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Perceptual Learning of Dysarthria in Adolescence

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ABSTRACT

Purpose: As evidenced by perceptual learning studies involving adult listeners and speakers with dysarthria, adaptation to dysarthric speech is driven by signal predictability (speaker property) and a flexible speech perception system (listener property). Here, we extend adaptation investigations to adolescent populations and examine whether adult and adolescent listeners can learn to better understand an adolescent speaker with dysarthria.

Method: Classified by developmental stage, adult (n = 42) and adolescent (n = 40) listeners completed a three-phase perceptual learning protocol (pretest, familiarization, and posttest). During pretest and posttest, all listeners transcribed speech produced by a 13-year-old adolescent with spastic dysarthria associated with cerebral palsy. During familiarization, half of the adult and adolescent listeners engaged in structured familiarization (audio and lexical feedback) with the speech of the adolescent speaker with dysarthria; and the other half, with the speech of a neurotypical adolescent speaker (control).

Results: Intelligibility scores increased from pretest to posttest for all listeners. However, listeners who received dysarthria familiarization achieved greater intelligibility improvements than those who received control familiarization. Furthermore, there was a significant effect of developmental stage, where the adults achieved greater intelligibility improvements relative to the adolescents.

Conclusions: This study provides the first tranche of evidence that adolescent dysarthric speech is learnable—a finding that holds even for adolescent listeners whose speech perception systems are not yet fully developed. Given the formative role that social interactions play during adolescence, these findings of improved intelligibility afford important clinical implications.

To decipher speech, listeners must parse the continuous, incoming signal into word-sized frames and map them onto discrete meanings stored in the memory. While generally an accurate process, reflected in successfully understanding the spoken message, inaccuracies, and thus communication breakdowns, arise when the speech signal is degraded, as is the case with dysarthria. However, a large body of literature with adult populations has evidenced that, with experience, listeners can adapt to the dysarthric speech signal: Neurotypical adult listeners familiarized with the speech of adult speakers with dysarthria show significant improvements in intelligibility performance relative to listeners familiarized with neurotypical, control speech (see Borrie & Lansford, 2021, for a review). This experience-induced adaptation is known as perceptual learning. The phenomenon of perceptual learning of noncanonical adult speech has also been extensively studied in experimental paradigms with laboratory-modified speech, including synthetic (e.g., Francis et al., 2007; Greenspan et al., 1988), noise-vocoded (e.g., Davis et al., 2005; 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). According to theoretical models, experience with the

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noncanonical 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).

Signal predictability (speaker property) drives the perceptual learning phenomenon: During familiarization, listeners exploit statistical regularities available in the speech signal, subsequently retuning their linguistic categories to account for the aberrant, yet still informative, acoustic–phonetic information (Kleinschmidt & Jaeger, 2015). Empirical support for this theoretical account of perceptual learning of speech has been well documented in the dysarthria literature. Intelligibility improvements for listeners familiarized with types of dysarthria that present with relatively consistent segmental and suprasegmental degradations (e.g., spastic, hypokinetic, ataxic) have been reliably observed across the literature (e.g., Borrie et al., 2012, 2017a; Borrie & Schäfer, 2015). In contrast, intelligibility improvements have not been observed for listeners familiarized with hyperkinetic dysarthria—a speech signal in which the degradations (e.g., irregular articulatory breakdowns, inappropriate silences, variable rate, and rhythm) are largely unpredictable (Borrie et al., 2018; Lansford et al., 2019, 2020).

Perceptual learning also requires that listeners identify and acquire knowledge of a speaker's underlying cue distributions. Thus, in addition to signal predictability, perceptual learning is driven by a flexible speech perception system (listener property). In a study examining the perception of degraded speech (i.e., dysarthric speech and speech in noise), Borrie, Baese-Berk, et al. (2017) found that intelligibility performance was predicted by the listener's ability to adapt their perceptual strategies to identify and extract salient acoustic information from the impoverished speech signals. Relatedly, cognitive–linguistic resources have been implicated in supporting perceptual learning of dysarthric speech. While relationships were complex, a recent large-scale study involving 156 adult listeners revealed that cognitive–linguistic abilities, including vocabulary knowledge, working memory, and cognitive flexibility, predicted the extent to which listeners benefited from familiarization with dysarthric speech (Lansford et al., 2023).

While perceptual learning of dysarthric speech has been well evidenced in adult populations (e.g., Borrie et al., 2017b; Lansford et al., 2018), systematic investigations have not extended to younger populations. Yet, according to theoretical postulations of the ideal adaptor framework of speech perception (Kleinschmidt & Jaeger, 2015), there is reason to hypothesize that learning may be challenged when the speaker with dysarthria is an adolescent. Adolescence is a time of rapid and extensive changes across several realms, including the ongoing development of motor control and continuing maturation of motor planning strategies (Sadagopan & Smith, 2008). As such, the speech-motor behaviors of adolescents are more variable than those of adults (e.g., Smith & Zelaznik, 2004; Walsh & Smith, 2002). This increased speech variability translates to reduced acoustic predictability in both segmental (Jacewicz et al., 2021; Kent & Rountrey, 2020; Smith & Zelaznik, 2004) and suprasegmental (Sadagopan & Smith, 2008; Walsh & Smith, 2002) properties of the signal. Cerebral palsy (CP), a common cause of dysarthria in adolescence, likely intensifies the perceptual consequences of such increased speech-motor variability in adolescent speakers. Indeed, intelligibility impairments in CP are associated with characteristics such as irregular speech breathing (short phrases or rapid speech production on short breath cycles), imprecise articulation, and hypernasal speech (e.g., Hodge & Wellman, 1999; Yorkston et al., 1999). Currently, we know of no studies that have examined perceptual learning of adolescent speech. However, given that signal predictability is reduced, particularly for adolescents with dysarthria, it is plausible that adolescent speech may be less amenable to perceptual learning.

Empirical findings suggest that learning may be reduced when the listeners are adolescents. While speech precepts emerge in infancy (e.g., Houston & Jusczyk, 2000; van Heugten & Johnson, 2012), children's speech perception abilities continue to develop into adolescence (e.g., Bent, 2018; Hazan & Barrett, 2000; Jones et al., 2017; McCullough et al., 2019; McMurray et al., 2018). For example, processing of suprasegmental (i.e., temporal) cues has been shown to be a later developing precept (e.g., Banai et al., 2011; Dawes & Bishop, 2008). Relatedly, the cognitive–linguistic processes that support a flexible speech perception system, including working memory (e.g., Ferguson et al., 2021; Mizuno et al., 2011), vocabulary knowledge (e.g., Duff & Brydon, 2020; Ricketts et al., 2020), and cognitive flexibility (e.g., Luna et al., 2004; Williams et al., 1999), continue to mature throughout adolescence. While the literature on adolescent perception of any type of speech is sparse, evidence suggests developmental differences between adolescents and adults in deciphering an improvised speech signal. In a study examining the perception and learning of noise-vocoded speech—a spectrally degraded signal—Huyck (2018) showed that early adolescents (11–13 years old) performed significantly worse than older adolescents (14–16 years old) and young adults (18–22 years old) in their initial perception of the degraded speech, although no age differences were observed in subsequent adaptation to the speech signal. No studies have examined adolescent perception or learning of dysarthric speech; however, given the need to identify and extract salient acoustic information (in both segmental and suprasegmental domains), this type of degraded speech signal may challenge the still-developing adolescent speech perception system.

While important theoretical implications exist for studying perceptual learning in adolescent populations, key being whether the adolescent dysarthric speech contains sufficient signal predictability and whether adolescent listeners have sufficiently developed perceptual systems to support adaptation, it is also of significant clinical value. During adolescence, positive social interactions and friendships become increasingly important, impacting social, emotional, and behavioral development (e.g., Jose et al., 2012; Whitmire, 2000). For example, adolescents who report closer friendships also report a more positive self-concept, higher self-esteem, less loneliness, and lower levels of depression (Levitt et al., 1993; Lodder et al., 2017; Pachucki et al., 2015). It is a little surprise, therefore, that adolescents with communication impairments experience challenges with social interaction, which have been linked with negative consequences on identity, learning, confidence, and quality of friendships (Buckeridge et al., 2020; Durkin & Conti-Ramsden, 2007). In interviews with adolescents with congenital motor speech disorders and their parents, participants reported that the impact of the motor speech disorder on social interactions became increasingly apparent in adolescence relative to the childhood years (Connaghan et al., 2022). This is supported by evidence showing increased reliance on talking during adolescent interactions (Larson, 2001; McNelles & Connolly, 1999; Raffaelli & Duckett, 1989). Key themes that emerged from the interviews in Connaghan et al. (2022) were that adolescents with motor speech disorders experienced negative interactions with peers, including sparse and superficial relationships. In addition, parents reported a desire for interventions that supported successful social interactions. The intelligibility impairments experienced by people with dysarthria result in not only reduced listener understanding and communication breakdowns but also in reduced participation in situations that involve interacting with others (Borrie et al., 2022). As such, adolescents with dysarthria may stand to particularly benefit from an intervention that trains their peers and community to better decipher their speech.

In this study, we examined whether neurotypical adult and adolescent listeners can learn to better understand an adolescent speaker with dysarthria. Specifically, we utilized the speech of a 13-year-old adolescent with spastic dysarthria due to CP whose patient-reported outcome measure of communicative participation indicated that his motor speech disorder restricted his ability to interact and engage with others in a variety of social settings. The following two key research questions were addressed: (a) Does dysarthria familiarization facilitate intelligibility improvements for adult and adolescent listeners? (b) Does the magnitude of intelligibility improvements following dysarthria familiarization differ for adult and adolescent listeners? Despite acknowledgment of increased variability in adolescent speech, given the relatively predictable presentation of spastic dysarthria, and theoretical and empirical evidence of an adaptable speech perception system, we hypothesized greater intelligibility improvements for adult and adolescent listeners familiarized with adolescent dysarthric speech as compared to those familiarized with control speech. However, given evidence that the speech perception system continues to develop throughout adolescence, we hypothesized that intelligibility improvements for adolescent listeners would be reduced relative to adult listeners.

Method

Listener Participants

Data were collected from 44 neurotypical adults, aged 18–49 years (M = 21.33, SD = 5.00), and 41 neurotypical adolescents, aged 12–17 years (M = 14.13, SD = 1.76). Adult and adolescent listeners were native speakers of American English and reported no significant experience interacting with people with motor speech disorders. Additionally, adult and adolescent listeners passed a hearing screening at 20 dB for 1000, 2000, and 4000 Hz in both ears and presented with no cognitive deficits, indicated by scores on the Kaufman Brief Intelligence Test–Second Edition (KBIT-2; Kaufman & Kaufman, 2004). Adult listeners presented with no self-reported language impairment. Language skills of adolescent listeners were confirmed as within normal limits on the Recalling Sentences subtest of the Clinical Evaluation of Language Fundamentals–Fifth Edition (CELF-5; Wiig et al., 2013). The speech productions of all listeners were highly intelligible, with no evidence of impairment. Data from two adults were excluded due to poor task engagement (operationally defined as nonresponses for > 15% of sentences in the pretest phase), and data from one adolescent were excluded due to performance outside of normal limits on the cognitive assessment. Thus, the final data set used in the study analysis was drawn from 42 adult and 40 adolescent listeners. Participants were recruited from Utah State University (USU) and surrounding communities and received course credit or a gift card for participating in the study.

Speakers and Stimuli

Speech stimuli used in this study consisted of audio-recorded productions of testing sentences and familiarization passages produced by a 13-year-old male speaker with moderate dysarthria secondary to CP and familiarization passages produced by a 13-year-old neurotypical male speaker with no evidence of speech impairment. The adolescent speakers who produced the stimuli were both native speakers of American English, with pubescent speech patterns and comparable pitch levels. Both adolescent speakers also presented with no cognitive or language impairments, as indicated by scores on the KBIT-2 and the Following Directions and Recalling Sentences subtests of the CELF-5 (see Table 1 for details). Thus, the key difference between these two speakers was the presence or absence of neurologically degraded speech.

The adolescent speaker with dysarthria exhibited cardinal perceptual features of spastic dysarthria as diagnosed by two certified speech-language pathologists. His speech was characterized by strained–strangled vocal quality, slow speech rate, equal and excess stress, and imprecise articulation. Speech was further classified as moderately impaired, with low levels of speech naturalness. The adolescent speaker with dysarthria scored 22 on the short-form Communicative Participation Item Bank (Baylor et al., 2013), indicating that his dysarthria substantially interfered with his ability to participate in everyday interactions.

The testing sentences consisted of 100 sentences from the Basic English Lexicon nonsense corpus (O'Neill et al., 2020). These sentences are semantically anomalous but syntactically plausible, explicitly designed to restrict the listener's use of higher level cognitive–linguistic information to resolve the speech signal. The sentences range from five to seven simple words, ensuring that adolescent results were not confounded by linguistic complexity. The familiarization passages comprised the Caterpillar Passage (Patel et al., 2013) and the Rainbow Passage (Fairbanks, 1960). These contextual passages commonly used in the dysarthria literature consist of 16 sentences of varying length and sample the entire English phonetic repertoire. The audio recordings of the passage readings were paired with orthographic transcription of the intended targets. The use of linguistically rich passage readings during the familiarization phase has been shown to facilitate cue-to-category mapping during familiarization (e.g., Liss et al., 2002) and optimize learning outcomes at posttest (Borrie, McAuliffe, Liss, Kirk, et al., 2012; Borrie, McAuliffe, Liss, O'Beirne, & Anderson, 2012).

Experimental Paradigm

Perceptual learning of adolescent dysarthric speech was examined using a three-phase, lexically guided perceptual training paradigm (pretest, familiarization, and posttest), used in a body of work examining perceptual learning of dysarthria speech (e.g., Borrie et al., 2017b; Lansford et al., 2018). A lexically guided familiarization phase was selected because hypothesis-driven manipulations of the familiarization task have revealed that perceptual learning of dysarthric speech is superior when the stimuli produced by a speaker with dysarthria are paired with orthographic transcripts of the intended targets (see Borrie & Lansford, 2021, for a review). The paradigm was programmed in Gorilla, an online research platform used to create and host experiments (https://www.gorilla.sc), and was administered via a computer in the Human Interaction Lab at USU. The experiment took place with one listener participant and a research assistant in the laboratory together. After indicating consent and completing a demographic questionnaire, listeners were fitted with headphones. Prior to beginning the perceptual training paradigm, participants were presented with two short audio clips and asked to adjust the volume to a comfortable listening level. The volume remained at this level for the duration of the perceptual tasks. All listeners completed a nearly identical paradigm. However, for the familiarization phase, listeners were randomly assigned to one of these two conditions—half of the adult and adolescent listeners were presented with passages produced by the speaker with dysarthria (i.e., dysarthria condition), while the other half were presented with passages produced by the neurotypical speaker (i.e., control condition). Note that all listeners, regardless of condition, were presented with dysarthric speech during the pretest and posttest phases.

Table 1. Cognition and language scores for the two speakers.

Assessment Subtest	Speaker with dysarthria	Control speaker
Cognition (KBIT-2)		
Verbal	109	112
Nonverbal	128	110
Composite	122	113
Language (CELF-5)		
Following Directions	13	11
Recalling Sentences	13	12

Note. Standard scores are reported. KBIT-2 = Kaufman Brief Intelligence Test–Second Edition; CELF-5 = Clinical Evaluation of Language Fundamentals–Fifth Edition.

During the pretest phase, listener participants were informed that they would be presented with short phrases produced by someone with a speech disorder and that while the phrases all contained real English words, they would not necessarily make sense. Participants were instructed to listen carefully, as they would hear each sentence only once. A random selection of 25 of the 100 training sentences was then presented one at a time to the participant via headphones. Following each presentation, listeners were asked to verbally state what they thought was said. Listeners were encouraged to guess if unsure and were given as much time as necessary to produce a response. The research assistant then typed the listeners' response into the program. Listeners were then asked to confirm that what the research assistant had typed was correct or state any changes that should be made to the response before moving on to the next item. Following the pretest, listeners received familiarization (with dysarthria or control speech) in which they listened to the audio-recorded passages (2 times each) and were instructed to use written subtitles (lexical feedback) displayed on the monitor to help them understand what was being said. No response was required during the familiarization phase. After this, listeners completed the posttest, which was identical in structure to the pretest but presented and requested verbal responses for the remaining 75 testing sentences. Sentence selection and presentation order during testing was randomized across all listener participants.

Transcript Analysis

The data set consisted of orthographic transcripts of the testing stimuli for each listener participant. Transcripts were scored for keywords correct using Autoscore,[1] an open-source computer application for automated intelligibility scoring of orthographic transcriptions (http://autoscore.usu.edu/; Borrie et al., 2019). Words were scored as correct if they matched the intended target exactly or differed only by tense or plurality. Homophones and obvious spelling errors were scored as correct using a list of common misspellings in the testing stimuli created by the second author (T. J. H.). A percent words correct score was tabulated for the pretest and posttest, resulting in a pretest intelligibility score and a posttest intelligibility score for each listener.

Statistical Analysis

To examine intelligibility changes following familiarization with the adolescent speaker with spastic dysarthria, we initially used simple paired-samples *t* tests to assess intelligibility changes from pretest to posttest for all four experimental groups (i.e., adult and adolescent listeners in dysarthria and control familiarization conditions). We then used ordinary least squares (OLS) linear regression to assess differences between posttest intelligibility scores across developmental stage (adult vs. adolescent) and familiarization condition (dysarthria vs. control) while controlling for pretest intelligibility scores (i.e., making participants statistically equal at pretest). This approach allows us to quantify intelligibility improvements following speaker-specific familiarization (i.e., dysarthria condition) relative to those that simply occurred from engaging in the pretest and posttest with the same speaker with dysarthria (i.e., control condition). The OLS regression modeling employed can be generally expressed via the following equation:

$$\begin{aligned} &Posttest\,PWC_i \sim N(\mu_i, \sigma^2) \\ &\mu_i = \beta_0 + \beta_1 \times Pretest\,PWC_i + \beta_2 \\ &\times Familiarization\,Condition_i + \beta_3 \times Development\,Stage_i. \end{aligned} \tag{1}$$

The first regression model examined the main effects of familiarization condition and developmental stage, while a second model examined the interaction between developmental stage and familiarization condition. All analyses were performed in the R statistical environment (R Version 4.2.3; R Development Core Team, 2023). Data cleaning and visualization relied on the tidyverse packages (Wickham et al., 2019). Our second exploratory analysis (see below) also relied on the lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) packages.

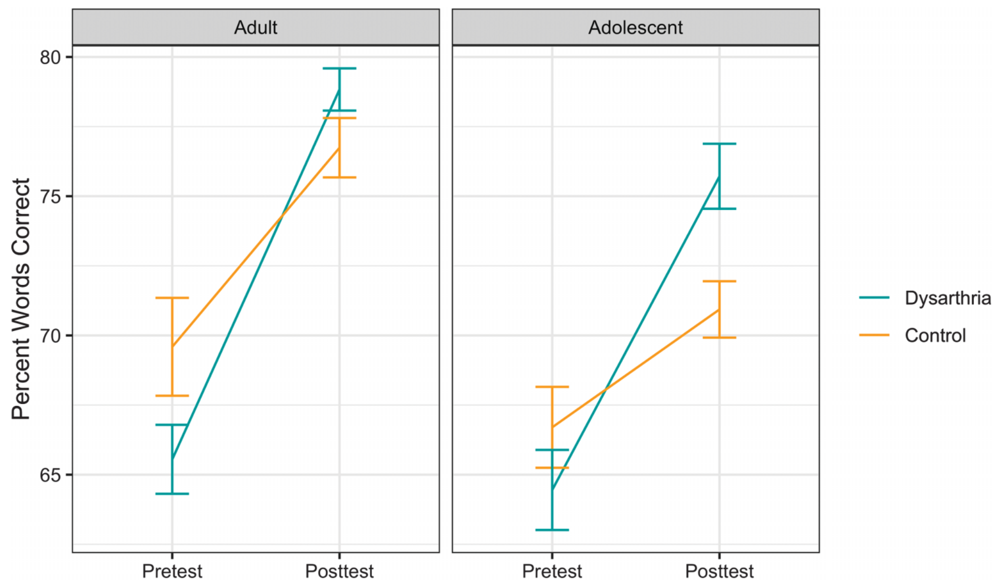
Results

Pretest and posttest intelligibility means for each condition are presented in Figure 1. Simple paired-samples *t* tests indicated a significant increase in intelligibility scores, from pretest to posttest, for all four groups, with 13.28 percentage points, $t(19) = 9.71$, $p < .001$, for adult listeners familiarized with dysarthric speech; 7.15 percentage points, $t(21) = 5.18$, $p < .001$, for adult listeners familiarized with control speech; 11.27 percentage points, $t(19) = 8.98$, $p < .001$, for adolescent listeners familiarized with dysarthric speech; and 4.23 percentage points, $t(19) = 2.75$, $p < .001$, for adolescent listeners familiarized with control speech. Thus, intelligibility increased from pretest to posttest for both developmental stages and both conditions.

Linear regression examined intelligibility improvements across familiarization conditions and developmental stages. Results showed a significant effect of familiarization condition ($b = 4.4$ percentage points, $p < .001$), as illustrated in Figure 2. Specifically, listeners who received

[1]Autoscore has been validated as a highly accurate (99% accuracy) and efficient scoring tool on both in-house and independent data sets (Borrie et al., 2019).

Figure 1. Mean pretest and posttest intelligibility scores by familiarization condition and developmental stage. The error bars represent ±1 standard error.

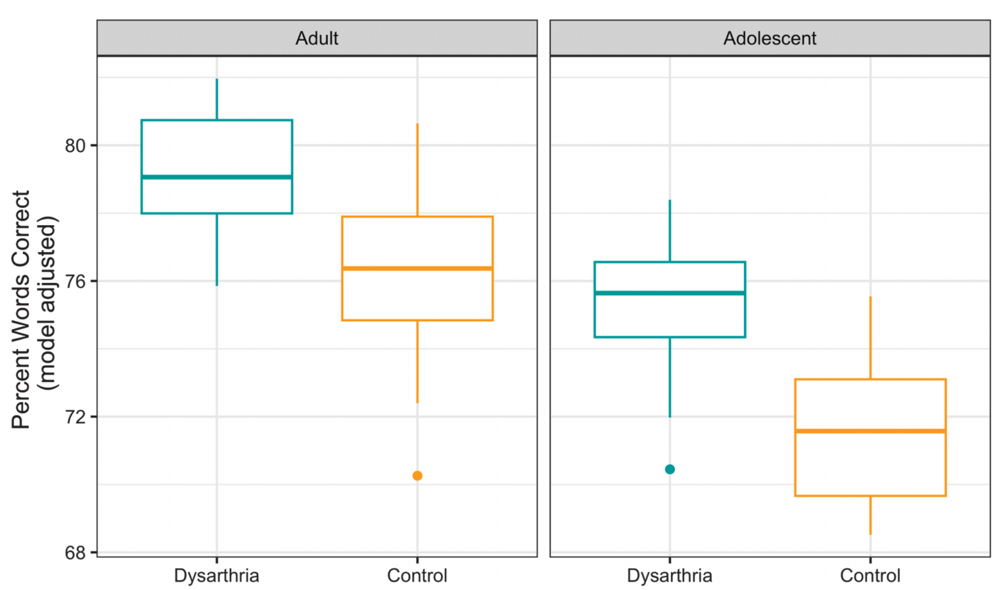


dysarthria familiarization achieved significantly higher intelligibility scores in the posttest relative to listeners who received control familiarization. Additionally, there was a significant effect of developmental stage (b = 3.9 percentage points, $p < .001$), such that adult listeners achieved higher intelligibility scores in the posttest relative to adolescent listeners. Finally, the interaction between familiarization condition and developmental stage was not significant, indicating dysarthria familiarization facilitated greater intelligibility benefits than control familiarization for both adult and adolescent listeners.

Exploratory Analyses

Motivated by the result showing that the intelligibility scores at posttest of the adolescent listeners were reduced relative to adult listeners, we performed a post hoc analysis to examine whether age in years predicted

Figure 2. Box plots showing model-corrected posttest intelligibility scores following dysarthria or control familiarization by developmental stage, with adolescent and adult listeners in the left and right panels, respectively.



posttest intelligibility scores. For this analysis, participants spanning the ages of adolescence (12 through 17 years) and early adulthood (18 through 22 years) were included. Adults aged 26 years and older were not included because the small number of participants at these ages (i.e., six participants total) could bias the results. From a theoretical perspective, we would expect the relationship between intelligibility and age to be nonlinear (i.e., intelligibility would increase across adolescence and begin to level off during early adulthood). Accordingly, a square root transformation was used to analyze the relationship between age in years and posttest intelligibility scores (while controlling for pretest intelligibility scores). This model revealed a significant effect of age in years ($b = 4.64$, $p < .001$), with intelligibility increasing across adolescence with a slight leveling off during early adulthood years, as illustrated in Figure 3. There was no significant interaction between age in years and familiarization condition.

Motivated by the result showing intelligibility gains for listeners who received control familiarization, we examined the degree to which passive learning transpired during the posttest. Given the nature of the phrases (three to five words) and the nature of dysarthria (some phrases are inherently more intelligible than others), sentences were aggregated by 25 phrases to yield a more accurate representation of intelligibility than what would be obtained on a trial-by-trial basis (note: the study design does not allow a thorough test of learning over time, particularly during the pretest as there were not enough phrases to assess differential performance across phrases). Figure 4 shows the means and standard errors for each subsequent 25 phrases (i.e., phrases 26–50, 51–75, and 76–100) across all phrases presented in pretest and posttest. Linear mixed-effects models showed that neither group of adolescents (dysarthria and control) showed evidence of passive learning during the posttest ($ps > .371$). However, adults in the control condition ($p = .01$), but not the dysarthria condition ($p = .39$), showed passive learning.

Discussion

Prior work has established that adult listeners benefit from familiarization with an adult speaker with dysarthria. Here, we extend these findings to adolescent populations. In this study, all listeners, regardless of age, familiarized with the speech of an adolescent with dysarthria achieved intelligibility improvements superior to those familiarized with control speech. Thus, structured, speaker-specific familiarization elevated intelligibility improvements. This initial work with an adolescent speaker with dysarthria informs theories of learning in several important ways. It has been established that perceptual learning of dysarthric speech relies on statistical predictability of acoustic cues available in the speech signal (Borrie et al., 2018; Lansford et al., 2019, 2020). Thus, despite adolescent speech being more acoustically variable than adult speech in general (Walsh & Smith, 2002; Smith & Zelaznik, 2004), the results of this study implicate that the speech of an adolescent with dysarthria contains sufficient acoustic regularity for listeners to identify and acquire knowledge of the speaker's underlying cue distributions. This suggests that there may be a predictability threshold necessary for learning to occur and that, by 13 years of age, the motor speech processes may be appropriately developed for the realization of category-specific cue distributions. Further inquiry into this speculation is well warranted.

Figure 3. Age (in years) predicts model-corrected posttest intelligibility scores following dysarthria or control familiarization.

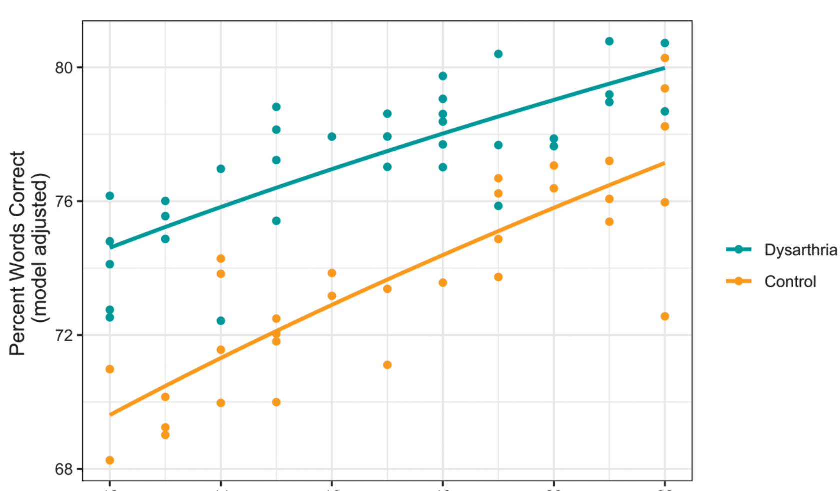
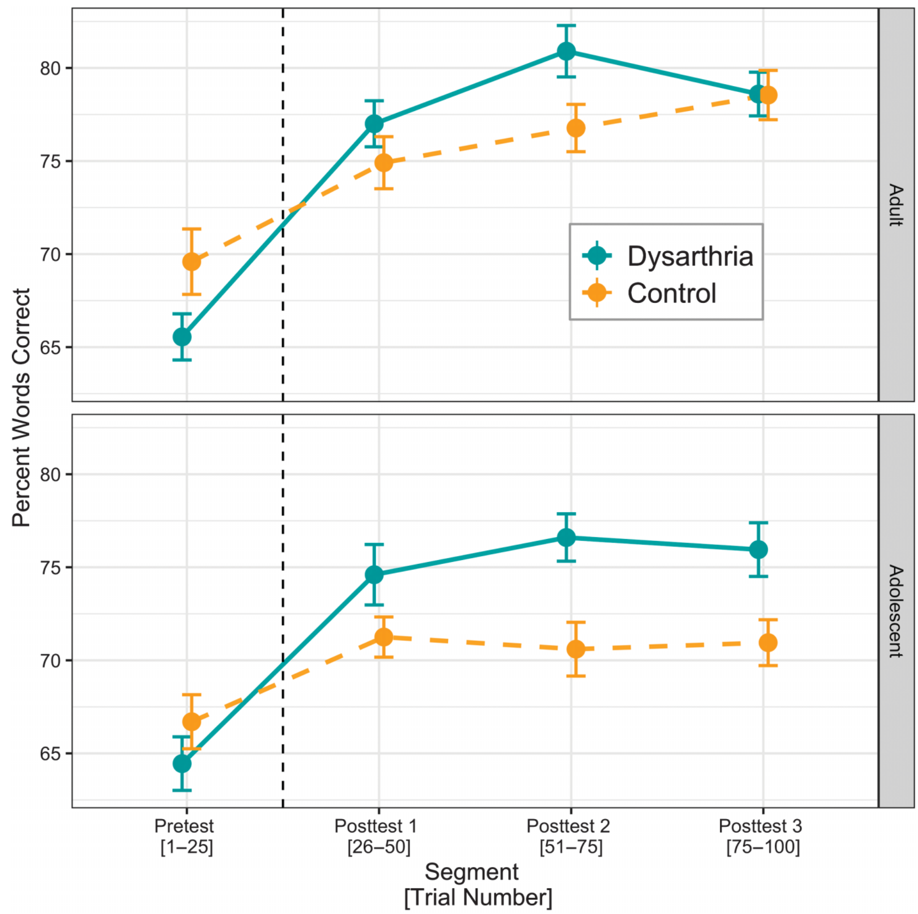


Figure 4. Intelligibility scores over the course of testing. Note that segments represent scores aggregated across 25 consecutive phrases.



Both adult and adolescent listeners benefited more from dysarthria familiarization than familiarization with control speech. However, adult listeners learned more than adolescent listeners. This finding suggests that the speech perception systems of adolescent listeners are indeed sufficiently flexible to identify and acquire knowledge of category-specific cue distributions afforded by the impoverished speech signal. However, the findings also suggest that perceptual learning may be a protracted process and that fully developed speech perception systems may be required to take optimal advantage of familiarization with dysarthric speech. Furthermore, while not the research question of this study, an exploratory post hoc analysis with the intelligibility data from the 12- to 22-year-old listeners revealed a relationship with age in years, suggesting that development of this ability to deal with the variability present in the adolescent dysarthric speech continues into early adulthood. However, this relationship was nonlinear, indicating that the degree of learning is greatest in adolescence and begins to plateau slightly during early adulthood. While much greater listener numbers at all ages are required to assess the time course over which maximal performance appears, this idea of a prolonged maturational trajectory for perception and learning of speech is consistent with prior studies with children and adolescents (e.g., Bent, 2018; Bent & Holt, 2018; Huyck & Wright, 2011, 2013).

Another finding of this study was that regardless of age or condition, all listeners experienced intelligibility improvements from pretest to posttest. That is, while significantly less than listeners who received structured familiarization with dysarthric speech, intelligibility improvements were also observed for listeners in the control condition. We entertain two explanations. Firstly, the results suggest that some degree of passive learning transpired during the testing phases, in which listeners listened to the dysarthric speech stimuli and typed out what they thought was being said. While intelligibility improvement for control conditions has not been observed in the adult literature on perceptual learning of dysarthric speech (Borrie et al., 2017a; Borrie & Schäfer, 2015), those studies used speakers with lower baseline (i.e., pretest) intelligibility levels (~15%–50%) compared to the current speaker (~67% for adult listeners). However, a study with noise-vocoded speech found that the more intelligible the speech, the more likely learning transpired in the absence of external disambiguating lexical feedback (i.e., orthographic transcriptions of the speech; Guediche et al., 2016). Along similar lines, research with foreign-accented speech has shown that more intelligible speech signals require less familiarization for learning to occur (Bradlow & Bent, 2008). Thus, the relatively high baseline intelligibility of the speaker in this study may have made it possible for listeners to draw upon internal sources to identify and detect speech signal patterns during the two testing phases. Indeed, our exploratory analysis of passive learning over the course of the posttest revealed that this explanation may be the case for the adult listeners who received control familiarization—intelligibility improved over the course of the posttest. This passive learning over the course of the posttest, however, was not apparent for the adolescent listeners who received the control familiarization. For adolescents in the control condition, it is possible that passive learning transpired during the pretest; however, our stimuli selection (short phrases) and study design (brief pretest) do not allow for this to be examined. A comprehensive examination of learning over the course of the testing stimuli provides an interesting future direction for this work.

A second explanation, not mutually exclusive from the first, is that the use of an adolescent control speaker afforded the listeners experience with adolescent speech, and there was some shared structure with the adolescent with dysarthria such that generalization of learning, or speaker-independent adaptation, occurred. Indeed, the idea that some degree of speaker-independent adaptation may transpire is theoretically rooted. Models of learning propose that the speech perception system is sensitive to structure across speakers and similar speaking situations (Kleinschmidt & Jaeger, 2015). In this sense, the generative model and distributional beliefs developed and updated during familiarization with one speaker (e.g., control speaker) may generalize to improved understanding of a novel speaker (e.g., speaker with dysarthria) if the speakers share a distributional structure that unifies groups of speakers (e.g., 13-year-old male speakers from the same geographic location). Indeed, studies with adults have found that familiarization with a speaker with dysarthria can improve listener understanding of a novel speaker with a different perceptual presentation (and type) of dysarthria (Borrie et al., 2017a). This implies that speakers with dysarthria, regardless of presentation, exhibit some degree of shared structure that can be generalized across speakers. Whether and to what degree adolescent speakers, regardless of the presence of dysarthria, share speech behaviors should be examined.

Limitations, Future Directions, and Clinical Implications

The current results are based on the speech of an early adolescent speaker (13 years) with spastic dysarthria of moderate severity (i.e., ~70% words correct on anomalous phrases). This provides multiple directions for future work. First, whether the results hold for adolescent listeners familiarized with a speaker with more severe dysarthria warrants investigation. Studies with adult listeners show significant learning for adult speakers with greater speech degradation (i.e., ~20% words correct on anomalous phrases; Borrie & Schäfer, 2015, 2017). However, in theory, the more severely degraded speech would increase the computational load on the adolescents' still-developing speech perception system and thus may reduce (or eliminate) learning outcomes.

Extending investigations to younger child and later adolescent populations (speakers and listeners) also holds significant value. Indeed, familiar listeners of young children with and without speech disorders (i.e., mothers, caregivers) are more adept at understanding their child than unfamiliar listeners—though the precise mechanisms that drive this perceptual advantage remain unclear (e.g., Flipsen, 1995; Yu et al., 2023). Thus, examining perceptual learning as a function of *speaker age*, in addition to a quantitative acoustic metric of signal predictability, could establish the threshold of predictability required for learning to occur and whether there is an age at which the speech of a younger child with dysarthria is no longer learnable. Additionally, examining perceptual learning as a function of *listener age*, with much greater numbers of participants at each age (in years), could inform the developmental trajectory of adapting to degraded speech. Indeed, there exist no prior studies of child understanding or adaptation to dysarthric speech. Yet, studies examining child understanding of foreign-accented and unfamiliar dialects in noisy conditions (environmental degradation) suggest that the ability and success in contending with speech variability, mapping the noncanonical cues onto linguistic categories, has a protracted developmental trajectory (Bent, 2018).

Adolescents with dysarthria, including the 13-year-old speaker in our study, experience reduced communicative participation and less-than-optimal social interactions—prevailing conclusions from interviews with adolescents with dysarthria and their parents were that "beyond core family and very few close friends," these individuals experienced "sparse and superficial interactions at best and negative interactions at worst" (Connaghan et al., 2022, p. 13). Intelligibility of dysarthric speech has been causally linked with communicative participation (Borrie et al., 2022). As such, the current findings of improved intelligibility of an adolescent with dysarthria, in addition to the next steps discussed above, have important clinical implications.

Key being that they inform candidacy for listener-focused perceptual training to improve intelligibility for primary communication partners. For adolescents with dysarthria, primary communication partners may include peers (e.g., classroom, afterschool activity groups), teachers, and coaches. Given that social interactions have a particularly influential role during adolescence (e.g., Helseth & Misvaer, 2010), adolescents with dysarthria may stand to particularly benefit from an intervention approach that trains their peers and community to understand their speech.

As such, the clinical translation of this work into real-world interventions is a critical next step. Translational studies may involve examining the utility of increasing motivation by gamifying the familiarization phase, perhaps particularly relevant for adolescent listeners, and assessing intelligibility benefits in functional sentences, wherein listeners can also draw on linguistic and contextual knowledge. Additionally, the utility of deploying the learning paradigm in more familiar instructional environments, such as classroom or library settings, should be examined.

Conclusions

This study provides the first tranche of evidence that the speech of an adolescent speaker with dysarthria affords sufficient signal predictability to be learned by neurotypical listeners and that the speech perception systems of adolescent listeners are sufficiently flexible to adapt to the degraded speech signal. Additionally, adolescent listeners learned less than adults, demonstrating a developmental trajectory for perceptual learning of adolescent dysarthric speech. Given the formative role that social interactions play during adolescence, and prior work that adolescents with motor speech disorders experience challenges interacting with others, the current findings of improved understanding of an adolescent speaker with dysarthria afford important clinical implications and directions for continued investigation with adolescent and child populations.

Data Availability Statement

Anonymized listener data, analysis code, and model outputs associated with this work are available at the study repository hosted at https://osf.io/cq2y3/.

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