Aging of speech production, from articulatory accuracy to motor timing

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Abstract

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 non-lexical speech production task in which spoken syllable frequency and phonological complexity were systematically varied to test hypotheses about underlying mechanisms. A non-probabilistic sample of 60 cognitively healthy adults (18 - 83 years) produced meaningless nonwords aloud as quickly and accurately as possible. Error rate, vocal reaction time, vocal reaction time 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 induration 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 reaction time 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, Speech rate

Advancing age is associated with a decline in a number of functions, including memory, attention and executive control (e.g., Park, Lautenschlager, Hedden, Davidson, Smith, & Smith, 2002; Salthouse, 1996; Salthouse, 2009), as well as a decline in the planning of movements, which is reflected by longer reaction time (RT) across a variety of motor tasks (e.g., Cerella, 1985; Cerella & Hale, 1994; Jordan & Rabbitt, 1977; Niermeyer, Suchy, & Ziemnik, 2016; Perone & Baron, 1982; Rabbitt & Birren, 1967; Stelmach, Goggin, & Amrhein, 1988). Also declining with age is movement rate (age-related slowing) and movement duration (age-related increase in duration) (e.g. Aoki & Fukuoka, 2010; Cousins, Corrow, Finn, & Salamone, 1998; Darbutas, Juodzbaliene, Skurvydas, & Krisciunas, 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.

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 lifespan, 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, Flaisch, Wilser, Eulitz, Rockstroh, Conway, Gonzalez-Rothi, & Crosson, 2009; Meinzer, Seeds, Flaisch, Harnish, Cohen, McGregor, Conway, Benjamin, & Crosson, 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. Yet, 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, 1999; Moustafa, Chakravarthy, Phillips, Gupta, Keri, Polner, Frank, & Jahanshahi, 2016; Skodda, Gronheit, Mancinelli, & Schlegel, 2013; Skodda, Rinsche, & Schlegel, 2009) and also appears to be an early symptom of Alzheimer's disease (Cera, Ortiz, Bertolucci, & Minett, 2013; Meilan, Martinez-Sanchez, Carro, Lopez, Millian-Morell, & Arana, 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 non-speech orofacial movements (e.g. Bilodeau-Mercure, Kirouac, Langlois, Ouellet, Gasse, & Tremblay, 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 non-lexical speech production tasks or very simple word repetition tasks (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. Though 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, White, Mattys, Lansford, Lotto, Spitzer, & Caviness, 2009) and speech apraxia (Seddoh, Robin, Sim, Hageman, Moon, & Folkins, 1996). Taken together, these findings suggest that aging may affect motor aspects of speech production, though 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 (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), are louder and longer than consonants in 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 lifespan.

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 upon 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. While 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 current study aimed at extending prior work by testing hypotheses about aging of speech production from a motor control perspective using a cognitively simple, non-lexical 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 non-lexical stimuli, we expected stronger age effects on vocal response duration than vocal reaction times. 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. Based on 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 non-probabilistic 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. 100% 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 sore of 5.2/7). Participants were screened for depression using the Geriatric Depression Scale (GSD) (Yesavage, Brink, Rose, Lum, Huang, Adey, & Leirer, 1982). 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, Chertkow, Phillips, Bergman, & Whitehead, 2003). 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 3-syllable nonwords manipulated along two dimensions: (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 4 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, Audet, Drouin, Roy, Rivard, & Tremblay, 2016). 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 3-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-occur 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. Supplementary Table 1 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 Supplementary Table 2.

Procedures

All experimental procedures took place in a sound-attenuated room. Participants first completed a short practice session. On each trial, a 3-syllable nonword was presented visually on a 27-inch monitor (HP EliteDisplay E272q) that was located 45 cm from the participant. The stimuli were pale gray letters presented at the centre 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).

100 ms after the beginning of the presentation of the nonword, a short (250 ms) auditory 1000 Hz tone was presented. Vocal reaction times 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, CA 90404, USA) connected to an iMac computer. The recordings were made using Sound Studio 4 (Felt Tip Inc., NYC, USA) at a sampling signal of 48 kHz with 24 bits of quantization. Participants generally completed the session within 90 minutes including breaks. 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 signalled 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. Inter-trial intervals ranged from 2000 to 3000 ms. The conditions were completely randomized within each run and order was the same for all participants.

Data Analysis

All acoustic analyses were performed using Praat software (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 inter-judge 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 semi-automatic procedure was used in Praat to segment participants' responses and extract vocal response duration (RD) and vocal reaction time (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 (SD) 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-subject 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=0.05, bias-corrected bootstrapping with 20,000 samples.

Given the known behavioural 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. /sat/), while the nucleus is the vowel (e.g. /sat/), and the coda is the last consonant (e.g. /sat/). Mean-normalized Age was included in the analysis as a between-subject 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 Supplementary Table 3 (for the parameter estimates); only the main results are reported in the text.

Error Rate

As detailed in Table 3A and illustrated in Supplementary 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 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 (β = -.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 Supplementary Figure 2A.

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 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 3-way interaction between 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 (β = .004, t = 2.461, p = .015) but not for the rare syllables (β = .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 Supplementary Figure 2B.

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 2-way interaction is illustrated in Figure 3A. A 3-way interaction between Age, Syllable frequency and Phonological complexity ($p = .005$) indicated that the 2-way interaction was moderated by Age. The 3-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 (β = .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 Supplementary Figure 2C.

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, β = .-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 (β = .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 (β = -.297, $p \leq .005$) and medium values of the moderator (Age) (β = .-194, $p \leq .005$). That is, younger participants showed a strong negative relationship between RT and RD; this relationship was not present in older adults (β = -.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. Though 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. Bjorklund, 1991; Houlihan, Jette, Friedman, Paasche-Orlow, Ni, Wierbicky, Williams, Ducharme, Zazula, Cuevas, Rosenblum, & Williams, 2013; Magill & Powell, 1975). Further, 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, 1980). In the present study, responses could not be pre-programmed 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 non-speech 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 non-lexical 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, though 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, non-fluent 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 is 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 Limit 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 constrains 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 adult develop different strategies, allocating energy only where it is crucial (onset) to maintain communication efficiency with declining resources, consistent with the Selection-Optimisation-Compensation (SOC) model of aging, which suggests that older adults adjust their objectives and develop compensation strategies to optimize outcomes (Baltes & Carstensen, 1996; Baltes & Lindenberger, 1997; Baltes, Staudinger, & Lindenberger, 1999).

Limits

In this study, we examined the aging of speech production from the standpoint of a maximal performance task. Though 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 et al. (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., 2016), 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 the present work, represent 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. Further 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.

References

Aichert, I., & Ziegler, W. (2004). Syllable frequency and syllable structure in apraxia of speech. *Brain and language, 88*(1), 148-159.

Aoki, T., & Fukuoka, Y. (2010). Finger tapping ability in healthy elderly and young adults. *Med Sci Sports Exerc, 42*(3), 449-455. doi:10.1249/MSS.0b013e3181b7f3e1

Balota, D. A., & Duchek, J. M. (1988). Age-related differences in lexical access, spreading activation, and simple pronunciation. *Psychol Aging, 3*(1), 84-93.

Baltes, M. M., & Carstensen, L. L. (1996). The process of successful ageing. *Ageing and Society, 16*, 397–422.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychol Aging, 12*(1), 12-21.

Baltes, P. B., Staudinger, U. M., & Lindenberger, U. (1999). Lifespan psychology: theory and application to intellectual functioning. *Annu Rev Psychol, 50*, 471-507. doi:10.1146/annurev.psych.50.1.471

Bauer, D. J., & Curran, P. J. (2005). Probing Interactions in Fixed and Multilevel Regression: Inferential and Graphical Techniques. *Multivariate Behavioral Research, 40*(3), 373-400. doi:10.1207/s15327906mbr4003_5

Bedard, P., Audet, A. M., Drouin, P., Roy, J. P., Rivard, J., & Tremblay, P. (2016). SyllabO+: A new tool to study sublexical phenomena in spoken Quebec French. *Behavioral Research Methods*. doi:10.3758/s13428-016-0829-7

Bilodeau-Mercure, M., Kirouac, V., Langlois, N., Ouellet, C., Gasse, I., & Tremblay, P. (2015). Movement sequencing in normal aging: speech, oro-facial and finger movements. *Age, 37*(4), 37-78.

Bilodeau-Mercure, M., & Tremblay, P. (2016). Age Differences in Sequential Speech Production: Articulatory and Physiological Factors. *Journal of the American Geriatrics Society, 64*(11), e177-e182. doi:10.1111/jgs.14491

Bjorklund, R. A. (1991). Reaction time and movement time measured in a key-press and a key-release condition. *Percept Mot Skills, 72*(2), 663-673. doi:10.2466/pms.1991.72.2.663

Boersma, P., & Weenink, D. (2011). Praat: doing phonetics by computer (Version 5.2.10). Retrieved from http://www.praat.org/

Bohland, J. W., & Guenther, F. H. (2006). An fMRI investigation of syllable sequence production. *Neuroimage, 32*(2), 821-841. doi:10.1016/j.neuroimage.2006.04.173

Bowles, N. L., Obler, L. K., & Albert, M. L. (1987). Naming errors in healthy aging and dementia of the Alzheimer type. *Cortex; a journal devoted to the study of the nervous system and behavior, 23*(3), 519-524.

Britt, A. E., Ferrara, C., & Mirman, D. (2016). Distinct Effects of Lexical and Semantic Competition during Picture Naming in Younger Adults, Older Adults, and People with Aphasia. *Frontiers in psychology, 7*, 813. doi:10.3389/fpsyg.2016.00813

Brown, A. S., & Nix, L. A. (1996). Age-related changes in the tip-of-the-tongue experience. *The American Journal of Psychology, 109*(1), 79-91. doi:https://www.ncbi.nlm.nih.gov/pubmed/8714453

Burke, D. M., MacKay, D. G., Worthley, J. S., & Wade, E. (1991). On the tip of the tongue: What causes word finding failures in young and older adults? *Journal of Memory and Language, 30*(5), 542–579.

Byrd, D. (1996). Influences on articulatory timing in consonant sequences. *Journal of Phonetics, 24*(2), 209-244. doi:10.1006/jpho.1996.0012

Cera, M. L., Ortiz, K. Z., Bertolucci, P. H., & Minett, T. S. (2013). Speech and orofacial apraxias in Alzheimer's disease. *Int Psychogeriatr, 25*(10), 1679-1685. doi:10.1017/S1041610213000781

Cerella, J. (1985). Information processing rates in the elderly. *Psychological Bulletin, 98*(1), 67-83. doi:http://dx.doi.org/10.1037/0033-2909.98.1.67

Cerella, J., & Hale, S. (1994). The rise and fall in information-processing rates over the life span. *Acta Psychol (Amst), 86*(2-3), 109-197.

Cholin, J., Levelt, W. J., & Schiller, N. O. (2006). Effects of syllable frequency in speech production. *Cognition, 99*(2), 205-235.

Contreras-Vidal, J. L., Teulings, H. L., & Stelmach, G. E. (1998). Elderly subjects are impaired in spatial coordination in fine motor control. *Acta Psychol (Amst), 100*(1-2), 25-35.

Cooke, J. D., Brown, S. H., & Cunningham, D. A. (1989). Kinematics of arm movements in elderly humans. *Neurobiol Aging, 10*(2), 159-165.

Cousins, M. S., Corrow, C., Finn, M., & Salamone, J. D. (1998). Temporal measures of human finger tapping: effects of age. *Pharmacol Biochem Behav, 59*(2), 445-449.

Danev, S. G., DeWinter, C. R., & Wartna, G. F. (1971). On the relation between reaction and motion time in a choice reaction task. *Acta Psychol (Amst), 35*, 188-197.

Darbutas, T., Juodzbaliene, V., Skurvydas, A., & Krisciunas, A. (2013). Dependence of reaction time and movement speed on task complexity and age. *Medicina (Kaunas), 49*(1), 18-22.

Darling, W. G., Cooke, J. D., & Brown, S. H. (1989). Control of simple arm movements in elderly humans. *Neurobiol Aging, 10*(2), 149-157.

Duchin, S. W., & Mysak, E. D. (1987). Disfluency and rate characteristics of young adult, middle-aged, and older males. *J Commun Disord, 20*(3), 245-257.

Griffin, Z. M. (2003). A reversed word length effect in coordinating the preparation and articulation of words in speaking. *Psychon Bull Rev, 10*(3), 603-609.

Groves, R. (1973). Relationship of reaction time and movement time in a gross motor skill. *Percept Mot Skills, 36*(2), 453-454. doi:10.2466/pms.1973.36.2.453

Hayes, A. F. (2008). SPSS Macro for Multiple Mediation. Retrieved from http://www.comm.ohio-state.edu/ahayes/

Hayes, A. F. (2013). *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach*: The Guilford Press

Henry, F. M. (1960). Influence of motor and sensory sets on reaction and speed of discrete movements. *Research Quarterly, 31*, 459-468.

Ho, A. K., Iansek, R., Marigliani, C., Bradshaw, J. L., & Gates, S. (1999). Speech impairment in a large sample of patients with Parkinson's disease. *Behav Neurol, 11*(3), 131-137.

Houlihan, B. V., Jette, A., Friedman, R. H., Paasche-Orlow, M., Ni, P., Wierbicky, J., . . . Williams, S. (2013). A pilot study of a telehealth intervention for persons with spinal cord dysfunction. *Spinal Cord*. doi:10.1038/sc.2013.45

Howell, P., Au-Yeung, J., & Sackin, S. (2000). Internal Structure of Content Words Leading to Lifespan Differences in Phonological Difficulty in Stuttering. *Journal of fluency disorders, 25*(1), 1-20.

Jacks, A., Marquardt, T. P., & Davis, B. L. (2006). Consonant and syllable structure patterns in childhood apraxia of speech: developmental change in three children. *Journal of Communication Disorders, 39*(6), 424-441. doi:10.1016/j.jcomdis.2005.12.005

Jordan, T. C., & Rabbitt, P. M. (1977). Response times to stimuli of increasing complexity as a function of ageing. *British Journal of Psychology, 68*(2), 189-201. doi:https://www.ncbi.nlm.nih.gov/pubmed/871577

Kent, R. D., Kent, J. F., & Rosenbek, J. C. (1987). Maximum performance tests of speech production. *J Speech Hear Disord, 52*(4), 367-387.

Klapp, S. T., Patrick Wyatt, E., & Mac Lingo, W. (1974). Response programming in simple and choice reactions. *J Mot Behav, 6*(4), 263-271. doi:10.1080/00222895.1974.10735002

Krakow, R. A. (1999). Physiological organization of syllables: a review. *Journal of Phonetics, 27*(1), 23-54. doi:https://doi.org/10.1006/jpho.1999.0089

Laganaro, M., & Alario, F. X. (2006). On the locus of the syllable frequency effect in speech production. *Journal of Memory and Language, 55*, 178-196.

LaGrone, S., & Spieler, D. H. (2006). Lexical competition and phonological encoding in young and older speakers. *Psychol Aging, 21*(4), 804-809. doi:10.1037/0882-7974.21.4.804

Levelt, W. J., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behav Brain Sci, 22*(1), 1-38; discussion 38-75.

Lewis, B. A., Freebairn, L. A., Hansen, A. J., Iyengar, S. K., & Taylor, H. G. (2004). School-Age Follow-Up of Children With Childhood Apraxia of Speech. *Language, Speech, and Hearing Services in Schools, 35*.

Lima, S. D., Hale, S., & Myerson, J. (1991). How general is general slowing? Evidence from the lexical domain. *Psychol Aging, 6*(3), 416-425.

Liss, J. M., White, L., Mattys, S. L., Lansford, K., Lotto, A. J., Spitzer, S. M., & Caviness, J. N. (2009). Quantifying speech rhythm abnormalities in the dysarthrias. *Journal of Speech, Language, and Hearing Research, 52*(5), 1334-1352. doi:10.1044/1092-4388(2009/08-0208)

MacKay, D. G., & James, L. E. (2004). Sequencing, speech production, and selective effects of aging on phonological and morphological speech errors. *Psychol Aging, 19*(1), 93-107. doi:10.1037/0882-7974.19.1.93

Macoir, J., Gauthier, C., Jean, C., & Potvin, O. (2016). BECLA, a new assessment battery for acquired deficits of language: Normative data from Quebec-French healthy younger and older adults. *J Neurol Sci, 361*, 220-228. doi:10.1016/j.jns.2016.01.004

Magill, R. A., & Powell, F. M. (1975). Is the reaction time-movement time relationship 'essentially zero'? *Percept Mot Skills, 41*(3), 720-722. doi:10.2466/pms.1975.41.3.720

McNeil, M., Liss, J., Tseng, C., & Kent, R. (1990). Effects of Speech Rate on the Absolute and Relative Timing of Apraxic and Conduction Aphasic Sentence Production. *Brain and language, 38*, 135-158.

Meilan, J. J., Martinez-Sanchez, F., Carro, J., Lopez, D. E., Millian-Morell, L., & Arana, J. M. (2014). Speech in Alzheimer's disease: can temporal and acoustic parameters discriminate dementia? *Dement Geriatr Cogn Disord, 37*(5-6), 327-334. doi:10.1159/000356726

Meinzer, M., Flaisch, T., Wilser, L., Eulitz, C., Rockstroh, B., Conway, T., . . . Crosson, B. (2009). Neural signatures of semantic and phonemic fluency in young and old adults. *J Cogn Neurosci, 21*(10), 2007-2018. doi:10.1162/jocn.2009.21219

Meinzer, M., Seeds, L., Flaisch, T., Harnish, S., Cohen, M. L., McGregor, K., . . . Crosson, B. (2012). Impact of changed positive and negative task-related brain activity on word-retrieval in aging. *Neurobiol Aging, 33*(4), 656-669. doi:10.1016/j.neurobiolaging.2010.06.020

Moers, C., Meyer, A., & Janse, E. (2017). Effects of Word Frequency and Transitional Probability on Word Reading Durations of Younger and Older Speakers. *Lang Speech*, *60*(2), 289-317. doi:10.1177/0023830916649215

Morris, R., & Brown, W. S. (1987). Age-related voice measures among adult women. *Journal of voice, 1*(1), 43.

Morris, R. J., & Brown, W. S., Jr. (1994). Age-related differences in speech variability among women. *J Commun Disord, 27*(1), 49-64.

Mortensen, l., Meyer, A. S., & Humphreys, G. W. (2006). Age-related effects on speech production: A review. *Language and Cognitive Processes, 21*(1-3), 238-290. doi:10.1080/01690960444000278

Moustafa, A. A., Chakravarthy, S., Phillips, J. R., Gupta, A., Keri, S., Polner, B., . . . Jahanshahi, M. (2016). Motor symptoms in Parkinson's disease: A unified framework. *Neurosci Biobehav Rev, 68*, 727-740. doi:10.1016/j.neubiorev.2016.07.010

Nasreddine, Z. S., Chertkow, H., Phillips, N., Bergman, H., & Whitehead, V. (2003). Sensitivity and Specificity of The Montreal Cognitive Assessment (MoCA) for Detection of Mild Cognitive Deficits. *Can J Neurol Sci 30*(30).

Nebes, R. D. (1978). Vocal versus manual response as a determinant of age difference in simple reaction time. *J Gerontol, 33*(6), 884-889. doi:https://doi.org/10.1093/geronj/33.6.884

Newman, R. S., & German, D. J. (2005). Life span effects of lexical factors on oral naming. *Languahe and Speech, 48*(Pt 2), 123-156. doi:10.1177/00238309050480020101

Niermeyer, M. A., Suchy, Y., & Ziemnik, R. E. (2016). Motor sequencing in older adulthood: relationships with executive functioning and effects of complexity. *Clin Neuropsychol*, 1-21. doi:10.1080/13854046.2016.1257071

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychol Aging, 17*(2), 299-320.

Perone, M., & Baron, A. (1982). Age-related effects of pacing on acquisition and performance of response sequences: an operant analysis. *J Gerontol, 37*(4), 443-449. doi:https://doi.org/10.1093/geronj/37.4.443

Pierson, W. R., & Montoye, H. J. (1958). Movement time, reaction time, and age. *J Gerontol, 13*(4), 418-421.

Quinn, J. T., Jr., Schmidt, R. A., & Zelaznik, H. N. (1980). Target-size influences on reaction time with movement time controlled. *J Mot Behav*, *12*(4), 239-261.

Rabbitt, P., & Birren, J. E. (1967). Age and responses to sequences of repetitive and interruptive signals. *J Gerontol, 22*(2), 143-150.

Rastle, K. G., & Burke, D. M. (1996). Priming the tip of the tongue: Effects of prior processing on word retrieval in young and older adults. *Journal of Memory and Language, 35*(4), 586-605.

Redford, M. A., & Diehl, R. L. (1999). The relative perceptual distinctiveness of initial and final consonants in CVC syllables. *J Acoust Soc Am, 106*(3 Pt 1), 1555-1565. doi:http://dx.doi.org/10.1121/1.427152

Riecker, A., Brendel, B., Ziegler, W., Erb, M., & Ackermann, H. (2008). The influence of syllable onset complexity and syllable frequency on speech motor control. *Brain Lang, 107*(2), 102-113. doi:S0093-934X(08)00012-6 [pii]
10.1016/j.bandl.2008.01.008

Sadagopan, N., & Smith, A. (2013). Age differences in speech motor performance on a novel speech task. *J Speech Lang Hear Res, 56*(5), 1552-1566. doi:10.1044/1092-4388(2013/12-0293)

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychol Rev, 103*(3), 403-428.

Salthouse, T. A. (2009). Decomposing age correlations on neuropsychological and cognitive variables. *J Int Neuropsychol Soc, 15*(5), 650-661. doi:10.1017/S1355617709990385

Santiago, J., MacKay, D. G., Palma, A., & Rho, C. (2000). Sequential activation processes in producing words and syllables: Evidence from picture naming. *Language and Cognitive Processes, 15*(1). doi:10.1080/016909600386101

Searl, J. P., Gabel, R. M., & Fulks, J. S. (2002). Speech disfluency in centenarians. *J Commun Disord, 35*(5), 383-392.

Seddoh, S. A., Robin, D. A., Sim, H. S., Hageman, C., Moon, J. B., & Folkins, J. W. (1996). Speech timing in apraxia of speech versus conduction aphasia. *J Speech Hear Res, 39*(3), 590-603.

Shuster, L. I., Moore, D. R., Chen, G., Ruscello, D. M., & Wonderlin, W. F. (2014). Does experience in talking facilitate speech repetition? *Neuroimage, 87*, 80-88. doi:10.1016/j.neuroimage.2013.10.064

Skodda, S., Gronheit, W., Mancinelli, N., & Schlegel, U. (2013). Progression of voice and speech impairment in the course of Parkinson's disease: a longitudinal study. *Parkinsons Dis, 2013*, 389195. doi:10.1155/2013/389195

Skodda, S., Rinsche, H., & Schlegel, U. (2009). Progression of dysprosody in Parkinson's disease over time--a longitudinal study. *Mov Disord, 24*(5), 716-722. doi:10.1002/mds.22430

Smith, B. L., Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *J Speech Hear Res, 30*(4), 522-529.

Spirduso, W. W. (1975). Reaction and movement time as a function of age and physical activity level. *J Gerontol, 30*(4), 435-440.

Stelmach, G. E., Goggin, N. L., & Amrhein, P. C. (1988). Aging and the restructuring of precued movements. *Psychology and Aging, 3*(2), 151-157. doi:https://doi.org/10.1518/001872005467942

Towne, R. L., & Crary, M. A. (1988). Verbal reaction time patterns in aphasic adults: consideration for apraxia of speech. *Brain Lang, 35*(1), 138-153.

Tremblay, P., & Deschamps, I. (2016). Structural brain aging and speech production: a surface-based brain morphometry study. *Brain Struct Funct, 221*(6), 3275-3299. doi:10.1007/s00429-015-1100-1

Tremblay, P., Sato, M., & Deschamps, I. (2017). Age differences in the motor control of speech: An fMRI study of healthy aging. *Hum Brain Mapp, 38*(5), 2751-2771. doi:10.1002/hbm.23558

Tremblay, P., & Small, S. L. (2011). On the context-dependent nature of the contribution of the ventral premotor cortex to speech perception. *Neuroimage, 57*(4), 1561-1571. doi:10.1016/j.neuroimage.2011.05.067

Vitevitch, M. S., Luce, P. A., Charles-Luce, J., & Kemmerer, D. (1997). Phonotactics and syllable stress: implications for the processing of spoken nonsense words. *Lang Speech, 40 (Pt 1)*, 47-62.

Wishart, L. R., Lee, T. D., Murdoch, J. E., & Hodges, N. J. (2000). Effects of aging on automatic and effortful processes in bimanual coordination. *J Gerontol B Psychol Sci Soc Sci, 55*(2), P85-94.

Wohlert, A. B., & Smith, A. (1998). Spatiotemporal stability of lip movements in older adult speakers. *J Speech Lang Hear Res, 41*(1), 41-50.

Yesavage, J. A., Brink, T. L., Rose, T. L., Lum, O., Huang, V., Adey, M., & Leirer, V. O. (1982). Development and validation of a geriatric depression screening scale: a preliminary report. *Journal of psychiatric research, 17*(1), 37-49.

Ziegler, W. (2002). Task-related factors in oral motor control: speech and oral diadochokinesis in dysarthria and apraxia of speech. *Brain Lang*, *80*(3), 556-575. doi:10.1006/brln.2001.2614

Table 1. Descriptive Statistics (Means, Standard Deviations, and Correlations) for participants characteristics

	M	SD	Range	Age	Education (in years)	MOCA	Other languages	GDS	Perceived health	R PTA	L PTA
Age	48.9	18.2	18 – 83	1	-0.151	**-0.434**	-0.071	-0.068	0.155	**-0.568**	**-0.644**
Education (in years)	16.11	2.57	11 – 22	-0.151	1	**0.347**	**0.262**	0.021	-0.036	0.004	0.119
MOCA (/ 30) [a]	27.92	1.76	23 – 30	**-0.434**	**0.347**	1	0.074	-0.052	0.062	**0.335**	**0.375**
Other languages	1.62	1.18	0-6	-0.071	**0.262**	0.074	1	0.141	-0.026	0.152	0.173
GDS (/30) [b]	2.46	2.51	0 – 9	-0.068	0.021	-0.052	0.141	1	-0.178	0.033	0.078
Perceived health (/7)	5.2	0.78	3.5 - 7	0.155	-0.036	0.062	-0.026	-0.178	1	-0.014	-0.014
R PTA [c]	10.24	9	0 – 37	**-0.568**	0.004	**0.335**	0.152	0.033	-0.014	1	**0.908**
L PTA [c]	9.1	10.11	-2 – 44	**-0.644**	0.119	**0.375**	0.173	0.078	-0.014	**0.908**	1

Note. M = Mean. SD = standard deviation of the mean. Significant correlations ($p \leq .05$) are bolded.

[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 one 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 point. Participants with scores between 0 and 9 are considered normal, while scores between 10 and 19 indicate a depression, and scores between 20-30 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.

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	0.28 (0.15)	[.24, .32]
Simple and rare syllables	0.45 (0.16)	[.41, .49]
Complex and frequent syllables	0.33 (0.15)	[.29, .37]
Complex and rare syllables	0.35 (0.17)	[.30, .39]
B. Vocal reaction time (in sec) from onset of visual stimuli		
Simple and frequent syllables	0.47 (0.13)	[.44, .50]
Simple and rare syllables	0.5 (0.15)	[.47, .54]
Complex and frequent syllables	0.45 (0.13)	[.42, .49]
Complex and rare syllables	0.47 (0.13)	[.44, .51]
C. Vocal reaction time variability in SD (in sec)		
Simple and frequent syllables	0.15 (0.05)	[.13, .16]
Simple and rare syllables	0.16 (0.06)	[.14, .17]
Complex and frequent syllables	0.11 (0.04)	[.09, .12]
Complex and rare syllables	0.13 (0.05)	[.12, .14]
D. Vocal response duration (in sec)		
Simple and frequent syllables	0.94 (0.14)	[.90, .98]
Simple and rare syllables	1.06 (0.16)	[1.02, 1.1]
Complex and frequent syllables	1.28 (0.22)	[1.23, 1.34]
Complex and rare syllables	1.27 (0.17)	[1.22, 1.31]
E. Vocal response duration variability (in SD)		
Simple and frequent syllables	0.15 (0.049)	[.14, .16]
Simple and rare syllables	0.2 (0.09)	[.14, .16]
Complex and frequent syllables	0.2 (0.08)	[.18, .23]
Complex and rare syllables	0.15 (0.18)	[.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	0.25
Age X Phonological complexity	1, 165	2.44	0.12
Spoken syllable frequency	1,165	51.91	< .001
Age X Spoken syllable frequency	1, 165	1.47	0.23
Phonological complexity X Spoken syllable frequency	1, 165	31.76	< .001
Age X Phonological Complexity X Spoken syllable frequency	1, 165	0.38	0.54
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 X Phoneme position	1, 154	37.6	< .001
Age X Syllable position	1, 82	.12	0.736
Age X phoneme position	1, 101	18.37	< .001
Age X Syllable X Phoneme position	1, 219	.95	0.33
C. Vocal reaction time (in sec) from onset of visual stimuli			
Intercept	1, 56	503.36	< .001
Age	1, 56	0.23	0.64
Phonological complexity	1, 141	17.99	< .001
Age X Phonological complexity	1, 141	0.1	0.75
Spoken syllable frequency	1, 141	23.47	< .001
Age X Spoken syllable frequency	1, 141	2.49	0.12
Phonological complexity X Spoken syllable frequency	1, 141	1.74	0.19
Age X Phonological complexity X Spoken syllable frequency	1, 141	0.72	0.39
D. Vocal reaction time variability in SD (in sec)			
Intercept	1, 58	739.47	< .001
Age	1, 58	0.027	0.87
Phonological complexity	1, 151	37.38	< .001
Age X Phonological complexity	1, 151	0.72	0.39
Spoken syllable frequency	1, 151	6.54	.012

Age X Spoken syllable frequency	1, 153	0.18	0.66
Phonological complexity X Spoken syllable frequency	1, 151	1.95	0.16
Age X Phonological complexity X Spoken syllable frequency	1, 151	0.71	0.4
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 X Phonological complexity	1, 155	12.29	.001
Spoken syllable frequency	1, 155	60.26	< .001
Age X Spoken syllable frequency	1, 155	0.06	0.8
Phonological complexity x Spoken syllable frequency	1, 155	53.19	< .001
Age X Phonological complexity X Spoken syllable frequency	1, 155	5.39	0.021
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	0.21
Age X Phonological complexity	1, 142	0.89	0.35
Spoken syllable frequency	1, 142	0.19	0.66
Age X Spoken syllable frequency	1, 142	0.14	0.71
Phonological complexity X Spoken syllable frequency	1, 142	38.57	< .001
Age X Phonological complexity X Spoken syllable frequency	1, 142	8.26	.005

Figures

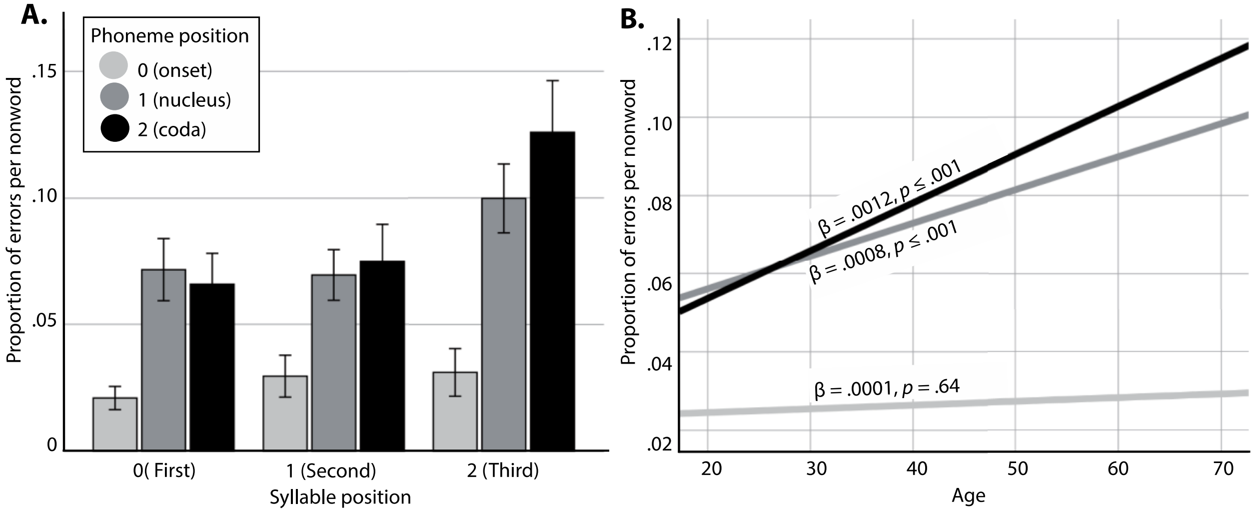

Figure 1. Error as a function of position. A. Decomposition of the interaction between syllable and phoneme position on Error rate. Error rate (proportion of errors per nonword) is displayed separately for each of the nine experimental conditions. Error bars represent the 95% confidence interval of the 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 βeta coefficient is reported (β).

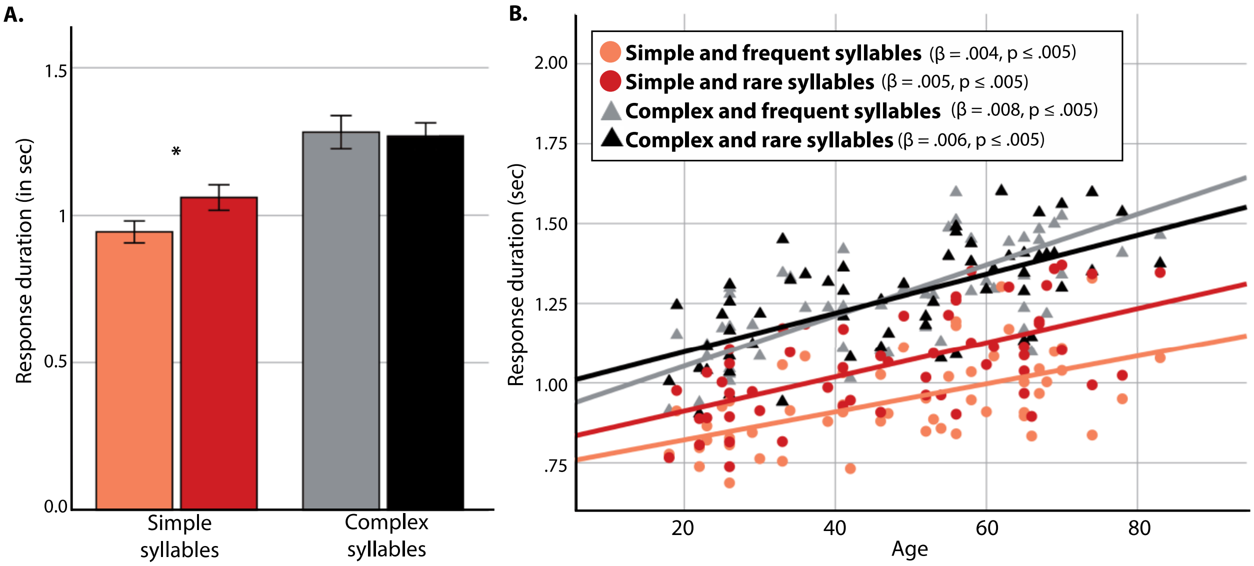

Figure 2. Response duration (RD). A. The bar charts represent RD ins seconds as a function of Syllable Frequency separately for the simple and complex syllables. The error bars represent the standard error of the mean. The asterisks indicate statistical significance ($p < .05$). B. The scatterplot represents RD (x) as a function of Age (y). 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.

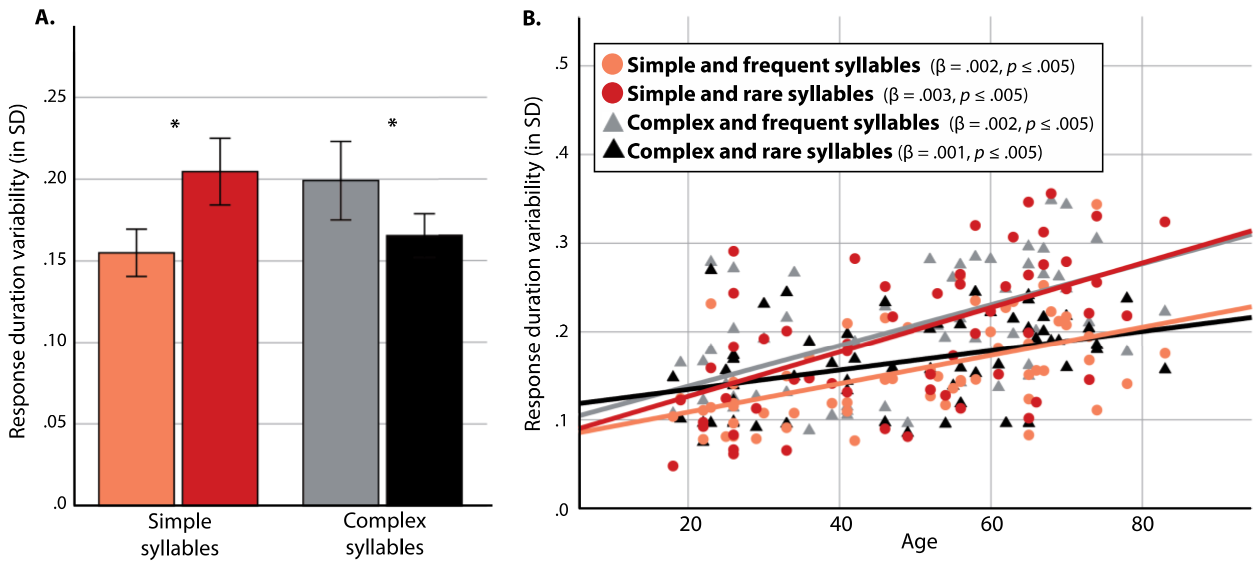

Figure 3. Response duration variability. A. The bar charts represent RD variability as a function of Syllable Frequency separately for the simple and complex syllables. The error bars represent the standard error of the mean. The asterisks indicate statistical significance (p < .05). B. The scatterplot represents RD variability (x) as a function of Age (y). 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.

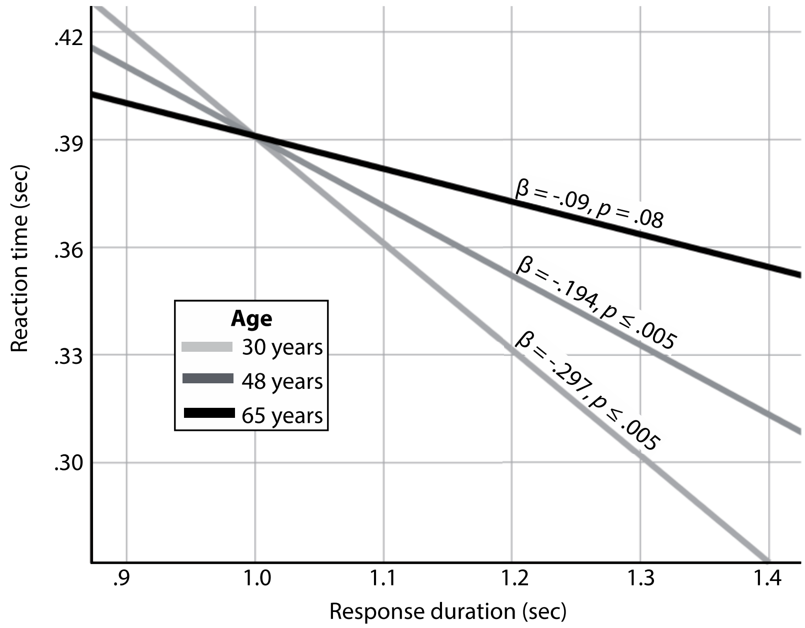

Figure 4. Analysis of the RT/RD relationship as a function of age. Relationship between RT in sec (y-axis) and RD (x-axis) as a function of Age (moderation analysis). Different levels of the factor Age are shown as pale gray (young), dark gray (middle-aged) and black (older participants). For each analysis,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

Supplementary Materials

Supplementary Tables

Table 1

Mean Syllable Frequency in each experimental condition.

Condition	Mean	SE	SD
Simple frequent syllables	98.64	.11	.56
Simple rare syllables	89	1.23	6.19
Complex frequent syllables	96.16	.66	3.31
Complex rare syllables	88.2	1.25	6.23

Note. M = mean. SE = Standard error of the mean. SD = Standard deviation of the mean.

Table 2

List of all stimuli

Visually presented stimuli	**Expected response(IPA)**	**Syllabic structure**	**Complexity**	**Frequency**	**Frequency S1**	**Frequency S2**	**Frequency S3**	**Average Frequency (centile)**
da man fô	da mã fo	CV CV CV	Simple	Frequent	98	100	97	98
di fé li	di fe li	CV CV CV	Simple	Frequent	100	96	99	98
dre târ kri	drə tɑr kri	CCV CVC CCV	Simple	Frequent	99	99	98	99
ke sa pou	kə sa pu	CV CV CV	Simple	Frequent	100	100	97	99
kon ti vé	kɔ̃ ti ve	CV CV CV	Simple	Frequent	99	99	98	99
lâ mè fi	lɑ mɛ fi	CV CV CV	Simple	Frequent	100	100	98	99
mon ré kô	mɔ̃ re ko	CV CV CV	Simple	Frequent	99	99	96	98
pé ra bin	pe ra bɛ̃	CV CV CV	Simple	Frequent	98	98	99	98
san ka zé	sã ka ze	CV CV CV	Simple	Frequent	99	99	98	99
sâ pi chu	sɑ pi ʃy	CV CV CV	Simple	Frequent	100	100	96	98

Visually presented stimuli	Expected response(IPA)	Syllabic structure	Complexity	Frequency	Frequency S1	Frequency S2	Frequency S3	Average Frequency (centile)
té la kou	te la ku	CV CV CV	Simple	Frequent	100	100	99	99
vè tou peu	vɛ tu pø	CV CV CV	Simple	Frequent	99	99	99	99
vi da su	vi da sy	CV CV CV	Simple	Frequent	99	98	97	98
za mi vu	za mi vy	CV CV CV	Simple	Frequent	99	99	95	98
jé né tan	ʒe ne tã	CV CV CV	Simple	Frequent	100	100	99	99
ba dou lou	ba du lu	CV CV CV	Simple	Rare	94	91	84	89
du ké ja	dy ke ʒa	CV CV CV	Simple	Rare	94	92	0	62
fu tun gô	fy tœ̃ go	CV CV CV	Simple	Rare	91	94	89	91
gâ chô ze	gɑ ʃo zə	CV CV CV	Simple	Rare	94	90	75	86
gon fu tun	gɔ̃ fy tœ̃	CV CV CV	Simple	Rare	89	91	94	91
kin rou jô	kɛ̃ ru ʒo	CV CV CV	Simple	Rare	87	89	80	86
kun don jou	kœ̃ dɔ̃ ʒu	CV CV CV	Simple	Rare	95	95	92	94
leu ba be	lø ba bə	CV CV CV	Simple	Rare	85	94	95	91
leu ro chè	lø rɔ ʃɛ	CV CV CV	Simple	Rare	85	92	87	88
gné dun kè	ɲe dœ̃ kɛ	CV CV CV	Simple	Rare	92	94	91	93
ro kin rou	rɔ kɛ̃ ru	CV CV CV	Simple	Rare	92	87	89	89
zô kun don	zo kœ̃ dɔ̃	CV CV CV	Simple	Rare	92	95	95	94
zo ron be	zɔ rɔ̃ bə	CV CV CV	Simple	Rare	93	90	95	93
jâ gou teu	ʒɑ gu tø	CV CV CV	Simple	Rare	94	93	76	88
ju mô zô	ʒy mo zo	CV CV CV	Simple	Rare	91	95	92	93
kor vrè pass	kɔr vrɛ pas	CVC CCV CVC	Complex	Frequent	96	98	96	97
lor stè pré	lɔr stɛ pre	CVC CCV CCV	Complex	Frequent	98	97	97	97
mèn pro pri	mɛn prɔ pri	CVC CCV CCV	Complex	Frequent	96	98	96	97

Visually presented stimuli	Expected response(IPA)	Syllabic structure	Complexity	Frequency	Frequency S1	Frequency S2	Frequency S3	Average Frequency (centile)
mil pèr for	mil pɛr fɔr	CVC CVC CVC	Complex	Frequent	95	98	96	96
nir kom rès	nir kɔm rɛs	CVC CVC CVC	Complex	Frequent	94	99	96	97
par kont vrè	par kɔ̃t vrɛ	CVC CVC CCV	Complex	Frequent	99	95	98	97
sur plu tra	syr ply tra	CVC CCV CCV	Complex	Frequent	99	99	98	98
sur pri sèt	syr pri sɛt	CVC CCV CVC	Complex	Frequent	99	96	97	98
tèl par sur	tɛl par syr	CVC CVC CVC	Complex	Frequent	96	99	99	98
teur pour juss	tœr pur ʒys	CVC CVC CVC	Complex	Frequent	97	99	97	98
tra vèr plu	tra vɛr ply	CCV CVC CCV	Complex	Frequent	98	98	99	98
tre pran tèl	trə prã tɛl	CCV CCV CVC	Complex	Frequent	97	95	96	96
tour dis par	tur dis par	CVC CVC CVC	Complex	Frequent	85	72	99	85
vèr tur lor	vɛr tyr lɔr	CVC CVC CVC	Complex	Frequent	98	96	98	97
zôt fèk tout	zot fɛk tut	CVC CVC CVC	Complex	Frequent	96	98	98	97
dun cha gun	dœ̃ ʃa gœ̃	CV CV CV	Complex	Rare	92	89	93	91
kout chèr kant	kut ʃɛr kãt	CVC CVC CVC	Complex	Rare	92	94	93	93
lak sèp tib	lak sɛp tib	CVC CVC CVC	Complex	Rare	91	92	57	80
lar chèt dal	lar ʃɛt dal	CVC CVC CVC	Complex	Rare	91	85	80	86
lèk tif meur	lɛk tif mœr	CVC CVC CVC	Complex	Rare	93	92	86	90
lèk tiv sta	lɛk tiv sta	CVC CVC CCV	Complex	Rare	93	93	93	93
mor tir dôt	mɔr tir dot	CVC CVC CVC	Complex	Rare	90	94	93	92
nès tri veur	nɛs tri vœr	CVC CCV CVC	Complex	Rare	91	93	74	86
nèt bèr sant	nɛt bɛr sãt	CVC CVC CVC	Complex	Rare	93	89	95	92
ral bom lès	ral bɔm lɛs	CVC CVC CVC	Complex	Rare	93	80	90	88

Visually presented stimuli	**Expected response(IPA)**	**Syllabic structure**	**Complexity**	**Frequency**	**Frequency S1**	**Frequency S2**	**Frequency S3**	**Average Frequency (centile)**
sté kol fran	ste kɔl frã	CCV CVC CCV	Complex	Rare	85	95	94	91
sul mar kab	syl mar kab	CVC CVC CVC	Complex	Rare	91	93	31	72
tal jik mint	tal ʒik mɛ̃t	CVC CVC CVC	Complex	Rare	93	90	93	92
tar kla vil	tar kla vil	CVC CCV CVC	Complex	Rare	83	89	92	88
tunn bonn sèk	tyn bɔn sɛk	CVC CVC CVC	Complex	Rare	92	93	90	92

Table 3

Linear Mixed Model results (Parameter Estimate)

Fixed effects	Estimate	SE	df	t	p
A. Error rate measured as the proportion of nonwords with errors)					
Intercept	0.352	0.019	80.87	17.7	0
Age	0.004	0.001	80.87	3.66	0
Phonological complexity (0)	0.089	0.019	78.97	4.67	0
Phonological complexity (1)	0a	0	.	.	.
Spoken syllable frequency (0)	-0.02	0.017	49.1	-1.21	0.23
Spoken syllable frequency (1)	0a	0	.	.	.
Phonological complexity (0) X Spoken syllable frequency (0)	-0.148	0.02	164.642	-5.636	0
Phonological complexity (0) X Spoken syllable frequency (1)	0a	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (0)	0a	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (1)	0a	0	.	.	.
Age X Phonological complexity (0)	-0.001	0.001	78.71	-1.509	0.135
Age X Phonological complexity (1)	0a	0	.	.	.
Age X Spoken syllable frequency (0)	-0.001	0.0009	49.1	-1.4	0.168

Age X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (0) X Spoken syllable frequency (0)	0.0008	0.001	165.45	0.615	0.539
Age X Phonological complexity (0) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (0)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (1)	0[a]	0	.	.	.

B. Error rate as a function of position

Intercept	0.025	0.004	76.56	6.88	*< .001
Age	0.0001	0.0002	49.75	.641	.52
Syllable position	.0044	0.0019	82.21	2.35	*< .021
Phoneme position	.022	0.0021	101.27	10.81	*< .001
Syllable position X Phoneme position	0.012	0.0021	219.79	6.13	*< .001
Age X phoneme position	0.00049	0.0001	100.8	4.28	*< .001
Age X Syllable position	-0.00003	0.0001	82.06	-.339	0.736
Age X Syllable X Phoneme position	0.0001	0.0001	219.28	.976	0.33

C. Vocal reaction time (in sec) from onset of visual stimuli

Intercept	0.372	0.017	59.888	21.939	0
Age	-0.001	0.001	59.888	-0.647	0.52
Phonological complexity (0)	0.032	0.009	66.47	3.61	0.001
Phonological complexity (1)	0[a]	0	.	.	.
Spoken syllable frequency (0)	-0.020	0.006	53.498	-3.15	0.003

Spoken syllable frequency (1)	0 [a]	0	.	.	.
Phonological complexity (0) X Spoken syllable frequency (0)	-0.015	0.011	141.901	-1.32	0.189
Phonological complexity (0) X Spoken syllable frequency (1)	0 [a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (0)	0 [a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (1)	0 [a]	0	.	.	.
Age X Phonological complexity (0)	0.000	0.000	66.47	-0.343	0.733
Age X Phonological complexity (1)	0 [a]	0	.	.	.
Age X Spoken syllable frequency (0)	0.000	0.000	53.498	0.657	0.514
Age X Spoken syllable frequency (1)	0 [a]	0	.	.	.
Age X Phonological complexity (0) X Spoken syllable frequency (0)	0.001	0.001	141.901	0.845	0.399
Age X Phonological complexity (0) X Spoken syllable frequency (1)	0 [a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (0)	0 [a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (1)	0 [a]	0	.	.	.
D. Vocal reaction time variability in SD (in sec)					
Intercept	0.132	0.007	70.943	19.544	0
Age	0.000	0.000	70.813	0.609	0.544
Phonological complexity (0)	0.024	0.007	78.001	3.304	0.001
Phonological complexity (1)	0 [a]	0	.	.	.
Spoken syllable frequency (0)	-0.020	0.006	66.926	-3.205	0.002
Spoken syllable frequency (1)	0 [a]	0	.	.	.
Phonological complexity (0) X Spoken syllable frequency (0)	0.014	0.010	150.891	1.397	0.165
Phonological complexity (0) X Spoken syllable frequency (1)	0 [a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (0)	0 [a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (1)	0 [a]	0	.	.	.
Age X Phonological complexity (0)	0.000	0.000	78.143	-1.188	0.239
Age X Phonological complexity (1)	0 [a]	0	.	.	.

Age X Spoken syllable frequency (0)	0.000	0.000	67.716	-0.335	0.738
Age X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (0) X Spoken syllable frequency (0)	0.000	0.001	150.798	0.844	0.4
Age X Phonological complexity (0) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (0)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (1)	0[a]	0	.	.	.

E. Vocal response duration (in sec)

Intercept	1.286	0.019	65.645	67.366	0
Age	0.007	0.001	66.631	6.632	0
Phonological complexity (0)	-0.202	0.012	72.181	-17.482	0
Phonological complexity (1)	0[a]	0	.	.	.
Spoken syllable frequency (0)	-0.004	0.012	38.021	-0.324	0.748
Spoken syllable frequency (1)	0[a]	0	.	.	.
Phonological complexity (0) X Spoken syllable frequency (0)	-0.119	0.016	154.529	-7.293	0
Phonological complexity (0) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (0)	0[a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (0)	-0.001	0.001	72.005	-0.836	0.406
Age X Phonological complexity (1)	0[a]	0	.	.	.
Age X Spoken syllable frequency (0)	0.001	0.001	38.228	1.428	0.161
Age X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (0) X Spoken syllable frequency (0)	-0.002	0.001	155.128	-2.324	0.021
Age X Phonological complexity (0) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (0)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (1)	0[a]	0	.	.	.

F. Vocal response duration variability (in SD)					
Intercept	0.166	0.007	55.786	25.404	0
Age	0.001	0.000	55.93	3.101	0.003
Phonological complexity (0)	0.033	0.010	69.663	3.352	0.001
Phonological complexity (1)	0[a]	0	.	.	.
Spoken syllable frequency (0)	0.038	0.009	72.971	4.313	0
Spoken syllable frequency (1)	0[a]	0	.	.	.
Phonological complexity (0) X Spoken syllable frequency (0)	-0.082	0.013	141.742	-6.211	0
Phonological complexity (0) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (0)	0[a]	0	.	.	.
Phonological complexity (1) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (0)	0.001	0.001	70.021	2.587	0.012
Age X Phonological complexity (1)	0[a]	0	.	.	.
Age X Spoken syllable frequency (0)	0.001	0.000	73.328	2.426	0.018
Age X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (0) X Spoken syllable frequency (0)	-0.002	0.001	142.157	-2.874	0.005
Age X Phonological complexity (0) X Spoken syllable frequency (1)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (0)	0[a]	0	.	.	.
Age X Phonological complexity (1) X Spoken syllable frequency (1)	0a	0	.	.	.

Random effects	Estimate	SE	Wald Z	p
A. Error rate (measured as the proportion of nonwords with errors)				
Random intercept (participants)	0.014	0.003	4.47	< .001
B. Error rate as a function of position				
Random intercept (participants)	0.0006	0.0001	4.24	< .001
C. Vocal reaction time (in sec) from onset of visual stimuli				

Random intercept (participants)	0.016	0.003	5.158	< .001
D. Vocal reaction time variability in SD (in sec)				
Random intercept (participants)	0.001	0.000	3.938	< .001
E. Vocal response duration (in sec)				
Random intercept (participants)	0.017	0.004	4.73	< .001
F. Vocal response duration variability (in SD)				
Random intercept (participants)	0.001	0.000	3.335	0.001

a. This parameter is set to zero because it is redundant.

Table 4

Pairwise Comparisons. Error rate for each phoneme position within each syllable position

Syllable position	Phoneme position	Phoneme position	Mean Difference	Std. Error	df	p	95% CI
First Syllable	Onset	Nucleus	-.049	0.006	452.888	0.000	[-0.064, -0.034]
	Onset	Coda	-.043	0.006	452.888	0.000	[-0.058, -0.029]
	Nucleus	Coda	0.006	0.006	452.762	1.000	[-0.009, 0.020]
Second Syllable	Onset	Nucleus	-.041	0.006	453.809	0.000	[-0.056, -0.027]
	Onset	Coda	-.047	0.006	453.809	0.000	[-0.061, -0.032]
	Nucleus	Coda	-0.005	0.006	452.762	1.000	[-0.020, 0.009]
Third Syllable	Onset	Nucleus	-.070	0.006	453.809	0.000	[-0.085, -0.055]
	Onset	Coda	-.096	0.006	453.809	0.000	[-0.111, -0.081]
	Nucleus	Coda	-.026	0.006	452.762	0.000	[-0.041, -0.011]

Note. CI = confidence interval

Table 5

Pairwise Comparisons. Error rate for each syllable position within each phoneme position

Phoneme position	Syllable position	Syllable position	Mean Difference	Std. Error	df	p	95% CI
Onset	First syllable	Second syllable	-0.006	0.006	453.925	1.000	[-0.020, 0.009]
	First syllable	Third syllable	-0.007	0.006	453.925	0.733	[-0.022, 0.008]
	Second syllable	Third syllable	-0.002	0.006	452.762	1.000	[-0.016, 0.013]
Nucleus	First syllable	Second syllable	0.002	0.006	452.762	1.000	[-0.013, 0.017]
	First syllable	Third syllable	-.028	0.006	452.762	0.000	[-0.043, -0.013]
	Second syllable	Third syllable	-.030	0.006	452.762	0.000	[-0.045, -0.015]
Coda	First syllable	Second syllable	-0.009	0.006	452.762	0.438	[-0.024, 0.006]
	First syllable	Third syllable	-.060	0.006	452.762	0.000	[-0.075, -0.045]
	Second syllable	Third syllable	-.051	0.006	452.762	0.000	[-0.066, -0.036]

Note. CI = confidence interval

Supplementary Figures

Figure 1

Overall relationship between Error rate (y) and age (x). The variance accounted for (r^2) and parameter estimates (unstandardized B), and are provided to quantify the strength of this linear relationship.

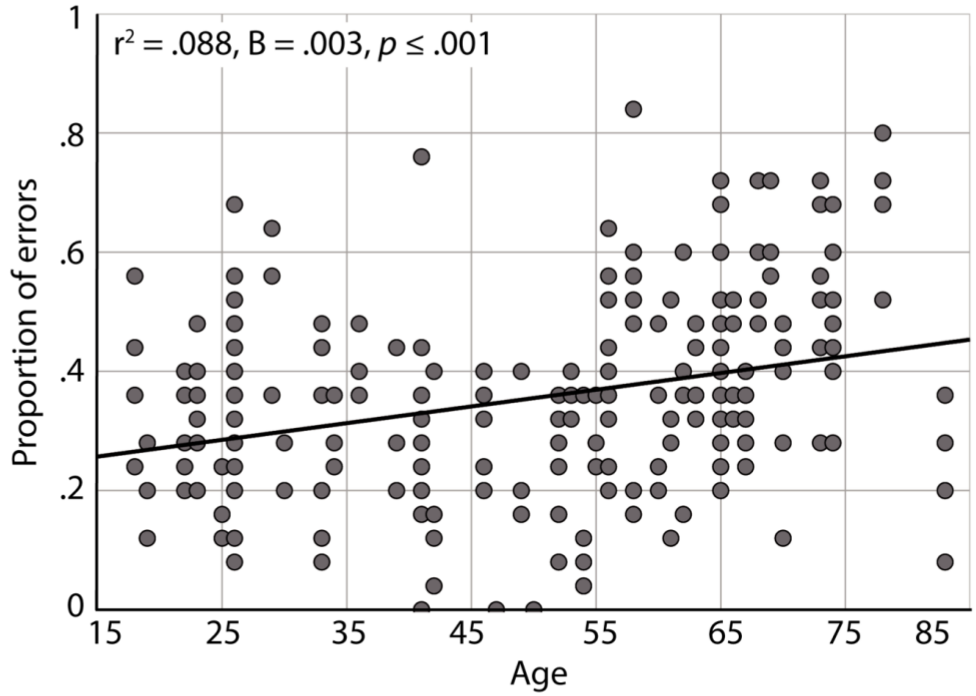

Figure 2

Moderation analyses were conducted to determine if Error rate influenced the relationship between speech timing measures (RT, RD and RD variability) (x) and Age (y). A. RT as a function of Age displayed at three different levels of the moderator (Error rate). B. A. RD as a function of Age at three different levels of the moderator (Error rate). C. RD variability as a function of Age at three different levels of the moderator (Error rate). Unstandardized B and inferential statistics are provided for the effect of Error rate on each timing measure (Error) and for the interaction (moderation) effect of Age and Error on each timing measure. As can be seen in the figure, the analyses show that there was no evidence of an impact of Error rate on the relationship between any of the speech timing measures and Age.