed.), *Motor speech disorders: Essays for Ray Kent* (pp. 187–219). Plural.

Liss, J. M., Spitzer, S. M., Caviness, J. N., & Adler, C. (2002). The effects of familiarization on intelligibility and lexical segmentation in hypokinetic and ataxic dysarthria. *The Journal of the Acoustical Society of America, 112*(6), 3022–3030. https://doi.org/10.1121/1.1515793

Loebach, J. L., Bent, T., & Pisoni, D. B. (2008). Multiple routes to the perceptual learning of speech. *The Journal of the Acoustical Society of America, 124*(1), 552–561. https://doi.org/10.1121/1.2931948

Mattys, S. L., White, L., & Melhorn, J. F. (2005). Integration of multiple speech segmentation cues: A hierarchical framework. *Journal of Experimental Psychology: General, 134*(4), 477–500. https://doi.org/10.1037/0096-3445.134.4.477

McAuliffe, M. J., Borrie, S. A., Good, P. V., & Hughes, L. E. (2010). Consideration of the listener in the assessment and treatment of dysarthria. *ACQuiring Knowledge in Speech, Language and Hearing, 12,* 16–19. http://hdl.handle.net/10092/5259

McAuliffe, M. J., Gibson, E. M. R., Kerr, S. E., Anderson, T., & LaShell, P. J. (2013). Vocabulary influences older and younger listeners' processing of dysarthric speech. *The Journal of the Acoustical Society of America, 134*(2), 1358–1368. https://doi.org/10.1121/1.4812764

Mitchell, C., Bowen, A., Tyson, S., Butterfint, Z., & Conroy, P. (2017). Interventions for dysarthria due to stroke and other adult-acquired, non-progressive brain injury. *Cochrane Database of Systematic Reviews, 1*(1), CD002088. https://doi.org/10.1002/14651858.CD002088.pub3

Nash, S. D., Cruickshanks, K. J., Klein, R., Klein, B. E. K., Nieto, F. J., Huang, G. H., Pankow, J. S., & Tweed, T. S. (2011). The prevalence of hearing impairment and associated risk factors: The Beaver Dam Offspring Study. *Archives of Otolaryngology—Head & Neck Surgery, 137*(5), 432–439. https://doi.org/10.1001/archoto.2011.15

Samuel, A. G., & Kraljic, T. (2009). Perceptual learning for speech. *Attention, Perception, & Psychophysics, 71*(6), 1207–1218. https://doi.org/10.3758/APP.71.6.1207

Sidaras, S. K., Alexander, J. E. D., & Nygaard, L. C. (2009). Perceptual learning of systematic variation in Spanish-accented speech. *The Journal of the Acoustical Society of America, 125*(5), 3306–3316. https://doi.org/10.1121/1.3101452

Sixt Börjesson, M., Hartelius, L., & Laakso, K. (2021). Communicative participation in people with amyotrophic lateral sclerosis. *Folia Phoniatrica et Logopaedica, 73*(2), 101–108. https://doi.org/10.1159/000505022

Spencer, K. A., Friedlander, C., & Brown, K. A. (2020). Predictors of health-related quality of life and communicative participation in individuals with dysarthria from Parkinson's disease. *International Journal of Neurodegenerative Disorders, 3*(1), 014. http://doi.org/10.23937/2643-4539/1710014

Spitzer, S. M., Liss, J. M., Caviness, J. N., & Adler, C. (2000). An exploration of familiarization effects in the perception of hypokinetic and ataxic dysarthric speech. *Journal of Medical Speech-Language Pathology, 8*(4), 285–293.

Stipancic, K. L., Tjaden, K., & Wilding, G. (2016). Comparison of intelligibility measures for adults with Parkinson's disease, adults with multiple sclerosis, and healthy controls. *Journal of Speech, Language, and Hearing Research, 59*(2), 230–238. https://doi.org/10.1044/2015_JSLHR-S-15-0271

Stipancic, K. L., Yunusova, Y., Berry, J. D., & Green, J. R. (2018). Minimally detectable change and minimal clinically important difference of a decline in sentence intelligibility and speaking rate for individuals with amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research, 61*(11), 2757–2771. https://doi.org/10.1044/2018_JSLHR-S-17-0366

Tjaden, K. K., & Liss, J. M. (1995a). The influence of familiarity on judgments of treated speech. *American Journal of Speech-Language Pathology, 4*(1), 39–48. https://doi.org/10.1044/1058-0360.0401.39

Tjaden, K. K., & Liss, J. M. (1995b). The role of listener familiarity in the perception of dysarthric speech. *Clinical Linguistics & Phonetics, 9*(2), 139–154. https://doi.org/10.3109/02699209508985329

Van Nuffelen, G., De Bodt, M., Vanderwegen, J., Van de Heyning, P., & Wuyts, F. (2010). Effect of rate control on speech production and intelligibility in dysarthria. *Folia Phoniatrica et Logopaedica, 62*(3), 110–119. https://doi.org/10.1159/000287209

Weismer, G., & Kim, Y. (2010). Classification and taxonomy of motor speech disorders: What are the issues? In B. Maassen & P. van Lieshout (Eds.), *Speech motor control: New developments in basic and applied research* (pp. 229–242). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199235797.003.0013

World Health Organization. (2001). *International Classification of Functioning, Disability and Health: ICF.*

Yorkston, K. M., & Beukelman, D. R. (1983). The influence of judge familiarization with the speaker on dysarthric speech intelligibility. In W. R. Berry (Ed.), *Clinical dysarthria* (pp. 155–164). College-Hill Press.

Yorkston, K. M., Beukelman, D. R., & Bell, K. R. (1988). *Clinical management of dysarthric speakers*. Pro-Ed.

Downloaded from: https://pubs.asha.org Stephanie Borrie on 08/09/2021, Terms of Use: https://pubs.asha.org/pubs/rights_and_permissions