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Aging of Speech Production, From Articulatory Accuracy to Motor Timing

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Despite the huge importance of spoken language production in everyday life, little is known about the manner and extent to which the motor aspects of speech production evolve with advancing age, as well as the nature of the underlying senescence mechanisms. In this cross-sectional group study, we examined the relationship between age and speech production performance using a nonlexical speech production task in which spoken syllable frequency and phonological complexity were systematically varied to test hypotheses about underlying mechanisms. A nonprobabilistic sample of 60 cognitively healthy adults (18–83 years) produced meaningless nonwords aloud as quickly and accurately as possible. Error rate, vocal reaction time (RT), vocal RT variability, vocal response duration, and vocal response duration variability were used as dependent variables to characterize speech production performance. The results showed an overall increase in error rate, which occurred mainly in the final syllable position (coda). There was also an increase in vocal response duration and in duration variability with age, which was moderated by phonological complexity and syllable frequency. Finally, we also found an age-related change in the relationship between vocal RT and vocal response duration. Together, these findings were interpreted as reflecting an age-related decline in the planning and execution of speech movements in cognitively healthy adults.

Keywords: movement time, response variability, aging, spoken language production, spoken syllable frequency

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Advancing age is associated with a decline in a number of functions, including memory, attention, and executive control (e.g., Park et al., 2002; Salthouse, 1996, 2009), as well as a decline in the planning of movements, which is reflected by longer RT across a variety of motor tasks (e.g., Cerella, 1985; Cerella & Hale, 1994; Jordan & Rabbitt, 1977; Niermeyer, Suchy, & Ziemnik, 2017; Perone & Baron, 1982; Rabbitt & Birren, 1967; Stelmach, Goggin, & Amrhein, 1988). Also declining with age are movement rate (i.e., age-related slowing) and movement duration (i.e., age-related increase in duration; e.g., Aoki & Fukuoka, 2010; Cousins, Corrow, Finn, & Salamone, 1998; Darbutas, Juodžbalienė, Skurvydas, & Kriščiūnas, 2013; Pierson & Montoye, 1958; Spirduso, 1975). Movement duration refers to the time required to complete a movement, which is often considered as an indication of motor execution processes. In addition to longer RT and longer movement duration, there is also evidence that movement stability decreases with age, as reflected in a number of movement parameters including RT and movement duration (e.g., Contreras-Vidal, Teulings, & Stelmach, 1998; Cooke, Brown, & Cunningham, 1989; Darling, Cooke, & Brown, 1989; Pierson & Montoye, 1958; Wishart, Lee, Murdoch, & Hodges, 2000) but also accuracy (e.g., Cooke et al., 1989; Darling et al., 1989; Wishart et al., 2000). Increased variability in the execution of movements results in less consistent actions in elderly adults compared to younger adults, which could reflect a decline in motor control and motor execution processes. In sum, these findings are indicative of a significant decline in fine motor planning and motor execution with age.

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Aging and Language Production

Perhaps surprisingly, much less is known about the manner and extent to which speaking, which is also a complex fine motor skill, evolves over the course of a life span, despite the huge functional importance of speaking in everyday life. Much of the research on language production in aging has focused on cognitive functions, such as semantic processing, lexical retrieval, or working memory. While semantic processing seems relatively preserved (e.g., Macoir, Gauthier, Jean, & Potvin, 2016), several studies have documented a decline in performance during lexical decision (e.g., Lima, Hale, & Myerson, 1991), word reading aloud (e.g., Balota & Duchek, 1988; Moers, Meyer, & Janse, 2017) and verbal fluency tasks (e.g., Britt, Ferrara, & Mirman, 2016; Meinzer et al, 2009; Meinzer et al., 2012), suggesting a decline affecting lexical processes in speech production. Moreover, older adults consistently show a decrease in accuracy and an increase in vocal RT during naming tasks (e.g., Bowles, Obler, & Albert, 1987; Britt et al., 2016; LaGrone & Spieler, 2006; Newman & German, 2005). For instance, LaGrone & Spieler found an age-related increase in vocal RT during a picture naming task, especially for pictures with low naming agreement. Because low naming agreement is associated with high lexical competition, this finding suggests an age-related decline in lexical selection mechanisms (LaGrone & Spieler, 2006). Several studies have shown that the tip of the tongue (TOT) phenomenon, a momentary inability to retrieve the phonological form of a word, is more common in the elderly than in younger adults, suggesting a decline in phonological encoding mechanisms during word production in aging (e.g., Brown & Nix, 1996; Burke, MacKay, Worthley, & Wade, 1991; Rastle & Burke, 1996). Other studies have documented an effect of age on the number of morphological and phonological errors using word reading tasks requiring participants to manipulate phonemes (MacKay & James, 2004). Clearly, the production of spoken language undergoes important changes throughout aging, affecting lexical access and phonological word form encoding (for a review, see Mortensen, Meyer, & Humphreys, 2006).

Aging and the Motor Aspects of Speech Production

Few studies have examined the impact of aging on the motor aspects of speech production. However, understanding how aging affects not only the cognitive but also the motor processes involved in speaking is crucial, from both a theoretical and a clinical perspective, in order to understand the nature of the mechanisms involved. This knowledge is also key for the early detection of abnormal speech production patterns, which is a key feature of Parkinson's disease (Ho, Iansek, Marigliani, Bradshaw, & Gates, 1998; Moustafa et al., 2016; Skodda, Grönheit, Mancinelli, & Schlegel, 2013; Skodda, Rinsche, & Schlegel, 2009) and also appears to be an early symptom of Alzheimer's disease (Cera, Ortiz, Bertolucci, & Minett, 2013; Meilán et al., 2014).

The motor aspects of speech production can be studied using tasks involving the production of isolated syllables or nonwords (i.e., meaningless sequences of syllables, which are not associated with a lexical form or a meaning) varying in motor complexity. In such tasks, variations in performance can be related to the motor/phonological complexity of the utterance, which provides an index of the aging of motor-related processes (e.g., motor planning, articulation) that is largely independent of cognitive processes such as lexical selection, semantic processes, and working memory.

Recent studies have reported an age-related decrease in accuracy during the production of phonologically complex nonwords and nonspeech orofacial movements (e.g., Bilodeau-Mercure et al., 2015; Sadagopan & Smith, 2013). In addition to a decline in accuracy, previous studies have also reported an age-related decrease in speech rate (Duchin & Mysak, 1987; Searl, Gabel, & Fulks, 2002; Wohlert & Smith, 1998) and an increase in the duration of individual speech sounds (i.e., an increase in vocal response duration) during syllables or nonword production (Morris & Brown, 1987; Sadagopan & Smith, 2013; Tremblay & Deschamps, 2016; Tremblay, Sato, & Deschamps, 2017). Only a few studies have examined age effects on vocal RT during nonlexical speech production tasks or very simple word repetition tasks (i.e., repeating yes or no; Nebes, 1978; Shuster, Moore, Chen, Ruscello, & Wonderlin, 2014; Tremblay et al., 2017). These studies found no effect of age on vocal RT. Interestingly, Shuster et al. found age differences in vocal RT for auditory word but not nonword repetition (Shuster et al., 2014), suggesting that vocal RT differences during word production tasks may be related to lexical or semantic processes rather than motor planning. These findings suggest that aging may be affecting response planning (RT) in speech production at the level of lexical access rather than motor planning. Overall, the literature suggests that speech motor performance declines with age in terms of accuracy, speech rate, and response duration, suggestive of an age-related decline in motor execution and motor timing.

Another important aspect of speech motor performance is speech movement variability, which is known to increase with age. Greater response variability can result from more variable neural commands to muscles, but it can also result from a decline in the biomechanical properties of the vocal tract. Although movement variability in normal aging has not been studied extensively in speech production, increased variability in voice control with aging has been shown, as well as increased variability in consonant duration (Morris & Brown, 1994; Smith, Wasowicz, & Preston, 1987). Moreover, variability in speech rhythm has also been shown to distinguish between healthy speakers and speakers with speech disorders such as dysarthria (Liss et al., 2009) and speech apraxia (Seddoh et al., 1996). Taken together, these findings suggest that aging may affect motor aspects of speech production, although additional studies are needed to clarify the nature of the most affected component processes (e.g., rhythm regulation, speech planning, speech motor control).

Linguistic Factors Affecting Motor Speech Performance

An important challenge that remains is to understand the linguistic factors (e.g., phonological complexity) that affect speech production performance in aging in order to begin developing more comprehensive cognitive aging models that will incorporate spoken language production. Previous research shows strong age-related decline for the production of long but not short nonwords as well as for phonologically complex nonwords (Bilodeau-Mercure et al., 2015; Sadagopan & Smith, 2013), but not for the production of sequences of simple syllables (Bilodeau-Mercure & Tremblay, 2016). Phonological complexity is often manipulated by adding a consonant to a simple syllable formed by a consonant and a vowel (CV) to form a syllable with a consonant cluster in the onset (e.g., CCV) or the coda position (e.g., CVCC), or by adding a coda to form a syllable with a consonant-vowel-consonant structure (CVC). Research shows that reading words with a consonant cluster in the onset position is slower than reading words beginning with a single consonant (Santiago, MacKay, Palma, & Rho, 2000). In childhood and adult apraxia of speech, a disorder of speech motor control, more errors are committed on syllables containing consonant clusters compared to simpler syllables (Aichert & Ziegler, 2004; Jacks, Marquardt, & Davis, 2006; Lewis, Freebairn, Hansen, Iyengar, & Taylor, 2004). Consonant clusters located at the onset of a word are also associated with an increased probability of stuttering (Howell, Au-Yeung, & Sackin, 2000). Previous studies using functional MRI have shown that words containing consonant clusters are associated with stronger activity in brain regions involved in speech production compared to words containing simpler syllabic structure, suggesting increased difficulty (Bohland & Guenther, 2006; Riecker, Brendel, Ziegler, Erb, & Ackermann, 2008; Tremblay & Small, 2011). More generally, it has been suggested that consonants in the initial position may have tighter articulatory constrictions (Krakow, 1999), are less variable (Byrd, 1996; Krakow, 1999), and are louder and longer than consonants in the final position. This makes initial consonants more easily identifiable (Redford & Diehl, 1999), but could also make them more vulnerable to aging, given that they are probably more effortful. In sum, these findings are strongly suggestive of a change in the impact of phonological complexity and phoneme position on speech production over the course of the life span.

Another type of factor that may affect speech motor performance in aging is the familiarity of individual speech sounds. This is important because it has been proposed that the motor programs of the most frequent syllables in a language are stored in a “mental syllabary” (Levelt, Roelofs, & Meyer, 1999). According to this view, less frequent syllables are not stored as precompiled motor routines, and therefore need to be assembled online from smaller units (phonemes or diphones), a process that relies on motor sequencing mechanisms. This view has received extensive empirical support, with a number of studies revealing that more frequent syllables are produced faster and more accurately than rare syllables of the same phonological complexity (e.g., Cholin, Levelt, & Schiller, 2006; Laganaro & Alario, 2006; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). Understanding if aging affects frequent and infrequent speech sounds similarly could therefore shed light on the underlying mechanisms. Although an age-related decline affecting the production of all syllables regardless of their frequency would suggest a general decline in motor control, an effect targeting specifically infrequent syllables would, instead, suggest a decline in the neuromotor mechanisms that are responsible for assembling syllables from phonemes. This information may therefore be useful for understanding underlying aging mechanisms, as well as in guiding clinical interventions in this population.

The Present Study

The current study aimed at extending prior work by testing hypotheses about the aging of speech production from a motor control perspective using a cognitively simple, nonlexical task. The first hypothesis was that aging would be associated with changes in movement timing as well as more errors, reflecting a decline in motor control and execution for speech. Based on our previous work (Tremblay & Deschamps, 2016; Tremblay et al., 2017), and because we used nonlexical stimuli, we expected stronger age effects on vocal response duration than on vocal RTs. The second hypothesis was that the relationship between age and speech production performance would be moderated by phonological complexity and everyday syllable usage (i.e., syllable frequency). According to Levelt’s model of speech production (Levelt et al., 1999), only frequent syllables have a stored motor representation. Therefore, if age affects the production of rare syllables only, this would suggest that the affected mechanism is the ability to assemble syllables online from phonemes. If only frequent syllables are affected, the distinctiveness of the neural representations of syllables may be the underlying mechanism. Finally, if phonological complexity affects speech performance irrespective of frequency, then the decline may be related to the planning and execution of complex speech movements. A final, exploratory analysis examined whether error rate is modulated by phoneme position within a nonword in an age-dependent manner. On the basis of the psycholinguistic literature, we expected that the number of errors in the syllable-onset position would increase with age given that phonemes produced in this position are more effortful. To test these hypotheses, a cross-sectional study was conducted in which 60 healthy adults were asked to produce nonwords manipulated along two dimensions: phonological complexity and spoken syllable frequency.

Method

Participants

A nonprobabilistic sample of 60 healthy adults (mean age 48.56 ± 18.14; 33 females) was recruited to participate in this study through emails, posters, and flyers distributed in the community in Québec City. All participants were native speakers of Canadian French. One hundred percent of the participants were schooled in French at the elementary and high school levels. English was spoken as a second language by the large majority of participants (56/60 participants; 93%). Participants had normal or corrected-to-normal vision and no self-reported speech, voice, language, swallowing, psychological, neurological, neurodegenerative, or respiratory disorder. Participants reported to be in good health in general (average score of 5.2/7). Participants were screened for depression using the Geriatric Depression Scale (GSD; Yesavage et al., 1982–1983). One additional participant was originally recruited, but he was excluded because he scored above 10 (indicative of depression) on the GSD. Cognitive level was assessed using the Montreal Cognitive Assessment scale (MOCA; Nasreddine et al., 2005). All participants had normal to mild hearing loss for standard pure tone average (PTA: average of thresholds at .5, 1, and 2 kHz). Participants’ characteristics are reported in Table 1. The study was approved by the Institutional Ethical Committee of the Institut Universitaire en Santé Mentale de Québec (#366–2015).

Stimuli

The stimuli were visually presented, meaningless Québec French-like three-syllable nonwords manipulated along two di-

Table 1
Descriptive Statistics (Means, Standard Deviations, and Correlations) for Participants Characteristics

Participants characteristics	*M*	*SD*	Range	Age	Education (in years)	MOCA (/30)	Other languages	GDS (/30)	Perceived health (/7)	R PTA	L PTA
Age	48.9	18.2	18–83	1	−.151	**−.434**	−.071	−.068	.155	**−.568**	**−.644**
Education (in years)	16.11	2.57	11–22	−.151	1	**.347**	**.262**	.021	−.036	.004	.119
MOCA (/30)[a]	27.92	1.76	23–30	**−.434**	**.347**	1	.074	−.052	.062	**.335**	**.375**
Other languages	1.62	1.18	0–6	−.071	**.262**	.074	1	.141	−.026	.152	.173
GDS (/30)[b]	2.46	2.51	0–9	−.068	.021	−.052	.141	1	−.178	.033	.078
Perceived health (/7)	5.2	.78	3.5–7	.155	−.036	.062	−.026	−.178	1	−.014	−.014
R PTA[c]	10.24	9	0–37	**−.568**	.004	**.335**	.152	.033	−.014	1	**.908**
L PTA[c]	9.1	10.11	−2–44	**−.644**	.119	**.375**	.173	.078	−.014	**.908**	1

Note. *M* = mean; *SD* = standard deviation of the mean. Significant correlations ($p \leq .05$) are in bold.
[a] MoCA = Montreal Cognitive Assessment scale. The MOCA is a short cognitive test that is scored on a 30-point scale. Higher scores indicate better cognitive functions. [b] GDS = Geriatric Depression Screening Scale. The GDS includes 30 questions. Each "negative" answer is worth one point; thus, a higher score indicates a more depressed state. For example, question 1 asks whether the person is globally satisfied with his/her life. A "no' answer is worth one point, whereas a "yes" answer is worth no points. Participants with scores between 0 and 9 are considered normal, while scores between 10 and 19 indicate a depression, and scores between 20 and 30 indicate a severe depression. [c] PTA = pure tone average, measured in dB HL; L = left ear; R = right ear. Normal hearing should range between 0 and 10 dB HL.

mensions: (1) phonological complexity (simple, complex) and (2) Syllable Frequency (high, low). The orthography of the nonwords was adapted from French to be transparent in terms of pronunciation. *Nonwords* are meaningless sequences of syllables that are used to obtain a measure of speech production that is considered largely independent of word-level lexical and semantic processes.

This design resulted in four experimental conditions with 25 trials each (total of 100 trials): (1) simple syllable, high frequency (e.g., "di fe li" [stimuli] ⇒ /di fe li/[response in phonetic alphabet]), (2) complex syllables, high frequency (e.g., "kor vrè pass" [stimuli] ⇒ /kɔr vrɛ pas/[response]), (3) simple syllables, low frequency (e.g., "ju mô zô" [stimuli] ⇒ /ʒy mo zo/[response]), and (4) complex syllables, low frequency (e.g., /tar kla vil/[stimuli and response identical]).

The nonwords were selected from SyllabO+ (http://speechneurolab.ca/en/syllabo), a database of over 360,000 spoken syllables based on a corpus of 225 speakers of Québec French recorded in natural communication contexts (Bedard et al., 2017). For each speaker in the database, spoken utterances are decomposed into syllables and sequences of two and three co-occurring syllables, forming words, part words, and nonwords. For example, the utterance "My name is Jane" includes the following three-syllable sequences:/My-name-is/ and /name-is-Jane/. This was done to extract statistics about syllable co-occurrence frequency in natural spoken language production. For each sequence of syllables that co-occurs at least once in the database, the algorithm calculates distributional statistics (e.g., percentile frequency). The nonwords used in the present studies were chosen from the list of nonwords and part words in SyllabO+. Words were excluded. The stimuli sounded native to the participants because they were composed of native syllables.

The experiment also included an additional 100 trials that contained nonwords that we created (i.e., nonwords that had no occurrence in the database). These nonwords were not analyzed because the frequency of occurrence of the syllables forming these nonwords could not be matched to the frequency of occurrence of the syllables forming nonwords extracted from the database (i.e., syllable frequency was significantly lower for the made-up nonwords).

For phonological complexity, we manipulated the structure of the syllables that formed the nonwords by selecting either three simple syllables (i.e., syllables composed of one consonant and one vowel [CV]) or three complex syllables, which included an additional phoneme (i.e., two consonants and one vowel [CCV or CVC]). All syllables in the database were classified as either frequent or rare based on their ranked order in percentile. Table 1 in the supplementary materials provides the descriptive statistics for each condition. The mean percentile Syllable Frequency for the frequent syllables was of 98 ± 2.5 *SD*, and for the rare syllables it was 88 ± 6.8. As was expected, the average Syllable Frequency of the syllables forming the nonwords differed across the levels of the Syllable Frequency factor ($F_{(1,96)} = 86.7$, $p \leq .001$), but not across the levels of the Phonological Complexity factor ($F_{(1,96)} = 3.04$, $p = .08$), and there was no interaction between Syllable Frequency and Phonological Complexity ($F_{(1,96)} = .79$, $p = .38$). A complete list of stimuli is presented in Table 2 in the supplemental materials.

Procedures

All experimental procedures took place in a sound-attenuated room. Participants first completed a short practice session. On each trial, a three-syllable nonword was presented visually on a 27-in. monitor (HP EliteDisplay E272q) that was located 45 cm from the participant. The stimuli were pale gray letters presented at the center of a black background in the font Times New Roman with a size of 100. Each letter was approximately 4 cm tall and 1–2 cm wide. The stimuli were presented using Presentation software (Neurobehavioral Research).

A short (250 ms) auditory 1000-Hz tone was presented 100 ms after the beginning of the presentation of the nonword. Vocal RTs were calculated automatically from the offset of the tone (see Data Analysis section). Participants' responses were recorded using a Shure headset microphone (Microflex Beta 53) connected to a Quartet USB audio interface (Apogee Electronics, Santa Monica) connected to an iMac computer. The recordings were made using

Sound Studio 4 (Felt Tip Inc., New York City) at a sampling signal of 48 kHz with 24 bits of quantization. Participants were given 2500 ms to respond. The nonword remained on the screen for the entire duration of the trial to minimize working memory demands. The end of the trial was signaled by the disappearance of the nonword from the screen, which was replaced by a crosshair fixation (+). The participants' task was to read the nonword aloud as quickly and accurately as possible following the presentation of the tone. Intertrial intervals ranged from 2000 to 3000 ms. The conditions were completely randomized within each run, and order was the same for all participants. Participants generally completed the session within 90 min including breaks.

Data Analysis

All acoustic analyses were performed using Praat freeware (Boersma & Weenink, 2011). Two young adult female judges with training in phonetics listened to and transcribed all nonwords into the international phonetic alphabet (IPA) based on a detailed transcription protocol that was elaborated by the team prior to beginning the transcriptions. When the two transcriptions differed (which occurred in 2.2% of all trials), a third judge, also trained in phonetics, transcribed the sequence to reach an interjudge agreement of 2/3. Following transcription, the number of errors was computed. Errors included misses, sound exchanges, production of additional syllables, and the production of unintelligible syllables. Error rate was calculated as the proportion of nonwords that contained at least one error in each experimental condition.

A semiautomatic procedure was used in Praat to segment participants' responses and extract vocal response duration (RD) and vocal RT for the correct trials only. The procedure involved the automatic detection of the tone, followed by the automatic segmentation of each nonword based on an intensity and duration algorithm detection. Based on minimal duration and low intensity energy parameters, the algorithm automatically established the nonword boundaries. These boundaries were visually inspected and manually adjusted when necessary, based on waveform and spectrogram information. The algorithm also calculated the time from the tone offset to the response onset.

All trials containing an incorrect response were excluded from the analysis of RT and RD. Next, trials containing outliers were removed from the dataset. Outliers were defined as values that were three standard deviations (*SDs*) away from the mean within each condition and each participant. The mean RT (in seconds) from the onset of the nonword, mean RT variability (in *SD* in seconds), mean RD (in seconds), and mean RD variability (in *SD* in seconds) were computed for each condition and each participant.

Statistical analyses focused on five dependent measures: error rate, RD, RD variability, RT and RT variability. Linear mixed model (LMM) analyses were conducted in SPSS Version 25 for Mac (IBM), separately for each dependent variable, with Phonological Complexity (simple, complex) and Syllable Frequency (high, low) as within-subject (repeated) fixed factors, and Age as a mean-normalized (centered) between-subjects continuous fixed factor. Participants were included as a random factor in the model. For all post hoc analyses (regressions and moderation analyses), we report unstandardized beta coefficients (β) and probabilities (p). All moderation analyses were conducted using the PROCESS macro (model #1) for SPSS (Hayes, 2008, 2013) with the following parameters: $p = .05$, bias-corrected bootstrapping with 20,000 samples.

Given the known behavioral effects of phoneme position, an additional LMM analysis was conducted on error rate to determine whether the position of errors varied as a function of age. Error rate in this analysis was calculated as the proportion of errors in each phoneme and syllable position. This analysis was conducted only on the CVC syllables (the only ones with a coda). The LMM analysis was conducted with Phoneme Position (onset = 0, nucleus = 1, coda = 2), and Syllable Position (first = 0, second = 1, last = 2) as continuous (repeated) fixed factors. Note that syllable onset refers to the first consonant in a syllable (e.g., /*s*at/), while the nucleus is the vowel (e.g., /s*a*t/), and the coda is the last consonant (e.g., /sa*t*/). Mean-normalized Age was included in the analysis as a between-subjects continuous factor. Participants were included as a random factor.

Results

The descriptive statistics for each dependent variable (error rate, RT, RT variability, RD, and RD variability) are reported in Table 2. The results of the Linear Mixed Model (LMM) analyses are provided in Table 3 (for the inferential statistics) and in Table 3 in the supplemental materials (for the parameter estimates); only the main results are reported in the text.

Table 2
Descriptive Statistics for Each of the Dependent Variable in Each Experimental Condition

Condition	*M* (*SD*)	[95% CI]
A. Error rate (measured as the proportion of nonwords with errors)		
Simple and frequent syllables	.28 (.15)	[.24, .32]
Simple and rare syllables	.45 (.16)	[.41, .49]
Complex and frequent syllables	.33 (.15)	[.29, .37]
Complex and rare syllables	.35 (.17)	[.30, .39]
B. Vocal reaction time (in sec) from onset of visual stimuli		
Simple and frequent syllables	.47 (.13)	[.44, .50]
Simple and rare syllables	.5 (.15)	[.47, .54]
Complex and frequent syllables	.45 (.13)	[.42, .49]
Complex and rare syllables	.47 (.13)	[.44, .51]
C. Vocal reaction time variability in *SD* (in sec)		
Simple and frequent syllables	.15 (.05)	[.13, .16]
Simple and rare syllables	.16 (.06)	[.14, .17]
Complex and frequent syllables	.11 (.04)	[.09, .12]
Complex and rare syllables	.13 (.05)	[.12, .14]
D. Vocal response duration (in sec)		
Simple and frequent syllables	.94 (.14)	[.90, .98]
Simple and rare syllables	1.06 (.16)	[1.02, 1.1]
Complex and frequent syllables	1.28 (.22)	[1.23, 1.34]
Complex and rare syllables	1.27 (.17)	[1.22, 1.31]
E. Vocal response duration variability (in *SD*)		
Simple and frequent syllables	.15 (.049)	[.14, .16]
Simple and rare syllables	.2 (.09)	[.14, .16]
Complex and frequent syllables	.2 (.08)	[.18, .23]
Complex and rare syllables	.15 (.18)	[.15, .17]

Note. CI = confidence interval.

Table 3
Linear Mixed Model Results (Type III F Tests)

Effect	*df*	*F*	*p*
A. Error rate (measured as the proportion of nonwords with errors)			
Intercept	1, 56	435.14	<.001
Age	1, 56	9.13	.004
Phonological complexity	1, 165	1.3	.25
Age × Phonological Complexity	1, 165	2.44	.12
Spoken syllable frequency	1, 165	51.91	<.001
Age × Spoken syllable frequency	1, 165	1.47	.23
Phonological Complexity × Spoken syllable frequency	1, 165	31.76	<.001
Age × Phonological Complexity × Spoken syllable frequency	1, 165	.38	.54
B. Error rate as a function of position			
Intercept	1, 51	47.29	<.001
Age	1, 50	.41	.52
Syllable Position	1, 82	5.51	.021
Phoneme Position	1, 220	117.53	<.001
Syllable × Phoneme Position	1, 154	37.6	<.001
Age × Syllable Position	1, 82	.12	.736
Age × Phoneme Position	1, 101	18.37	<.001
Age × Syllable × Phoneme Position	1, 219	.95	.33
C. Vocal reaction time (in sec) from onset of visual stimuli			
Intercept	1, 56	503.36	<.001
Age	1, 56	.23	.64
Phonological Complexity	1, 141	17.99	<.001
Age × Phonological Complexity	1, 141	.1	.75
Spoken syllable frequency	1, 141	23.47	<.001
Age × Spoken syllable frequency	1, 141	2.49	.12
Phonological Complexity × Spoken syllable frequency	1, 141	1.74	.19
Age × Phonological Complexity × Spoken syllable frequency	1, 141	.72	.39
D. Vocal reaction time variability in *SD* (in sec)			
Intercept	1, 58	739.47	<.001
Age	1, 58	.027	.87
Phonological Complexity	1, 151	37.38	<.001
Age × Phonological Complexity	1, 151	.72	.39
Spoken syllable frequency	1, 151	6.54	.012
Age × Spoken syllable frequency	1, 153	.18	.66
Phonological Complexity × Spoken syllable frequency	1, 151	1.95	.16
Age × Phonological Complexity × Spoken syllable frequency	1, 151	.71	.4
E. Vocal response duration (in sec)			
Intercept	1, 51	4238.56	<.001
Age	1, 51	46.69	<.001
Phonological Complexity	1, 155	1026.44	.001
Age × Phonological Complexity	1, 155	12.29	.001
Spoken syllable frequency	1, 155	60.26	<.001
Age × Spoken syllable frequency	1, 155	.06	.8
Phonological Complexity × Spoken syllable frequency	1, 155	53.19	<.001
Age × Phonological Complexity × Spoken syllable frequency	1, 155	5.39	.021
F. Vocal response duration variability (in *SD*)			
Intercept	1, 65	1171.21	<.001
Age	1, 65	42.06	<.001
Phonological Complexity	1, 142	1.6	.21
Age × Phonological Complexity	1, 142	.89	.35
Spoken syllable frequency	1, 142	.19	.66
Age × Spoken syllable frequency	1, 142	.14	.71
Phonological Complexity × Spoken syllable frequency	1, 142	38.57	<.001
Age × Phonological Complexity × Spoken syllable frequency	1, 142	8.26	.005

Error Rate

As detailed in Table 3A and illustrated in supplemental Figure 1, the LMM analyses revealed a main effect of Age ($p = .004$) on overall error rate, with error rate increasing with advancing age.

The LMM analysis conducted on the location of errors in the CVC syllables revealed an interaction between Phoneme and Syllable position ($p < .0001$). As detailed in Table 3B and illustrated in Figure 1A, in general, participants made more mistakes in the nucleus and coda positions, relative to onset, in all syllable positions. The pairwise comparisons are reported in supplementary Tables 4 and 5. In addition to the interaction between Phoneme and Syllable Position, there was also a two-way interaction between Age and

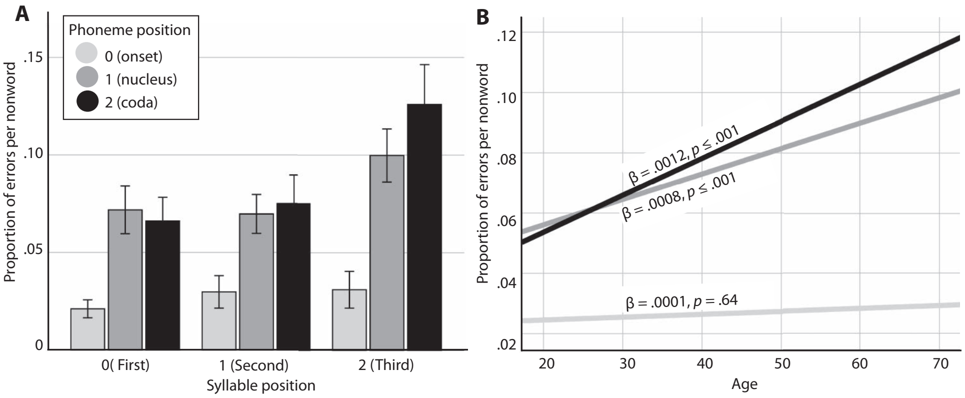

Figure 1. Error rate as a function of position. (A) Decomposition of the interaction between syllable and phoneme position on error rate. Error rate (proportion of errors per nonword) is displayed separately for each of the nine experimental conditions. Error bars represent the 95% confidence interval of the mean. (B) Decomposition of the interaction between age and phoneme position on error rate. Linear regressions were performed to quantify the relationship between error rate (*y*-axis) and age (*x*-axis) within each phoneme position. For each analysis, an unstandardized beta coefficient is reported (β).

Phoneme Position ($p < .0001$). This interaction revealed that error rate in the coda and nucleus positions was higher with advancing in age. This effect was not found in the onset position (Figure 1B).

Vocal Reaction Time (RT)

As detailed in Table 3C and 3D, for mean RT and mean RT variability, no main effect of age nor an age interaction was found.

To examine whether the absence of a relationship between Age and RT was related to a potential speed–accuracy trade-off, we conducted a moderation analysis in which the dependent variable was overall RT, the predictor variable was Age, and Error Rate was the continuous moderator. No moderating effect of Error Rate was found on the relationship between Age and RT ($\beta = -.002$, $p = .80$), that is, the relationship between RT and Age did not vary as a function of Error Rate, and there was no evidence of a speed–accuracy trade-off. These results are illustrated in Figure 2A in the supplemental materials.

Vocal Response Duration (RD)

As detailed in Table 3E, the LMM analysis revealed a significant main effect of Age, which indicated that older age was associated with longer RD. There was also an interaction between Phonological Complexity and Syllable Frequency, with the effect of Frequency only significant for the simple syllables, as illustrated in Figure 2A. The analysis also revealed an interaction between

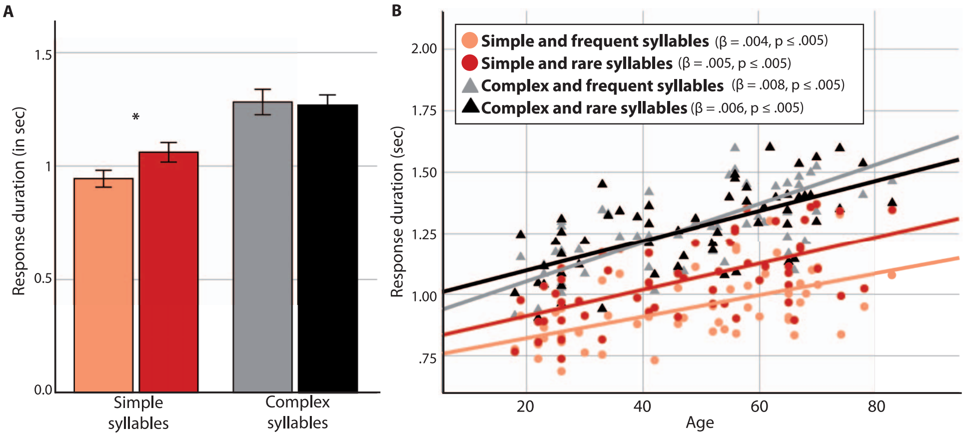

Figure 2. Response duration (RD). (A) The bar chart represents RD in seconds as a function of Syllable Frequency separately for the simple and complex syllables. The error bars represent the standard error of the mean. The asterisks indicate statistical significance ($p < .05$). (B) The scatterplot represents RD (x-axis) as a function of Age (y-axis). The lines represent the linear fit for each of the four experimental conditions. The unstandardized beta coefficients (β) are reported along with probability for each condition. See the online article for the color version of this figure.

Age and Phonological Complexity, indicating a stronger relationship between Age and RD for the complex syllables compared to the simple syllables. With advancing age, RD becomes differentially longer for the complex syllables. Finally, a three-way interaction among Age, Phonological Complexity and Syllable Frequency, illustrated in Figure 2B, was also found. To decompose this interaction, we examined the interaction between Age and Phonological Complexity using linear regressions separately for the frequent and rare syllables. Results show a significant interaction between Age and Phonological Complexity for the frequent syllables ($\beta = .004$, $t = 2.461$, $p = .015$) but not for the rare syllables ($\beta = .001$, $t = .536$, $p = .593$).

To test the hypothesis that the age-related increase in RD was a strategy to maintain accuracy—a form of speed–accuracy trade-off—we conducted a moderation analysis in which the dependent variable was overall RD, the predictor variable was Age, and Error Rate was the continuous moderator. No moderating effect of Error Rate was found on the relationship between Age and RD ($\beta = .006$, $p = .46$), meaning that the relationship between RD and Age did not vary as a linear function of Error Rate, and there was no evidence of a speed–accuracy trade-off. These results are illustrated in Figure 2B in the supplemental materials.

RD Variability (Expressed as *SD* in Seconds)

As detailed in Table 3F, the LMM analysis revealed a significant main effect of Age ($p < .001$), indicating that RD variability increased with age. There was also a significant interaction between Syllable Frequency and Phonological Complexity ($p < .001$), whereby variability increased as a function of Syllable Frequency for the simple syllables and decreased as a function of Syllable Frequency for the complex syllables. The two-way interaction is illustrated in Figure 3A. A three-way interaction among Age, Syllable Frequency, and Phonological Complexity ($p = .005$) indicated that the two-way interaction was moderated by Age. The three-way interaction is illustrated in Figure 3B. As can be seen in the figure, until approximatively 40 years of age, there was no difference in variability between the conditions. After this point, the two-way interaction pattern described above progressively emerged and remained stable. The relationship between RD variability and Age was significant in all conditions ($p \leq .005$).

To examine whether the age-related increase in RD variability was related to accuracy, we conducted a moderation analysis in which the dependent variable was overall RD variability, the predictor variable was Age, and Error Rate was the continuous moderator. No moderating effect of Error rate was found on the relationship between Age and RD variability ($\beta = .001$, $p = .61$), meaning that the relationship between RD variability and Age did not vary as a function of Error Rate, and there was no evidence of a speed–accuracy trade-off. These results are illustrated in Figure 2C in the supplemental materials.

Relationship Between RT and RD

Next, we examined the relationship between RT and RD. If speakers begin articulating a nonword prior to completely assembling the articulatory code, then one should observe lengthened RD for those speakers using less preparation prior to speech onset (i.e., an inverse relationship between RT and RD). Such relationship has been shown in previous research (e.g., Griffin, 2003). To test this hypothesis, first, a linear regression was conducted, which revealed the presence of a negative relationship between RT and RD ($r^2 = .06$, $\beta = -.40$, $p \leq .001$). To determine whether Age affected this relationship, we conducted a moderation analysis in which the dependent variable was RT, the predictor variable was RD, and the continuous moderator was Age. A significant moderating effect of Age was found on the relationship between RT and RD ($\beta = .006$, $p = .01$). This effect is illustrated in Figure 4. The pick-a-point approach (Bauer & Curran, 2005) was used to probe the interaction. This analysis revealed that the relationship between RT and RD was significant at low ($\beta = -.297$, $p \leq .005$) and medium values of the moderator (Age) ($\beta = .-194$, $p \leq$

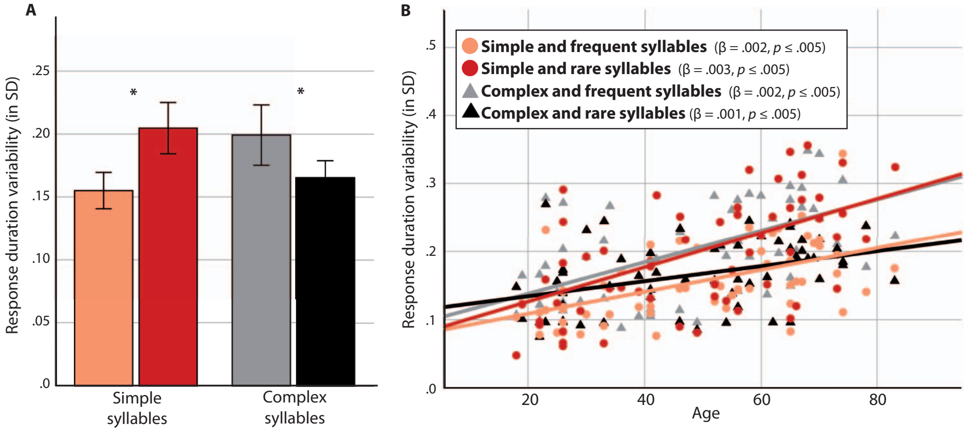

Figure 3. Response duration variability. (A) The bar charts represent RD variability as a function of Syllable Frequency separately for the simple and complex syllables. The error bars represent the standard error of the mean. The asterisks indicate statistical significance ($p < .05$). (B) The scatterplot represents RD variability (x-axis) as a function of Age (y-axis). The lines represent the linear fit for each of the four experimental conditions. The unstandardized beta coefficients (β) are reported along with probability for each condition. See the online article for the color version of this figure.

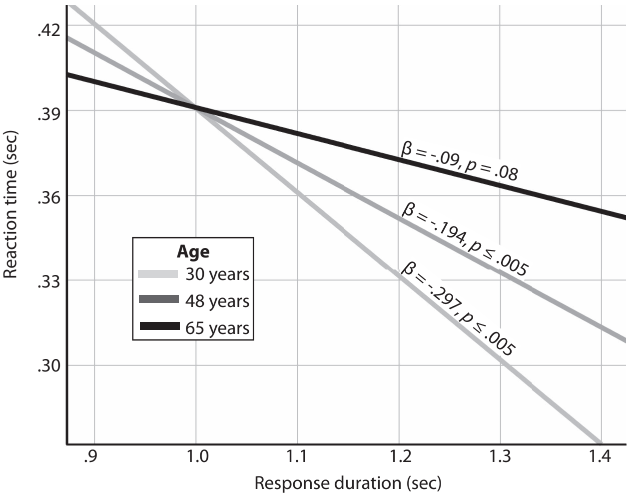

Figure 4. Analysis of the RT/RD relationship as a function of age. Relationship between RT in sec (*y*-axis) and RD (*x*-axis) as a function of Age (moderation analysis). Different levels of the factor Age are shown as pale gray (young), dark gray (middle-aged), and black (older participants). For each analysis, an unstandardized beta coefficient is reported (β) along with the probability.

.005). That is, younger participants showed a strong negative relationship between RT and RD; this relationship was not present in older adults ($\beta = -.09$, $p = .08$).

Discussion

Despite the central role that speaking plays in social interactions, several questions remain regarding the manner in which the speech motor system evolves with age. The main objective of this study was to test hypotheses about the nature of the mechanisms that underlie age-related decline in speech production from a motor control perspective. Our results show an overall increase in error rate with aging, especially in the coda position, and important changes in response timing, suggestive of a general decline in the planning and execution of speech. These results are discussed in the following paragraphs.

Speech Planning and Execution in Aging

Our main hypothesis, which was verified, was that aging would be associated with a decrease in accuracy and changes in speech timing, suggestive of a decline in the planning and execution of speech movements, most likely of neural origin. Although a contribution of peripheral factors, such as muscular endurance in the lips and tongue, cannot be excluded, in a recent study, we showed that age-related decline in speech production performance was only marginally related to such factors (Bilodeau-Mercure & Tremblay, 2016). Moreover, prior studies from our group have shown that age-related increase in RD is associated with abnormal activation pattern and structural decline in several areas including the primary motor cortex and striatum (Tremblay & Deschamps, 2016; Tremblay et al., 2017). Together, these findings suggest that speech production decline may originate from brain senescence. Here we suggest that speech planning and execution processes decline with age. Indeed, we found that younger and middle-aged adults produce shorter responses at longer RT while this relationship disappears in older adults, suggesting a declining ability to adjust planning in older adults. While some authors have argued that RD reflects motor execution while RT reflects perceptual encoding and motor planning (Groves, 1973; Henry, 1960), others have, in contrast, shown a relationship between the two (Danev, DeWinter, & Wartna, 1971; Griffin, 2003), with RD responding to some aspects of stimulus evaluation and movement planning, such as practice and complexity (e.g., Bjørklund, 1991; Houlihan et al., 2013; Magill & Powell, 1975). Furthermore, it has been shown that, when response programming begins at the onset of a start cue, a relationship between RT and RD is found (e.g., Klapp, Patrick Wyatt, & Mac Lingo, 1974; Quinn, Schmidt, Zelaznik, Hawkins, & McFarquhar, 1980). In the present study, responses could not be preprogrammed because different nonwords were produced on every trial. Our results therefore suggest that, when planning is not completed before speech onset, articulation is slowed down to complete planning online, a strategy that disappears in older age. This finding is coherent with previous studies showing less efficient planning with age in nonspeech motor tasks (e.g., Cerella, 1985; Cerella & Hale, 1994; Jordan & Rabbitt, 1977; Perone & Baron, 1982; Stelmach et al., 1988), and with the word production literature (e.g., Balota & Duchek, 1988; Bowles et al., 1987; Britt et al., 2016; LaGrone & Spieler, 2006; Newman & German, 2005). Since planning in the present study included the transformation of a visual cue into a sound-based representation, the retrieval/assembling of motor programs, the organization of these programs into a smooth sequence and, finally, articulation, it is difficult to attribute the change in the RT/RD relationship to a decline in a specific process (e.g., sequencing) or even to a specific stage (planning vs. execution). However, because of the nonlexical aspect of the stimuli, it is unlikely to reflect lexical planning. Additional studies are needed to investigate aging of distinct speech motor processes.

Aging of Speech Production: Specific or General?

Another aim of the study was to determine if aging targets specific speech motor processes or if, instead, the decline is general. Specifically, we wanted to test the following hypotheses: (1) Aging reduces the ability to assemble (rare) syllables online, and (2) aging is associated with a decline in the stored representations of syllables, making the retrieval of complex syllables more difficult. The alternative hypothesis was that decline is general, affecting all syllables. These hypotheses were derived from previous work from our group showing sequencing difficulties in aging (Bilodeau-Mercure et al., 2015; Bilodeau-Mercure & Tremblay, 2016; Tremblay & Deschamps, 2016; Tremblay et al., 2017) and from Levelt's spoken language production model (Levelt et al., 1999). To test these predictions, we manipulated the frequency and complexity of our stimuli. RD and RD variability were found to be distinctively sensitive to these factors in an age-dependent manner, but not RT or errors, which showed age-independent effects. Overall, our results are most consistent with a general decline in the planning/execution of speech.

Specifically, we show that performance in the production of syllables, frequent or rare, declined with age in terms of RD and RD variability. This finding does not support the hypothesis that aging specifically affects the mechanism of assembling rare syllables online, because all syllables, not just the rare ones, were affected. Our results thus suggest a global decline in speech motor control/execution resulting in longer and more variable response duration, affecting both assembling mechanisms and stored representations. Additional studies are needed to clarify the weight of the decline affecting each mechanism.

Our finding of distinct aging patterns for RD and RD variability suggests that these measures are indexing different response properties, although both patterns support the notion of a global decline in speech planning/execution. For RD, we found a clear effect of Phonological Complexity with age, with complex syllables being more strongly affected by aging than simple syllables. The effect of Syllable Frequency was less straightforward. While the effect of Syllable Frequency increased with age for the simple syllables, complex syllables were not affected by frequency. This unexpected finding could reflect a *plateau* effect, whereby, to maintain fluency and intelligibility, responses can only become so much longer. Disordered speech timing is a cardinal symptom in several speech disorders including apraxia of speech, nonfluent aphasia, and dysarthria (McNeil, Liss, Tseng, & Kent, 1990; Seddoh et al., 1996; Towne & Crary, 1988). Speech rate has been shown to be related to perceived disorder severity in speech disorders, with increased syllable duration being associated with perceived higher severity (Ziegler, 2002). Hence, syllable duration can only increase up to a certain point before it affects intelligibility. Additional data are needed to put this hypothesis to an empirical test by measuring perceived intelligibility in healthy adults and relating these measures to measures of RD. Alternatively, the rare complex syllables may not have been rare enough to challenge the speech motor system enough to reveal a Frequency Effect on speech performance (see also the Limits section for a discussion of this matter).

For RD variability, we found that, in younger adults, there was no effect of Phonological Complexity or Syllable Frequency. In older adults, however, variability increased as a function of Syllable Frequency for the simple syllables and decreased as a function of Syllable Frequency for the complex syllables. It is difficult to explain why frequent complex syllables are less variable than rare complex syllables. Additional data is needed on response variability to better understand the specific underlying mechanisms.

Location of Speech Errors

A final objective of this study was to examine if, with advancing age, the error rate in the onset position would increase compared to other positions (nucleus, coda) reflecting difficulty maintaining the additional loudness and duration constraints of consonants in the initial position (Redford & Diehl, 1999), as well as their tighter articulatory constrictions (Krakow, 1999) and reduced variability (Byrd, 1996; Krakow, 1999). Instead, we found increased difficulty for older adults in the final (coda) position. Given that consonants in the coda require less energy, being produced less distinctively and consistently than the same consonants in the onset position, it is possible that less energy is allocated in older compared to younger adults for the articulation of sounds that may be less critical to communicate effectively. Additional evidence is needed to clarify the source of the difficulty experienced by older adults, whether related to a decline in phonological encoding processes (i.e., specification of the syllable structure) or a decline in speech motor planning/execution. Alternatively, it is possible that older adults develop different strategies, allocating energy only where it is crucial (onset) to maintain communication efficiency with declining resources, consistent with the Selection-Optimization-Compensation (SOC) model of aging, which suggests that older adults adjust their objectives and develop compensation strategies to optimize outcomes (M. M. Baltes & Carstensen, 1996; P. B. Baltes & Lindenberger, 1997; P. B. Baltes, Staudinger, & Lindenberger, 1999).

Limits

In this study, we examined the aging of speech production from the standpoint of a maximal performance task. Although unlike day-to-day performance, maximal performance tasks have wide clinical applications in speech pathology, cognitive psychology, and neurology. Moreover, as pointed out by Kent, Kent, and Rosenbek (1987),

> Even though the requirements of speech may be well within the maximal performances of normal speakers, it can be important to determine when a disordered talker has a reduced reserve. A reduced reserve can impair a talker's flexibility and can also mean that speaking for an individual is a taxing process.

Future work focusing on analyzing an oral corpus or spontaneous language production data, such as SyllabO+ (Bedard et al., 2017), could contribute to our understanding of the aging of natural spoken language production. Another limit of the present work is the use of Syllable Frequency as an arbitrary binary factor (low, high) with a limited range. It is likely that very low Syllable Frequency, not included in the present work, represents an additional challenge for the motor system. Additional work is needed with stimuli covering a broader range of spoken syllable frequencies. A final limitation is that, in the present study, participants were asked to speak as soon as a response cue was presented, rather than as fast as they could. It is therefore possible that younger adults did not optimize the timing of their response to their maximal capacity, and that a faster task could have revealed stronger age differences in RT. However, the response cue occurred quickly, 100 ms after the beginning of the trial, providing participants with little time to read the stimuli and prepare a response. Additional studies are needed to resolve this issue, by examining vocal RT using an experimental paradigm with a stronger emphasis on speed.

Conclusion

Appropriate diagnosis and treatment for older adults with speech production difficulties depend upon the ability to tease apart normal from pathological speech patterns, as well as knowledge about the nature and range of normal aging mechanisms. The present study provides new empirical evidence of a decline in the planning and execution of speech production in healthy older adults, as well as a framework for future investigations. Specifically, we show that aging is associated with a decline in speech response accuracy, especially in the coda position, and in the control of speech timing. Additional studies are needed to further explore the relationship between age and spoken language production by comparing the impact of lexical and phonological complexity on speech planning and execution, and by investigating the impact of cognitive decline on speech production to clarify the nature and scope of underlying senescence processes.

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