

Research Article

Sensorimotor Adaptation to a Nonuniform Formant Perturbation Is Preserved in Healthy Aging

Hung-Shao Cheng,^a  Caroline A. Niziolek,^{a,b}  and Benjamin Parrell^{a,b} 

^aWaisman Center, University of Wisconsin–Madison ^bDepartment of Communication Sciences and Disorders, University of Wisconsin–Madison

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ABSTRACT

Purpose: Young adult speakers can be induced to increase the acoustic contrast between vowels through exposure to a nonuniform auditory “centralization” feedback perturbation that makes vowels sound less distinct from one another. While this result suggests that sensorimotor adaptation is a promising learning mechanism to drive behaviorally relevant changes related to speech intelligibility, existing research on sensorimotor adaptation in speech has largely focused on younger adults. Given established age-related deficits in speech motor performance, it is possible that healthy aging itself negatively impacts speech motor learning; however, these potential effects of age are currently unknown. Here, we examine the effects of healthy aging on the magnitude of both adaptation to the complex “centralization” paradigm as well as the generalization of this learning to untrained vowels.

Method: Forty-three neurobiologically healthy speakers (age range: 18–73 years) read monosyllabic words with corner vowels, while their auditory feedback was shifted toward the center of the vowel space. Adaptation was measured as the increase in vowel contrast induced by this perturbation. Generalization was tested in monosyllabic words with noncorner vowels produced under masking noise.

Results: Speakers adapted to the perturbation, producing the trained corner vowels farther from the vowel center, with increased acoustic contrast among them. This learning generalized robustly to untrained noncorner vowels. Crucially, age did not affect the magnitude of adaptation nor the magnitude of the generalization.

Conclusion: These findings demonstrate that healthy aging does not impair sensorimotor adaptation in speech, further establishing that sensorimotor adaptation can be leveraged to drive behaviorally relevant changes in speech in older adults with acquired motor speech disorders.

Healthy aging, even in the absence of any neurological disorders, causes changes throughout the central nervous system, including the deterioration of structural integrity in various parts of the brain such as the prefrontal cortex, parietal cortex, and cerebellum (Nyberg et al., 2010; Raz et al., 2005; Seidler et al., 2010). These aging-related changes can also be observed in behavior, where aging is associated with decreased sensory acuity and a

variety of difficulties in motor performance such as a general slowdown of movement, decreased movement accuracy, and increased movement variability (Seidler et al., 2010). Aging-related motor control difficulties, while perhaps most well-documented in limb control, also occur in speech production across the phonatory and articulatory systems (Jacewicz et al., 2009; Kuruvilla-Dugdale, 2020; Liss et al., 1990; Mefferd & Corder, 2014; Sadagopan & Smith, 2013; Smith et al., 1987; Tremblay et al., 2018; Tucker et al., 2021; Wohlert & Smith, 1998). For example, when compared to young adults, older adults have a slower speaking rate (Jacewicz et al., 2009; Liss et al., 1990; Tucker et al., 2021) and exhibit reduced production accuracy when repeating novel nonwords based on an

Correspondence to Hung-Shao Cheng: hcheng223@wisc.edu. Caroline A. Niziolek and Benjamin Parrell contributed equally to this work.

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auditory prompt (Sadagopan & Smith, 2013; Tremblay et al., 2018; Wohlert & Smith, 1998). While aging is thus widely known to negatively impact speech motor *performance*, the extent to which speech motor *learning* is impacted by the effects of age remains incompletely understood. One type of motor learning, learning from the mismatch between predicted and observed sensory outcomes (or *sensorimotor adaptation*), is an especially critical skill that allows us to maintain accurate movement in the face of an ever-changing body and environment (Shadmehr et al., 2010). In speech, sensorimotor adaptation is commonly studied by using external perturbations to speakers' perceived auditory feedback, where participants' speech is recorded, altered, and played back to them in near-real time, such as saying "bed" but hearing "bad." Repeated exposure to this feedback alteration can drive adaptive change in speech production that minimizes the error in auditory feedback (Houde & Jordan, 1998; Purcell & Munhall, 2006). Despite both the importance of sensorimotor adaptation for maintaining accurate speech and it being one of the most studied speech motor learning processes (for reviews, see Caudrelier & Rochet-Capellan, 2019; Parrell & Houde, 2019), the majority of past studies have either ignored potential effects of age (and have included mostly young adults) or, when age has explicitly been considered, have only compared the magnitude of speech adaptation in adults with acquired neurological disorders to that of an age-matched control group of older adults. As a result, how healthy aging affects speech sensorimotor learning remains poorly understood.

Understanding how age may affect sensorimotor learning is particularly critical for translating adaptation from the laboratory to the clinic. For example, speakers can be induced to increase the acoustic contrast between vowels via adaptation to a nonuniform "centralization" perturbation field that reduces vowel distinctiveness by pushing the first and second formants (F1/F2) of the vowel closer to the center of a speaker's vowel formant space (Parrell et al., 2024; Parrell & Niziolek, 2021). As a larger vowel formant space is associated with higher speech intelligibility (Thompson et al., 2023), the increase in contrast can have beneficial effects on intelligibility (Beach et al., 2024). While this finding positions sensorimotor adaptation as a promising rehabilitative tool to improve speech intelligibility in individuals with neurogenic disorders, many of which are characterized by reduced vowel contrast (Duffy, 2013), age is a potential barrier for applying such paradigms clinically. Individuals with a neurogenic disorder who may benefit from the intervention tend to be much older than the participants in past studies of speech sensorimotor adaptation, and it is possible that aging could negatively impact speech motor learning similar to its negative effect on other aspects of speech motor control.

Much of our current understanding of the age effect on sensorimotor adaptation comes from the extensive literature examining limb movements (Bock, 2005; Buch et al., 2003; Cisneros et al., 2024; Clayton et al., 2024; Fernandez-Ruiz et al., 2011; Hermans et al., 2025; Heuer & Hegele, 2008, 2015; McNay & Willingham, 1998; Roller et al., 2002; Ruitenberg et al., 2023; Seidler, 2006; Seidler et al., 2010; Vandevorode & Orban De Xivry, 2019, 2020, 2021). When compared to young adults, some studies have found that older adults exhibited reduced magnitude of reach adaptation (Bock, 2005; Ruitenberg et al., 2023), whereas other studies showed the opposite pattern, with older adults exhibiting either enhanced (Cisneros et al., 2024; Seidler, 2006; Vandevorode & Orban De Xivry, 2021) or at least comparable (Buch et al., 2003; Hermans et al., 2025; Heuer & Hegele, 2008; Roller et al., 2002; Vandevorode & Orban De Xivry, 2019) adaptation. While these results point to an equivocal effect of age on sensorimotor adaptation at first glance, a consistent pattern emerges when examining age effects on the underlying learning mechanisms that contribute to adaptation. Adaptation to the visuomotor rotations typically used in these studies involves both explicit cognitive-based aiming strategies (Benson et al., 2011; Bond & Taylor, 2015; Taylor et al., 2014) and implicit sensorimotor recalibration (for a review, see J. W. Krakauer et al., 2019); isolating each type of learning demonstrates that aging impairs the explicit component of learning but spares, or even enhances, implicit adaptation (Cisneros et al., 2024; Clayton et al., 2024; Vandevorode & Orban De Xivry, 2020).

Because speech adaptation to formant perturbation has been suggested to be driven largely by implicit automatic processes and to lack an explicit learning component (Kim & Max, 2021; J. Krakauer et al., 2024; Lametti et al., 2020; Munhall et al., 2009), we expect, given the limb control literature, that adaptation should be unaffected, or possibly increased, in older age. Indeed, in their recent study comparing the magnitude of adaptation to a single formant perturbation (i.e., saying "bed" but hearing "bid") across three age groups spanning the full adult lifespan (18–25, 55–70, 80+ years), de Witte et al. (2026) found no significant age effect on the magnitude of speech adaptation, tentatively supporting the hypothesis that aging does not impair implicit speech sensorimotor adaptation. While this result suggests that age does not affect sensorimotor adaptation to a single formant perturbation in auditory feedback, it remains unclear whether adaptation to a more complex perturbation, such as the more clinically relevant "centralization" perturbation described above, is similarly unaffected by age as age effects in implicit motor learning may become more prominent only with an increase in task demands (Howard et al., 2004).

To be useful for motor rehabilitation, clinical interventions must promote not only learning during training

but also the generalization of that learning: the ability to apply what we learned to a novel context. For speech specifically, clinical interventions should ideally lead to robust generalization to novel sound targets. Sensorimotor adaptation to a single perturbation transfers across vowels (Rochet-Capellan et al., 2012) and words (Lametti et al., 2018). Our recent work shows that sensorimotor adaptation to a nonuniform centralization perturbation also robustly generalizes to new vowel sounds (Parrell et al., 2024): When participants adapted to the perturbation (by producing the corner vowels farther from the center of the vowel space), they also generalized this learning to the production of untrained neighboring noncorner vowels (/ɪ/, /e/, /ɛ/, /ʌ/, and /o/). However, as for sensorimotor adaptation generally, no studies to date have investigated the effect of age on the magnitude of generalization. Thus, another aim of the current study was to replicate and expand our generalization findings in young adults by additionally examining how age may affect the generalization of sensorimotor adaptation to a complex auditory perturbation.

There is limited work examining the effect of healthy aging on the magnitude of generalization in the limb control literature. To our knowledge, the only study on this topic showed that in participants ranging from children to older adults, age did not affect the magnitude of generalization of visuomotor adaptation to untrained targets that were 45° and 90° away from the training target (Clayton et al., 2024). Based on this finding, we expect that age will not affect the magnitude of generalization in speech sensorimotor adaptation.

In summary, the primary goals of this study are to examine possible effects of age on (a) the magnitude of speech sensorimotor adaptation to a complex nonuniform centralization perturbation field and (b) the magnitude of the generalization of this adaptation to untrained vowels. As an additional assessment of the effects of age on the motor system outside of sensorimotor adaptation, we examine the effect of age on baseline speech motor performance in vowel production.

Method

Participants

Forty-three participants, all native speakers of American English, completed the study. In order to assure an even distribution of ages across the adult lifespan, roughly equivalent numbers of participants were recruited in three groups: 16 younger adults (age range: 18–29 years; $M_{\text{age}} \pm SD$: 21.2 $\pm$ 2.91 years; 15 females, one male), 13 middle-aged adults (age range: 33–54 years; $M_{\text{age}} \pm SD$:

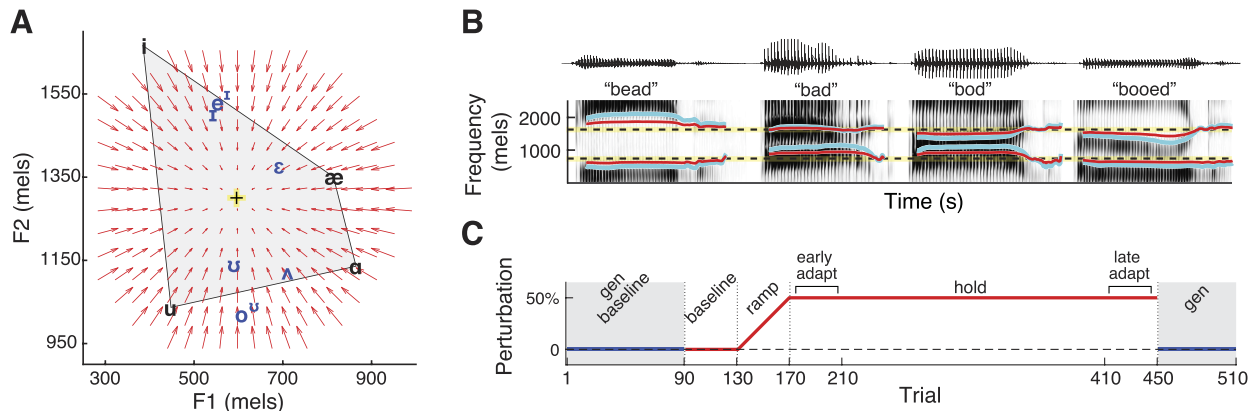
41.5 $\pm$ 7.82 years; seven females, six males), and 14 older adults (age range: 58–73 years; $M_{\text{age}} \pm SD$: 65 $\pm$ 5.07 years; nine females, five males). In total, participants ranged in age from 18 to 73 years. All participants reported no history of speech, language, and neurological disorders. All younger and middle-aged participants passed a hearing screening with thresholds no greater than 25 dB HL at 250, 500, 1000, 2000, and 4000 Hz. For older adults, many of whom have age-related hearing loss, we allowed thresholds of no greater than 40 dB HL at frequencies up to 2000 Hz and no greater than 55 dB HL at 4000 Hz. All participants gave informed consent before the experiment and received either monetary compensation or course credit for their time. The protocol was approved by the institutional review board of the University of Wisconsin–Madison (Protocol 2017-1128).

Auditory Perturbation

Participants' speech was recorded with a head-mounted microphone (AKG C520) and sampled at 48 kHz with an external audio interface (Focusrite Scarlett 2i2). The signal was then downsampled to 16 kHz for processing with Audapter (Cai et al., 2008; Tourville et al., 2013) and for later data analysis. Audapter uses linear predictive coding (LPC) and filtering techniques to estimate and, when required, perturb the first two vowel formants. For all trials (both with unperturbed and perturbed speech feedback), the filtered signals were played back to the participants over closed-back circumaural headphones (Beyerdynamic DT 770) in near-real time (latency of less than 18 ms, measured following Kim et al., 2020). The signal was played back at approximately 80 dB SPL and mixed with speech-shaped noise at 60 dB SPL to limit the perception of unperturbed speech feedback via either air or bone conduction. On some trials, no speech feedback was given (noise-only trials; see Procedure). For these trials, participants received only speech-shaped masking noise, with the amplitude of the noise scaled in real time by the amplitude of participants' speech (~80 dB). This procedure effectively masks participants' own speech while minimizing the influence of background noise on speaking (e.g., the Lombard effect; Lombard, 1911).

A modified version of Audapter was used to independently manipulate F1 and F2, as shown in Figure 1. For each participant, we created a unique perturbation field that shifts both F1 and F2 toward the center of that participant's vowel space, as a percentage of the distance between the center and the F1 and F2 values at each sample (Parrell et al., 2024; Parrell & Niziolek, 2021). The center of the vowel space was estimated based on each participant's production of words containing the four corner vowels (10 repetitions of each of "bead," "bad," "bod,"

Figure 1. Experimental protocol. (A) An illustration of the formant perturbation field used in the ramp and hold phases for one participant. Formants (F1/F2) are shifted (red arrows, magnitude not to scale) toward the center of the vowel space (+ sign, yellow) for the four corner training vowels (black). Generalization vowels are represented in blue for illustration purposes. No formant shifts were applied to these vowels. (B) Example waveform and spectrograms of the four training words. The produced formants are shown in cyan and the shifted formants in red. The formant values for the center of the vowel space are shown as a yellow-highlighted dotted line. (C) Phases of the experiment. Generalization trials are shown in blue; training trials are shown in red. Shaded gray areas denote phases with noise-only feedback to mask participants' own speech. Time windows for measuring adaptation are marked with straight brackets; the early adapt window (Trials 170–210) measures the initial learning rate, whereas the late adapt window (Trials 410–450) measures the maximal magnitude of adaptation.



and “booed,” order of stimuli randomized) in a calibration phase with veridical (unperturbed) feedback prior to the generalization baseline phase (see below).

Procedure

On each trial, a written target word was visually presented on an LCD monitor. Participants were instructed to say the target word out loud when they saw the stimulus appear. Each stimulus was presented for 1.5 s, with a randomly jittered interstimulus interval ranging from 0.75 to 1.5 s. The words all had the form /bVd/, with the vowel (V) varying across stimuli. The words (and vowels) varied by the phase of the experiment. The training words, used to assess sensorimotor adaptation, contained the four corner vowels: /i/ (“bead”), /æ/ (“bad”), /a/ (“bod”), and /u/ (“booed”). The generalization words, used to test the generalization of learning to untrained vowels, contained vowels intermediate to those of the training words: /ɪ/ (“bid”), /e/ (“bayed”), /ɛ/ (“bed”), /ʌ/ (“bud”), /oʊ/ (“bode”). We additionally included the diphthong /aɪ/ (“bide”) for a separate analysis that is not discussed here. Words were presented pseudorandomly in each of five phases:

1. A *generalization baseline phase*, where participants produced 15 repetitions of each generalization word (90 trials) while receiving noise-only feedback.
2. A *baseline phase*, where participants produced 10 repetitions of each training word (40 trials) while receiving veridical (unperturbed) feedback of their produced speech.

3. A *ramp phase*, where participants produced 10 repetitions of each training word (40 trials). During this phase, participants received perturbed auditory feedback of their speech, where the magnitude of shift was gradually increased from 0% to 50% of the distance from the F1/F2 values at each sample to the center of the vowel space.
4. A *hold phase*, where participants produced 70 repetitions of each training word (280 trials) while receiving perturbed auditory feedback, with the magnitude of the formant shift held constant at 50% of the distance to the center of the vowel space.
5. A *generalization phase*, where participants produced 10 repetitions of each generalization word (60 trials). Participants received noise-only feedback during this phase in order to minimize the gradual reduction in adaptation observed when veridical feedback is restored after an extended period of exposure to a formant perturbation.

Participants received a short break every 30 trials.

Data Analysis

Formants were tracked using wave_viewer (Niziolek & Houde, 2015), a MATLAB GUI interface to formant tracking in Praat (Boersma & Weenink, 2023). Vowel onset and offset were first identified based on samples above a participant-specific amplitude threshold. These events were subsequently hand-checked and corrected when needed using acoustic landmarks from the waveform and spectrogram. Vowel onset was marked as the sample

in time where vowel formants, especially F2, first became visible. Vowel offset was marked when F2 and higher formants became invisible. Formants were tracked using participant-specific LPC order and preemphasis values, and tracking errors on individual trials were resolved by making minor adjustments to these values. A small handful of trials with uncorrectable tracking errors, or speech errors such as disfluency or mispronunciation, were discarded (1.8% in total, 0%–6% across participants). For each trial, single values for F1 and F2 were measured as the average formant values between the interval of 50–100 ms after the vowel onset (J. Krakauer et al., 2024). This temporal window was chosen to minimize the effect of coarticulation on vowel formants and the potential influence of feedback correction, especially for trials with perturbed auditory feedback. These formant values were converted to the mel scale in order to better represent perceptually equivalent changes across participants with different baseline formant values.

Analysis of Sensorimotor Adaptation

Our primary outcome measure was the average Euclidean distance, in F1/F2 space, between each pair of vowel stimuli, or *average vowel spacing* (AVS). We calculated AVS separately per block of 10 repetitions: 40 trials for training stimuli and 50 trials for generalization stimuli. We excluded the first 25 trials in the generalization baseline phase to allow participants to get used to speaking with noise feedback. We then normalized each block's AVS value by dividing by the AVS value in the corresponding baseline phase.

To measure the degree of initial learning rate to the perturbed auditory feedback, we used the normalized AVS values calculated in the first block of the hold phase, or *early adaptation*. To measure the maximal magnitude of adaptation, we used the normalized AVS values from the last block of the hold phase, or *late adaptation*. To measure the generalization of learning, we used the normalized AVS values from the generalization phase. One-tailed *t* tests with Holm correction for multiple comparisons were used to determine whether each normalized AVS value was larger than 1. To examine the effect of age on the magnitude of initial learning rate, maximal adaptation, and generalization, we fitted a linear regression model separately for each dependent variable with age as a continuous predictor variable. Because some of our older participants had a moderate degree of age-related hearing loss, we additionally included an interaction term between age and hearing thresholds in order to test whether the effect of age on each of our dependent variables differed by hearing ability. To quantify hearing threshold, we used the average of the dB HL thresholds at 500, 1000, and 2000 Hz, or pure-tone average, averaged between

both ears (Fletcher, 1929). These three frequencies roughly cover the range of the F1 and F2 frequencies of vowels. We additionally assessed whether the magnitude of adaptation was related to the magnitude of generalization using Spearman's rank correlation. All inferential statistics were conducted in R (R Core Team, 2017) via RStudio (RStudio Team, 2020).

Besides the global measure of AVS, we additionally analyzed vowel-specific adaptation. Because the perturbation pushed the first two formants toward the center of the vowel space, successful adaptation for a given vowel would entail producing that vowel farther from the center of the vowel space relative to the baseline. To quantify vowel-specific adaptation, we first calculated the Euclidean distance in 2D formant space from the vowel in each trial to the center of the participant's vowel space. We then averaged these distance values per block of 10 repetitions of each vowel and normalized each block's average distance by dividing by the distance in the corresponding baseline phase. Similar to the global AVS analysis, we examined the initial learning rate by using the normalized distance value from the first block of the hold phase. To examine the maximal magnitude of adaptation, we used the normalized distance value calculated in the last block of the hold phase. Generalization of learning was measured using the normalized distance value from the generalization phase. We examined whether age predicted initial learning rate, magnitude of maximal adaptation, and generalization by fitting three separate linear mixed-effects models that included age and vowel as the predictor variables, an interaction term between age and vowel, as well as an interaction term between age and pure-tone average. Adding these two interaction terms allowed us to test whether the effect of age on adaptation or generalization differed across vowels or across hearing threshold. Given that the vowel predictor variable is a categorical variable, we used a sum-coding scheme. A random intercept of Participant was added in all three models.

Lastly, our recent work found that the magnitude of generalization in each of the untrained vowels was significantly predicted by the weighted sum of adaptation in the four training vowels, scaled inversely by the acoustic distance from each generalization vowel to each of the training vowels (Parrell et al., 2024). We fitted a linear mixed-effect model with the magnitude of generalization in the generalization vowels as the outcome variable. The fixed-effect predictor variables included the weighted sum of maximal adaptation in the training vowels, age, as well as the interaction term between the weighted sum of maximal adaptation in the training vowel and age. Including this interaction term allows us to test whether the effect of maximal adaptation in the training vowels on the magnitude of

generalization in the generalization vowels differed across ages. A random intercept of Participant was included in the model.

$$\begin{aligned} mag_{gen} \sim & \beta_0 + \beta_1 * (mag_{iy}/dist_{iy} + mag_{ae}/dist_{ae} \\ & + mag_{aa}/dist_{aa} + mag_{uw}/dist_{uw}) + \beta_2 * age + \beta_3 \\ & * age * (mag_{iy}/dist_{iy} + mag_{ae}/dist_{ae} + mag_{aa}/dist_{aa} \\ & + mag_{uw}/dist_{uw}) + (1|Participant) \end{aligned} \quad (1)$$

All descriptive statistics report means and standard errors (*SEs*).

Analysis of Baseline Vowel Production

In addition to learning, we also wanted to examine whether vowel production itself, in the absence of any auditory perturbation, may be affected by age. All measurements were taken, in mels, during the baseline phase including the four corner vowels /i/, /æ/, /a/, and /u/. To operationalize vowel production, we focused on (a) the size of vowel space and (b) formant variability. To measure the size of vowel space, we used both the AVS measure outlined above as well as the area of the quadrilateral formed by the same corner vowels in F1/F2 space (*vowel space area* or VSA). VSA is a common measure of vowel space in the literature (Beach et al., 2024; Parrell & Niziolek, 2021; Thompson et al., 2023), though it may be less sensitive to small changes in behavior than AVS (Parrell & Niziolek, 2021). To examine the effects of age on the size of the vowel space, we fitted separate linear regression models for AVS and VSA with age as a continuous predictor variable, with additional factors of sex (sum-coded) and the interaction term between age and sex. Including the interaction term allows us to further test whether the effects of age on the size of vowel space differed between sexes. To measure production variability, we first calculated, for each corner vowel, the Euclidean distance of each production to the median formant values of that same vowel in F1/F2 space. For each vowel, the mean of these distances to the median was used as a measure of vowel-specific variability, where a smaller value reflects less variability. We then averaged across these four values to represent overall production variability of the corner vowels (Tang et al., 2022). To examine age effect on production variability, we fitted two linear models with age as the continuous predictor variable: The first model used a single average value for each participant across all four corner vowels to represent overall production variability of the corner vowels (Tang et al., 2022); the second model used all four individual per-vowel values for each speaker, with additional factors of vowel, the interaction between vowel and age, and a random intercept of participant.

Results

Effects of Age on Sensorimotor Adaptation

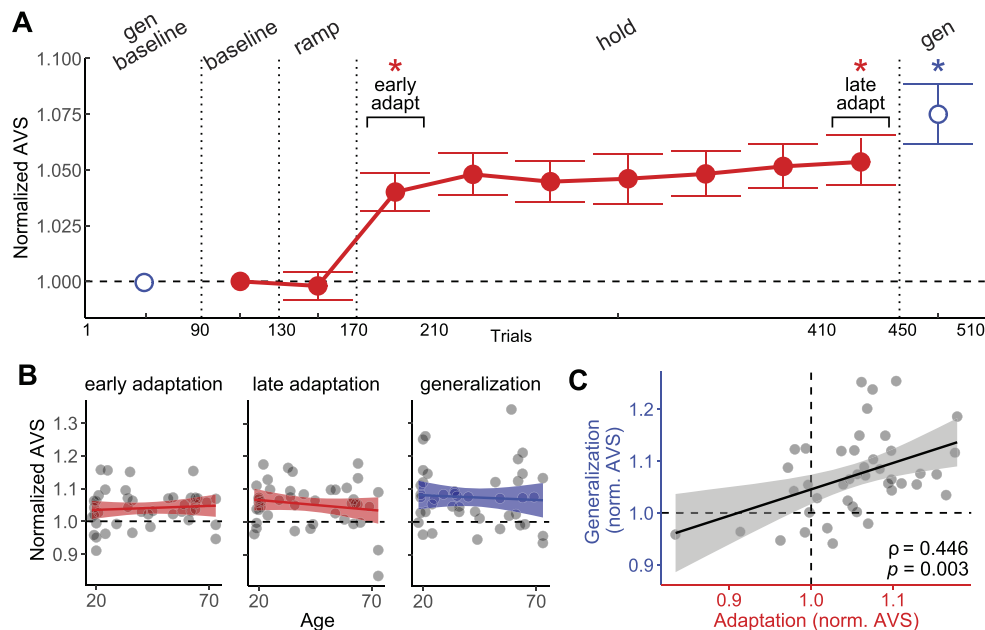
The primary aim of the present study is to examine effects of age on (a) the magnitude of adaptation to a nonuniform centralization perturbation that reduces the acoustic contrast between the four corner vowels produced during training and (b) the magnitude of the generalization of this adaptation to untrained noncorner vowels. Participants adapted to the perturbation, producing a significant mean increase in AVS of $4.0\% \pm 0.9\%$, $t(42) = 4.64$, $p < .0001$ (see Figure 2A), initially and $5.0\% \pm 1.0\%$, $t(42) = 5.18$, $p < .0001$ (see Figure 2A), at the end of the hold phase. This increased vowel contrast generalized to noncorner vowels, which were produced with a mean AVS of $7.0\% \pm 1.3\%$ higher than the generalization baseline, $t(42) = 5.62$, $p < .0001$ (see Figure 2A). Critically, age did not significantly affect initial learning rate, $R^2 = .07$, $p = .23$ (see Figure 2B); magnitude of maximal adaptation, $R^2 = .11$, $p = .11$ (see Figure 2B); or magnitude of generalization, $R^2 = .07$, $p = .24$ (see Figure 2B). The interaction between age and hearing threshold was not significant in all models (all p values $> .09$). At the individual level, magnitude of maximal adaptation was strongly associated with the magnitude of generalization, $\rho = 0.45$, $p = .003$ (see Figure 2C).

We also examined vowel-specific adaptive change to the centralization perturbation. For initial learning rate, we found that participants significantly increased the acoustic distance from the center of the vowel space for /i/, /æ/, and /a/, but not /u/ (see Figure 3A; /i/: $5.0\% \pm 1.1\%$, $t(42) = 4.25$, $p = .0002$; /æ/: $10\% \pm 1.9\%$, $t(42) = 5.09$, $p < .0001$; /a/: $4.0\% \pm 1.2\%$, $t(42) = 2.97$, $p = .005$; /u/: $2.0\% \pm 2.7\%$, $t(42) = 0.8$, $p = .2$). However, there was no significant difference across vowels in the magnitude of adaptation, $F(3, 120) = 0.49$, $p = .69$ (see Figure 3B). Age did not affect the initial learning rate, $F(1, 39) = 2.69$, $p = .11$ (see Figure 3B). There was neither a significant interaction between vowel category and age, $F(3, 120) = 0.27$, $p = .85$ (see Figure 3B), nor a significant interaction between age and hearing threshold, $F(1, 39) = 3.63$, $p = .06$.

For maximal adaptation, a similar increase in acoustic distance from the center was found for /i/, /æ/, and /a/, but not /u/ (see Figure 4A; /i/: $5.0\% \pm 1.3\%$, $t(42) = 4.04$, $p = .0004$; /æ/: $13\% \pm 1.7\%$, $t(42) = 7.64$, $p < .0001$; /a/: $8.0\% \pm 1.4\%$, $t(42) = 5.88$, $p < .0001$; /u/: $0.9\% \pm 3.0\%$, $t(42) = -0.31$, $p = .6$).

Again, however, there was no significant difference in the magnitude of adaptive change across the training vowels, $F(3, 120) = 1.72$, $p = .16$. Age did not affect the magnitude of maximal adaptation (see Figure 4B), $F(1, 39) = 0.11$, $p = .75$. There was neither a significant interaction between

Figure 2. Participants' ($n = 43$) adaptation to the nonuniform centralization perturbation field and generalization to untrained vowels. (A) Normalized average vowel spacing (AVS) over the course of each experimental phase. Mean values across participants are shown in filled red circles for training vowels and open blue circles for generalization vowels. Normalization is specific to each set of vowels. Error bars show standard error (SE) across participants. *Value significantly different from 1 ($p < .05$). (B) Normalized AVS across ages at early adaptation, late adaptation, and generalization; no effect of age was found for any measurement. Gray dots represent individual participants. (C) Adaptation and generalization are correlated across participants.



vowel category and age, $F(3, 123) = 0.54$, $p = .65$, nor a significant interaction between age and hearing threshold, $F(1, 39) = 1.81$, $p = .19$. For individual generalization vowels, we observed a significant increase in movement away from the center for all generalization vowels relative to baseline (see Figure 4A; /*h*/: $9.0\% \pm 2.1\%$, $t(42) = 4.44$, $p = .0002$; /*e*/: $7.0\% \pm 2.0\%$, $t(42) = 3.49$, $p = .002$; /*ɛ*/: $14\% \pm 2\%$, $t(42) = 5.51$, $p < .0001$; /*ʌ*/: $11\% \pm 1.5\%$, $t(42) = 7.59$, $p < .0001$; /*o*/: $5.0\% \pm 2.1\%$, $t(42) = 2.46$, $p = .02$), with no difference in the magnitude of generalization between vowels, $F(5, 200) = 0.92$, $p = .47$. Generalization was not affected by age (see Figure 4B), $F(1, 39) = 0.0002$, $p = .99$. There was neither a significant vowel by age interaction, $F(5, 200) = 0.92$, $p = .47$, nor a significant age by hearing threshold interaction, $F(1, 39) = 0.60$, $p = .44$.

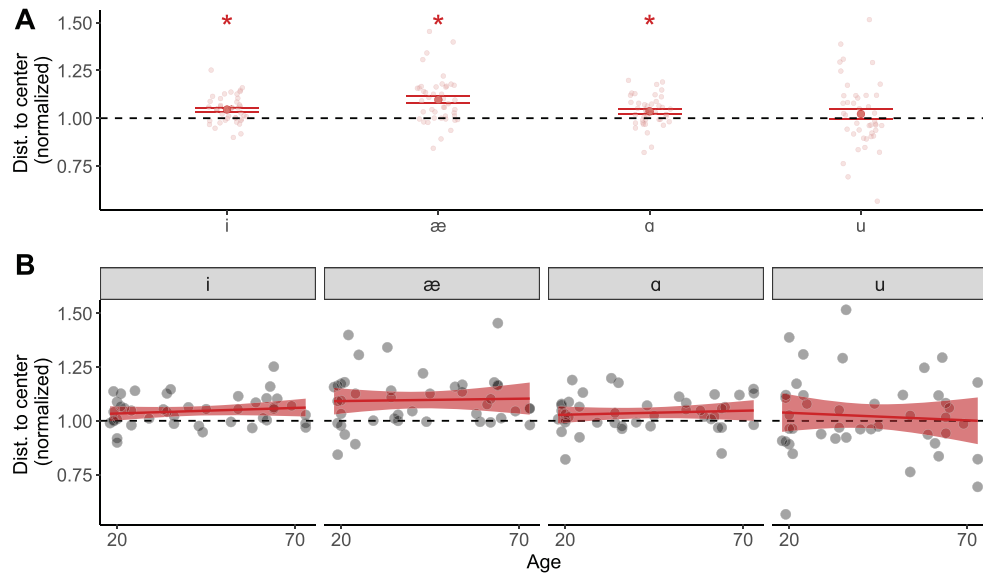
Lastly, the magnitude of generalization in the untrained vowels was significantly predicted by the weighted sum of the adaptation in the training vowels, $\beta = 24.47$, $SE = 7.8$, $t = 3.14$, $p = .002$, where the weight increased with decreased acoustic space between the training vowels and the generalization vowels. This result suggests that the magnitude of adaptation is determined by the magnitude of adaptation in nearby vowels. However, age did not affect the magnitude of generalization, $\beta = .04$, $SE = 0.12$, $t = 0.33$, $p = .75$, nor was there a significant interaction

between age and the weighted sum of the adaptation in the training vowels, $\beta = -.28$, $SE = 0.14$, $t = -2.02$, $p = .05$.

Effects of Age on Vowel Production

We additionally examined baseline vowel production as a measure of general effects of age on speech production outside of sensorimotor adaptation. For these measurements, only productions of the four corner vowels /*i*/, /*æ*/, /*a*/, and /*u*/ from the (unperturbed) baseline phase with veridical speech feedback were used. There was no significant effect of age on vowel spacing, either measured by AVS, $F(1, 39) = 0.96$, $p = .33$ (see Figure 5A), or VSA, $F(1, 39) = 2.06$, $p = .16$ (see Figure 5B). Neither sex nor the interaction between age and sex affected vowel spacing (all $p > .05$). However, these results are necessarily exploratory as we only had one male participant within the younger age range (younger: one male and 15 females, middle age: six males and seven females, older: five males and nine females). For production variability, age did not significantly predict overall vowel variability, $F(1, 41) = 0.88$, $p = .35$ (see Figure 5C). A separate model tested whether production variability differed between the vowels and whether there was an interaction between age and vowel. There was no main effect of age on variability, $F(1, 41) = 0.022$, $p =$

Figure 3. Initial learning rate of vowel-specific adaptive changes. (A) Normalized acoustic distance to the center of the vowel space for each training vowel. Small red dots represent individual participants. Larger dots represent group means; error bars show standard error (SE) across participants. *Value significantly different from 1 (corrected $p < .05$). (B) Vowel-specific changes for each training vowel across ages. Small gray dots represent individual participants.



.88. However, there was a significant main effect of vowel, $F(3, 123) = 4.21$, $p = .007$, as well as a significant age by vowel interaction, $F(3, 123) = 4.69$, $p = .004$. Post hoc analysis using emtrends from the emmeans package (Lenth,

2022) with Holm p -value correction revealed significant differences between /æ/ (decreasing variability with age), on the one hand, and /a/ and /u/ (increasing variability with age), on the other hand (all corrected $p < .05$; see Figure 5D).

Figure 4. Vowel-specific changes in distance to the center of the vowel space for maximal adaptation (red) and generalization (blue). (A) Normalized acoustic distance to the center of the vowel space for each training vowel (filled red dots) and generalization vowel (open blue dots). Small dots represent individual participants. Large dots represent means across participants. Error bars show standard error (SE) across participants. *Value significantly different from 1 (corrected $p < .05$). (B) Vowel-specific changes in distance to the center of the vowel space for each training and generalization vowel across ages. Gray dots represent individual participants.

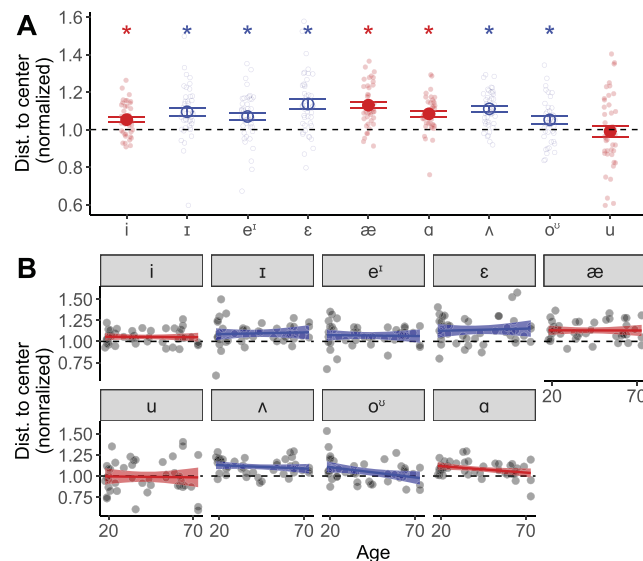
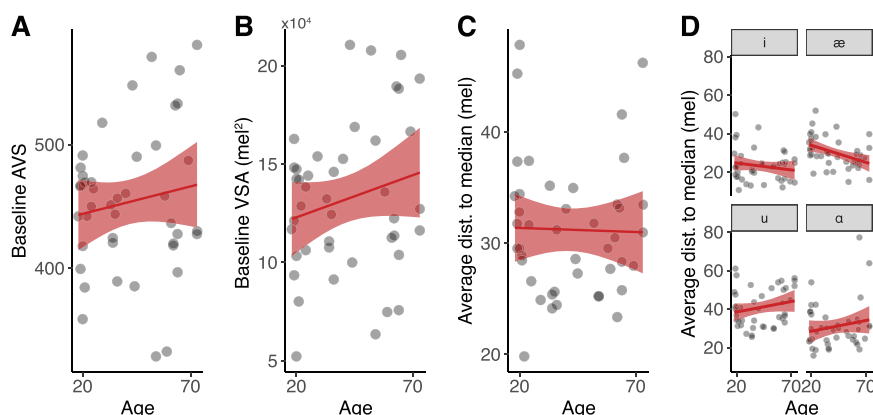


Figure 5. Baseline speech motor performance. All measurements taken from productions of the corner vowels /i/, /æ/, /a/, and /u/ during the baseline phase with veridical auditory feedback. (A) Vowel average vowel spacing (AVS) across ages. Small gray dots represent individual participants. (B) Vowel space area (VSA) across ages. Small gray dots represent individual participants. (C) Vowel production variability, averaged across all four vowels, across ages. Each gray dot represents each participant's averaged production variability across the vowels. (D) Production variability in individual vowels across ages. Small gray dots represent individual participants.



The effect of age on variability in /i/ did not differ from any other vowel (all corrected $p > .2$; see Figure 5D).

Discussion

In the present study, we examined the effect of healthy aging on sensorimotor adaptation to a clinically relevant, nonuniform auditory perturbation of vowel formants, as well as the generalization of this learning to novel, untrained vowels. As age is known to negatively affect both motor performance and motor learning (Seidler et al., 2010), healthy aging is a potential barrier to applying speech sensorimotor adaptation paradigms to drive speech motor changes in a clinical setting, given that many individuals who receive or may benefit from speech therapies are older than the young adults typically included in most studies on sensorimotor adaptation in speech. Broadly, across all ages, our results replicated our previous studies demonstrating the utility of this paradigm (Parrell et al., 2024; Parrell & Niziolek, 2021), extending these results from only younger speakers to a much wider age range across adulthood, including older adults in the age range likely to be affected by neurogenic speech motor disorders. Overall, participants adapted to the altered auditory feedback by producing the four corner vowels used during adaptation training (/i/, /æ/, /a/, and /u/) with increased acoustic contrast as measured by AVS. The magnitude of the increase in acoustic contrast, approximately 5% above baseline productions, is consistent with prior studies using the same paradigm. We also observed robust generalization of these production changes to untrained vowels: Following adaptation training, participants produced the untrained noncorner vowels (/ɪ/, /eɪ/, /ɛ/, /ɔ/, /oʊ/) with increased acoustic

contrast (average of 7% above baseline). As previously reported, the magnitude of adaptation was strongly associated with the magnitude of change in the untrained vowels, both at a global level (AVS) as well as locally, where changes in individual untrained vowels were best predicted by changes in nearby trained vowels. Taken together, these findings strongly demonstrate that we can leverage this specific paradigm to effectively drive speech motor behavioral changes to expand a speaker's vowel space and the contrast between vowels, which have been linked to improved intelligibility in individuals with speech motor disorders (Thompson et al., 2023).

Crucially, we found no significant age effect on adaptation, measured either through the initial learning or the magnitude of maximal adaptation, nor on the generalization of adaptation-driven changes in production to untrained vowels. The lack of age effect on the magnitude of adaptation is consistent with a previous study that examined adaptation of a single vowel to a single downward perturbation of the F1 (de Witte et al., 2026). Our work extends this result to a more complex perturbation paradigm, previously shown to induce behaviorally relevant changes in speech production, showing that older adults' increase in vowel contrast was comparable to that of younger speakers despite the increased task complexity. Additionally, we show for the first time that the generalization of sensorimotor adaptation in speech to untrained items is unaffected by healthy aging; such generalization is critical in a clinical setting (Maas et al., 2008). One potential limitation of our study is that our oldest participants are in their early 70s, and it is possible that age-related deficits in sensorimotor adaptation in speech may appear in much older adults. While previous results have shown

unimpaired adaptation of a single vowel in “older-old” adults over 80 years (de Witte et al., 2026), suggesting that adaptation to the centralization field used here will similarly be unaffected by age, future studies that include participants over the age range included here are needed to verify that this is the case. In addition, even though some of our older participants had a moderate level of hearing loss, this level of hearing loss did not affect the magnitude of either adaptation or generalization. Speech sensorimotor adaptation may be more affected in older adults (or, indeed, anyone) with more severe hearing loss, given reduced ability to process signals in auditory feedback. Future studies should explore this issue, as well as exploring the extent to which aging may impact other aspects of motor control, such as feedback control, to gain a comprehensive picture of how aging impacts the sensorimotor control system for speech.

In a broader context, prior work on sensorimotor adaptation in limb control has demonstrated that while explicit learning, which involves cognitive-based strategy use, is impaired by healthy aging, implicit sensorimotor adaptation is spared, or even enhanced, in older adults. Critically, given the fact that adaptation to formant perturbation is a largely an implicit process, our finding that sensorimotor adaptation in speech is unaffected by healthy aging, at least in individuals with no more than moderate hearing loss, provides additional support for this claim. As speech is very different from limb movements (cortico-bulbar vs. cortico-spinal control, auditory vs. visual feedback), our results additionally suggest a domain-general preservation of implicit learning with aging.

Our finding that speech sensorimotor learning is preserved in healthy aging has implications for speech motor rehabilitation. Given its implicit nature, speech sensorimotor adaptation holds promise to drive clinically relevant speech motor changes, particularly for individuals for whom explicit learning is difficult. For example, this method may be particularly useful for individuals with neurogenic disorders who struggle to improve their speech intelligibility through existing treatments that requires a higher level of cognitive resources, such as LSVT LOUD treatment for hypokinetic dysarthria in Parkinson’s disease (Narayana et al., 2022; Ramig et al., 2018).

While we generally observed adaptation in terms of both increased vowel contrast and peripheral movement of most individual vowels, the /u/ vowel did not show significant adaptation in either early or late time windows. This finding aligns with previous results showing limited adaptation for /u/ using the same perturbation (Parrell & Niziolek, 2021) and using upward and downward shifts to F1 (Mitsuya et al., 2015). One possible explanation is the higher formant variability for /u/, which may lead to a large

range of “acceptable” productions and, subsequently, reduced auditory errors for this vowel (see Parrell & Niziolek, 2021, for additional discussion on this point).

Lastly, as a secondary goal of the article, we examined the effect of age on baseline vowel production in the absence of any sensory perturbation. Consistent with previous reports (Fox & Jacewicz, 2017), we did not observe any significant effect of age on the size of vowel space formed by the four corner vowels /i/, /æ/, /a/, and /u/. Our results also showed that formant variability within these vowels, as a whole, was not affected by aging, though some vowels individually showed increases or decreases in variability with increasing age. While past work has demonstrated age-related deficits in speech motor performance, these deficits were most clearly documented with respect to the timing aspect of speech production; our results showed that healthy aging has minimal impacts on vowel formants, at least in the isolated words examined here. However, the extent to which these results would also hold in more typical, connected speech (which tends to be substantially hypoarticulated compared to isolated words produced in the lab) and in noncorner vowels remains to be tested.

Data Availability Statement

Data and analysis scripts are available on Open Science Framework (<https://osf.io/jx6fy/>).

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