Experimental Gerontology 126 (2019) 110695

Contents lists available at ScienceDirect

Experimental Gerontology

journal homepage: www.elsevier.com/locate/expgero

Age-related deficits in speech production: From phonological planning to motor implementation

Pascale Tremblay[a,b,*], Julie Poulin[a,b], Vincent Martel-Sauvageau[a,c], Catherine Denis[a,b]

[a] *Université Laval, Département de Réadaptation, Québec, Canada*
[b] *Centre de recherche CERVO, Québec, Canada*
[c] *Centre de recherche CIRRIS, Québec, Canada*

ARTICLE INFO

Section Editor: Willard Freeman

Keywords:
Speaking
Cognition
Hearing
Depression
Phonological planning

ABSTRACT

Speaking is one of the most complex motor actions that humans can perform, requiring the coordination between linguistic, cognitive, affective and sensorimotor systems. Perhaps counter-intuitively, it is also one of the easiest acts that humans perform, on a daily basis, from a very early age till the end of life, without even thinking about it. With age, however, spoken language production undergoes significant changes, with potential impacts on interpersonal communication and social participation. Unfortunately, the neurobiological mechanisms involved are unclear, which impedes efforts towards the development of clinical interventions, differential diagnosis strategies and even prevention strategies for this population. In the present study, we examined age differences in speech production using a simple diadochokinetic rates task in which phonological and sequential complexity were manipulated. 85 cognitively healthy adults (20–93 years) were recruited from the general population. Cognitive level, hearing and depression symptoms were measured. Participants produced short and long sequences of simple and complex syllables aloud as quickly, steadily and accurately as possible. Performance was assessed in terms of articulation rate, articulation rate stability and accuracy. Results show that, controlling for cognition, hearing and depression, articulation rate stability and accuracy declined significantly with age. The phonological manipulation had more impact on performance than the sequential manipulation. These findings were interpreted as reflecting age-related central disruptions at the level of phonological and motor planning, which provides important new cues into underlying neurobiological mechanisms.

1. Introduction

Aging is associated with asymmetric changes to language competences, with language comprehension relatively spared and language production more strongly affected, as detailed in the Transmission Deficit model (Burke et al., 2000). According to this theory, age-related changes in oral language production originate from difficulties at the phonological level, leading to the word finding failures and tip of the tongue experiences that are hallmarks of aging (Diaz et al., 2014; Rastle and Burke, 1996). There is also evidence suggesting that speech -the motor component of spoken language production- is disrupted, consistent with the well-known age-related decline in the cortical sensorimotor system (e.g. Bajaj et al., 2017), but important questions remain regarding the specific mechanisms that underlie these changes. Given that language production is a critical component of interpersonal relationships, difficulties affecting this ability may have important psychosocial and clinical implications. Isolating the biological mechanisms that contribute to this decline is therefore key to developing strategies to optimize communication, facilitate differential diagnostics, and promote social participation in older adults.

There is compelling evidence that the temporal properties of speech, such as articulation rate, articulation rate stability, and movement time (the time from movement initiation to completion), are disrupted in normal aging, most likely reflecting central difficulties at the level of speech motor planning or execution. Specifically, aging has been associated with an increase in the duration and duration variability of speech utterances in a variety of tasks including syllable and sentence repetition (e.g. Morris and Brown, 1987; Smith et al., 1987), syllable and nonword reading (Tremblay and Deschamps, 2016; Tremblay et al., 2018; Tremblay et al., 2017), and nonword repetition (Sadagopan and Smith, 2013). Perhaps the most commonly used task to evaluate articulation rate is the oral diadochokinetic rates (DDK) task, which requires participants to produce simple syllables or sequences of simple syllables as many times as possible during a short interval of 3–5 s

* Corresponding author at: Département de Réadaptation, Université Laval, Québec, QC G1V 0A6, Canada.
E-mail address: pascale.tremblay@fmed.ulaval.ca (P. Tremblay).

https://doi.org/10.1016/j.exger.2019.110695
Received 13 March 2019; Received in revised form 15 August 2019; Accepted 17 August 2019
Available online 22 August 2019

(Duffy, 1995, 2012; Kent et al., 1987). Several studies have reported an age-related decline in articulation rate in DDK tasks (Bilodeau-Mercure and Tremblay, 2016; Jacewicz et al., 2010; Padovani et al., 2009). However, comparing old (65–74 years) to very old (75–86 years) English speakers, Pierce et al. did not find an age difference (Pierce et al., 2013), potentially suggesting a non-linear aging trajectory with an initial decline followed by a plateau. However, in a study of Hebrew speakers aged 60 to 95 years, Ben-David and Icht (2017) found an effect of age on articulation rate. Follow-up analyses using the same age groups used in Pierce et al. (2013) revealed a significant slowing from old (65–74 years) to very old speakers (75–86 years), suggesting language-specific aging trajectories. In sum, the temporal properties of speech undergo important changes with age.

Most studies that investigated speech timing did not investigate accuracy even though error patterns can also provide important clues into underlying neurobiological mechanisms. Several studies have shown that articulation accuracy declines with age in nonword repetition (Sadagopan and Smith, 2013), and in syllable, nonword and sentence reading (Bilodeau-Mercure et al., 2015; Gollan and Goldrick, 2018; Tremblay et al., 2018). Another limitation is that most DDK studies did not manipulate phonological complexity. Yet, models of language aging suggest that phonology is the most affected language production component (Burke et al., 2000). It has been shown that accuracy decline in older adults is heightened for long compared to short nonwords, and for phonologically complex compared to simpler syllables (Bilodeau-Mercure et al., 2015; Sadagopan and Smith, 2013). Together, these studies suggest that disruption at the level of *phonological selection* – the selection of the phonological form of a word, which precedes motor planning and which is a function of the dorsal language stream (Bohland et al., 2010; Hickok, 2012)– can lead to changes in speech accuracy and timing.

The literature suggests that spoken language production decline is found in two distinct systems: phonological and motor, but important questions remain regarding underlying mechanisms. This is in part because in most studies, hearing, cognitive level and depression are not measured. Yet, age-related decline in these spheres is highly prevalent, and its potential impact on language production is important. Hearing impairment in adults can affect *intelligibility*, that is, the proportion of a speaker's output that a listener can readily understand (e.g. Perkell et al., 2000; Perkell et al., 2007). Depression is also common in aging (e.g., Balsamo et al., 2018; e.g. Rodda et al., 2011) and it can affect voice features and speech rate (Marmor et al., 2016; Mundt et al., 2007; Teasdale et al., 1980). Advancing in age is also associated with decline in working memory (e.g. Bopp and Verhaeghen, 2005; Park et al., 2002; Schroeder, 2014) and attention (e.g. Park et al., 2002; Salthouse, 1996; Salthouse, 2009), which could exacerbate, or even account for, decline in speech production. It was recently shown that older adults with mild cognitive impairment (MCI) have reduced DDK rates compared to heathy older adults (Watanabe et al., 2018). Therefore, understanding the mechanisms that are responsible for age-related speech production decline requires taking into consideration linguistics as well as non-linguistic factors.

The main objective of this study was to test hypotheses about the mechanism that underlie speech production decline in aging using a modified DDK task with a phonological manipulation, while controlling for hearing, cognitive level and depression. The first hypothesis was that aging would be associated with changes in speech timing (articulation rate, articulation rate stability), reflecting a disordered motor planning stage, and a decline in accuracy, reflecting a disordered phonological planning stage. The second hypothesis was that these disruptions would occur mainly in phonologically complex utterances, consistent with the hypothesis of a disordered phonological planning level (Burke et al., 2000). The third hypothesis was that these changes would be present after controlling for hearing, cognitive level and depression, demonstrating that age-related changes in speech production are not a by-product of changes to these systems, but, instead, originate from dysfunction within the speech/language system.

2. Method

2.1. Participants

A sample of 85 healthy native Canadian French speakers (mean 53.32 ± 19 years [20–93 years]; 53 females) was recruited through emails, posters and flyers distributed in Québec City, including University Laval's campus but also shops, restaurants, retirement homes, and community centres. The emails and ads targeted healthy adults. Using a detailed questionnaire, participants were questioned during a ~30-minute phone interview about present and past diagnostic of speech, voice, language, swallowing, psychological, neurological, neurodegenerative, and severe respiratory disorder. Any reported history of such diseases resulted in exclusion from the study. If participants were sick from a cold or suffered from allergies on the day of testing, their appointment was rescheduled. We did not have access to the participant's medical records.

All participants were schooled in French. English was spoken as a second language by most participants (95%). Participants had normal or corrected-to-normal vision. Participants were screened for depression using the Geriatric Depression Scale (GSD) (Yesavage et al., 1982). Cognitive level was assessed using the Montreal Cognitive Assessment scale (MOCA) (Nasreddine et al., 2003).

Pure tone audiometry was performed using a clinical audiometer (AC40, Interacoustic) in a quiet room, for each ear separately, at the following frequencies: 0.25, 0.5, 1, 2, 3, 4, 6, 8, 12 and 16 kHz. For each participant, a pure tone average (PTA) was computed for each ear (average of hearing thresholds at.5, 1, 2, 4 and 6 kHz). This value gives a snapshot of an individual's hearing level in each ear and is the most commonly used assessment tool for estimation of hearing loss. As speech sounds are more densely represented in the mid-frequency range, the outlying frequencies are not included in the PTA calculation. In the present study, PTA was included in all statistical analysis as a covariate. The result of the hearing assessment is provided in Supplementary Material 1. 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 (#294-2012).

Table 1
Descriptive statistics (means, standard deviations and ranges) for participants characteristics.

	M	SD	Min	Max
Age	53.72	19.04	21	93
Education (years)	17.01	3.75	6	24
Number of languages[a]	2.46	1.85	1	5
MoCA[b] (/30)	27.44	1.79	22.00	30.00
GDS[c] (/30)	2.36	2.53	0.00	10.0
R PTA[d]	−29.23	10.73	−60.8	−3.8
L PTA[d]	−30.67	11.7	−64.2	−10.2

Note. M = Mean. SD = standard deviation of the mean.

[a] Number of spoken languages including native language (French).

[b] 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.

[c] 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 and 30 indicate a severe depression.

[d] PTA = pure tone average (500, 1000, 2000, 4000 and 6000 Hz), measured in dB HL. R = right ear. L = left ear.

2.2. Speech evaluation

A DDK task was used to evaluate articulation performance. DDK is a maximal performance task which consists in repeating single syllables (e.g., /pa/), or sequences of syllables (e.g., /pa ta/, /pa ta ka/) as steadily and as many times as possible for ~5 s, while trying to minimize articulation errors. Speech samples were recorded using a high-quality head-worn microphone (Shure, Beta 53) connected to a sound card (Fast Track C400, M-audio) attached to a laptop computer. Speech samples were recorded with the Audacity software (Open source). Two manipulations were implemented: a sequential complexity manipulation and a phonological complexity manipulation. The sequential complexity manipulation consisted in comparing one-syllable (e.g., /pa/), two-syllable (e.g., /pa ta/), and three-syllable sequences (e.g., /pa ta ka/). The phonological complexity manipulation consisted in comparing simple syllables containing only one consonant and one vowel (e.g., /pa/, /ta/and/ka/) to complex syllables containing one consonant cluster and one vowel (e.g., /pʁa/ /tʁa/kʁa/). This resulted in 6 experimental conditions. Participants completed a total of 54 trials, each repeated three times. In this article, we only analyzed a subset of 24 trials per participants, each repeated 3 times, for a total of 72 trials. The list of all stimuli is provided in supplementary material S2.

2.3. Data analysis

Data analysis focused on three dependent measures: articulation rate, articulation rate stability, measured as the normalized vocalic Pairwise Variability Index (nPVI), and percentage of errors, all extracted from the speech recordings using Praat software (Boersma and Weenink, 2011). Two adult female judges (J.P., C.D.) with training in phonetics and speech-language pathology listened to and transcribed all syllables into the international phonetic alphabet (IPA) based on a detailed transcription protocol that was elaborated prior to beginning the transcriptions. For measurement of inter-rater reliability, a subset of 30 participants (equivalent to 35% of the sample), including 11 male and 19 female speakers aged 20 to 93, were transcribed by the two judges. For the analysis of inter-rater reliability, six sequences were analyzed: /pa/, /pʁa/, /pa ta/, /pʁa tʁa/, /pa ta ka/and/pʁa tʁa kʁa/, representing 11,538 measurements. When the two transcriptions differed (which occurred in 0.9% of all trials) a consensus was reached through discussion. The average measure intraclass correlation coefficient (ICCs) was high (0.875 with a 95% confidence interval from.87 to.879, $F_{(115,137,\ 115,137)} = 8.00$, $p < .001$).

Following transcription, the percentage of errors was computed as the percentage of responses that contained at least one error, in each experimental condition. Errors were categorized as within-syllable errors (sound insertion, exchange, inversion and deletion) and within-sequence error (syllable insertion, elision, or inversion). For the measurement of timing-related variables (articulation rate, articulation rate stability), a semi-automatic custom script was used in Praat to segment participants' responses and extract vocalic peak intensity, which was used to calculate articulation rate (number of syllables per second) and articulation rate stability in the form of the nPVI, which measures articulatory rhythm on the basis of vowel length. Specifically, the nPVI represents the overall mean of the difference between successive pairs of vowels divided by their sum and multiplied by 100 (Low et al., 2000). Measures of speech timing such as articulation rate and articulation rate stability are generally considered to index motor processing.

For each dependent variable (articulation rate, stability, percentage of errors), outliers were identified and removed. Outliers were defined as values that were three standard deviations (SD) away from the mean within each condition and each participant. There were no outliers for articulation rate. For nPVI, 3/510 were removed from the analyses (0.005%), while for the percentage of errors, 22/510 data points were removed (4.3%).

Linear mixed model (LMM) analyses were conducted in SPSS V. 25 for Mac (IBM), separately for each dependent variable, with Phonological complexity (simple, complex) and Sequence complexity (1, 2, 3 syllables) as within-subject (repeated) fixed factors, and age as a continuous between-subject fixed factor. To control for differences in hearing, depression and cognitive levels, the PTA, GDS and MOCA scores were entered in the model as continuous covariates. Sex was also entered in the model as a categorical covariate. Participants were included as a random factor in the model. For each dependent variable, a comparison of models was performed to select the optimal analytical model. For all dependent variables, it was found, using a REML-based likelihood ratio test, that allowing the residual variance to vary across conditions led to a better model fit. Non-significant covariates (sex, GDS, hearing and MOCA) were removed from the model (West et al., 2015). Residuals were visually inspected to assess normality using histograms and Q-Q plots. Simple regression analyses were used to decompose interactions involving the continuous age variable. For these analyses, we provide the unstandardized beta values, r^2 and p-values. Moderation analyses were conducted to identify potential trade-offs between articulation rate and accuracy and between articulation rate and variability, and to determine if these relationships are moderated by age. These analyses were conducted in SPSS with the PROCESS macro (model #1) (Hayes, 2008, 2013) with the following parameters: p = .05, bias-corrected bootstrapping with 20,000 samples. The pick-a-point approach (Bauer and Curran, 2005) was used to probe the interactions. For all significant group results, we show corresponding individual data (Weissgerber et al., 2015).

3. Results

The descriptive statistics for each dependent variable are reported in Supplementary Material S3. The results of the LMM analyses are provided in Table 2; only the main results are reported in the text. The raw data (speech recordings) as well as all the data used in the statistical analysis reported in this article are available in open access on the Scholars Portal Dataverse (https://doi.org/10.5683/SP2/RNBELU).

Table 2
Linear mixed model results (Type III F tests).

Effect	*df*	*F*	p
A. Articulation rate (number of syllables per second)			
Intercept	1, 55	0.466	.497
Age	1, 70	0.00	.994
Phonological complexity	1, 213	55.17	< .001
Sequential complexity	2, 162	0.652	.523
Phonological × sequential complexity	2, 162	2.32	.102
Age × phonological complexity	1, 213	1.69	.195
Age × sequential complexity	2, 162	0.03	.90
Age × phonological × sequential complexity	2, 162	0.09	.907
GDS	9, 55	2.51	.017
B. Articulation rate variability (nPVI)			
Intercept	1, 102	200.37	< .001
Age	1, 102	11.70	.001
Phonological complexity	1, 303	12.067	.001
Sequential complexity	2, 265	8.14	< .001
Phonological × sequential complexity	2, 265	1.14	.320
Age × phonological complexity	1, 305	7.965	.005
Age × sequential complexity	2, 265	15.885	< .001
Age × phonological × sequential complexity	2, 265	1.156	.316
C. Percentage of responses with at least one error			
Intercept	1, 263	11.66	.001
Age	1, 264	6.19	.013
Phonological complexity	1, 252	1.167	.281
Sequential complexity	2, 252	2.43	.091
Phonological × sequential complexity	2, 252	0.306	.736
Age × phonological complexity	1, 252	15.23	< .001
Age × sequential complexity	2, 252	0.565	.569
Age × phonological × sequential complexity	1, 252	1.29	.277

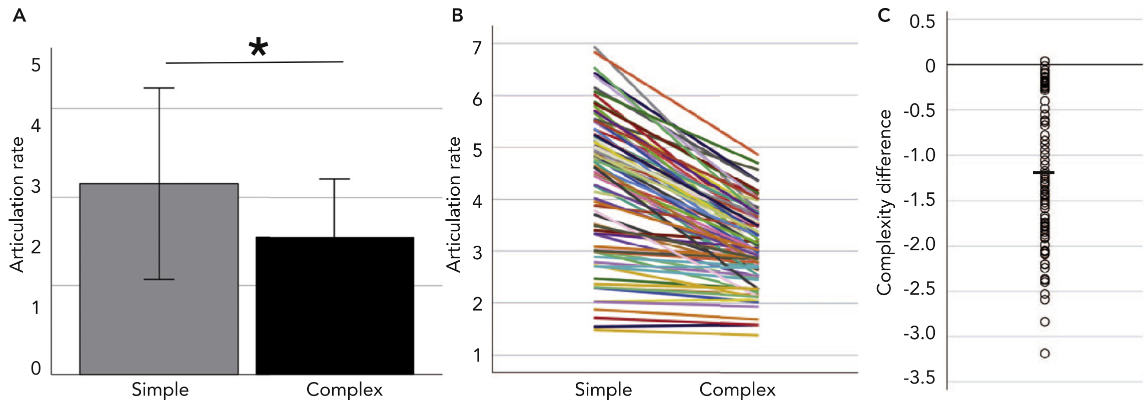

Fig. 1. Phonological complexity effect on articulation rate (number of syllables per seconds) A. The bar chart shows the group articulation rate separately for simple and complex syllables. Error bars in the graph represent the standard deviation of the mean; the asterisk indicates statistical significance ($p < .05$). B. The line chart illustrates individual articulation rate for each level of the phonological complexity variable. Each line represents one subject. C. The scatter plot represents differences in articulation rate (complex – simple) for each subject. Each subject is represented by a circle. Negative values indicate a lower rate for the complex syllables. The median difference is represented as a thick black line.

3.1. Articulation rate

The overall articulation rate, across all participants and conditions, was 3.7 ± 1.33 syllables per second. Results of the analysis with the full LMM model showed no effect of Sex, MOCA and PTA. These covariates were thus removed from the final model. Q-Q plot and histograms revealed that the residuals followed a fairly normal distribution. The analysis with the final LMM model revealed a main effect of phonological complexity ($p = .001$), with a lower rate for the complex syllables. These results are illustrated in Fig. 1. The analysis also revealed an effect of GDS ($p = .017$) on articulation rate. Though the GDS scores were within the normal range (0–9), variability started increasing at a score of 6/30, and a decrease in articulation rate was observed at a score of 8/30, which was followed by an increase. These results are illustrated in supplementary material S4.

3.2. Stability (nPVI)

The overall nPVI, across all participants and conditions, was 18.49 ± 7.28%. Results of the full LMM model showed no effect of Sex, PTA, MOCA and GDS. Therefore, all covariates were removed from the final model (West et al., 2015). Q-Q plot and histogram revealed that the residuals followed a fairly normal distribution. Analysis with the final LMM model revealed a main effect of phonological complexity ($p = .001$), with slightly lower variability for the complex syllables, possibly reflecting the reduced articulation rate associated with this condition. There was also a main effect of sequential complexity ($p \leq .001$), with increasing variability for longer sequences (two and three syllables) compared to the one-syllable sequences. These results are illustrated in Figs. 2 and 3. The analyses also revealed a main effect of age ($p = .001$), with variability increasing with advancing age, and an interaction between age and phonological complexity ($p = .005$). Simple linear regressions were conducted to decompose this interaction (Fig. 4a). These analyses indicated that age affected nPVI, resulting in more variable responses, for the complex syllables ($r^2 = 0.06$; $\beta = 0.098$; $p \leq .001$) but not for the simple syllables ($r^2 = 0.009$; $\beta = 0.033$; $p = .142$). Finally, the analysis also revealed an interaction between age and sequential complexity ($p \leq .001$) (Fig. 4b). Simple linear regressions were conducted to decompose this effect. These analyses indicated that, with increasing age, variability was higher for the 3-syllable ($r^2 = 0.14$; $\beta = 0.134$; $p \leq .001$) and the 2-syllable sequences ($r^2 = 0.025$; $\beta = 0.056$; $p = .038$) but not for the one-syllable sequences ($r^2 = 0.0$; $\beta = -0.003$; $p = .813$).

3.3. Percentage of errors

The overall percentage of errors across all participants and conditions was 5.96 ± 9.22%. Results with the full LMM model showed no effect of Sex, PTA, MOCA and GDS. Thus, the covariates were removed from the final model (West et al., 2015). The Q-Q plot and histogram revealed that the residuals followed a relatively normal distribution. The main LMM analyses revealed a main effect of age ($p = .005$), with errors slightly increasing with advancing age. There was also an interaction between age and phonological complexity ($p \leq .001$). Simple linear regressions were conducted to decompose this interaction. These analyses indicated that errors increased with age for the complex syllables ($r^2 = 0.034$; $\beta = 0.11$; $p = .004$) but not the simple syllables ($r^2 = 0.011$; $\beta = -0.017$; $p = .098$) (Fig. 5A).

Additional exploratory analyses were conducted to examine the types of errors committed. Because the error rate was very low for the simple syllables, these analyses were conducted on the complex syllables only, averaged across sequence complexity levels. First, we examined the types of errors that occurred within and across syllable boundaries. Error types were separated into sequence-level errors (syllable insertion, syllable omission, syllable inversion) and within-syllable errors. As shown in Fig. 5B and C, there were too few sequence-level errors to analyze. Next, within-syllable errors were separated into three main categories: voicing errors, simplifications of consonant clusters and other errors. This last category included exchanges, inversions and omissions, of which there were too few to analyze separately. A LMM analysis was conducted on the (log transformed) percentage of responses containing at least one within-syllable error as the dependent variable. Transformation was needed to normalize the distribution. The independent factors were the continuous variable age and error type (voicing errors, simplifications and other). The Q-Q plot and histogram revealed that the residuals followed a normal distribution. The main analysis revealed a significant interaction between age and error type ($p = .032$). Simple linear regressions were conducted to decompose this interaction. These analyses indicated that errors increased with age for simplifications ($r^2 = 0.092$; $\beta = 0.009$; $p = .006$) but not for voicing errors ($r^2 = 0.077$; $\beta = 0.003$; $p = .249$) or other kinds of errors ($r^2 = 0.025$; $\beta = 0.003$; $p = .166$) (Fig. 5D).

3.4. Relationship between the dependent variables

To determine whether articulation rate influenced accuracy and stability, and whether age moderated these relationships, two moderation analyses were conducted. In the first analysis, the dependent variable was nPVI, the predictor variable was articulation rate, and the

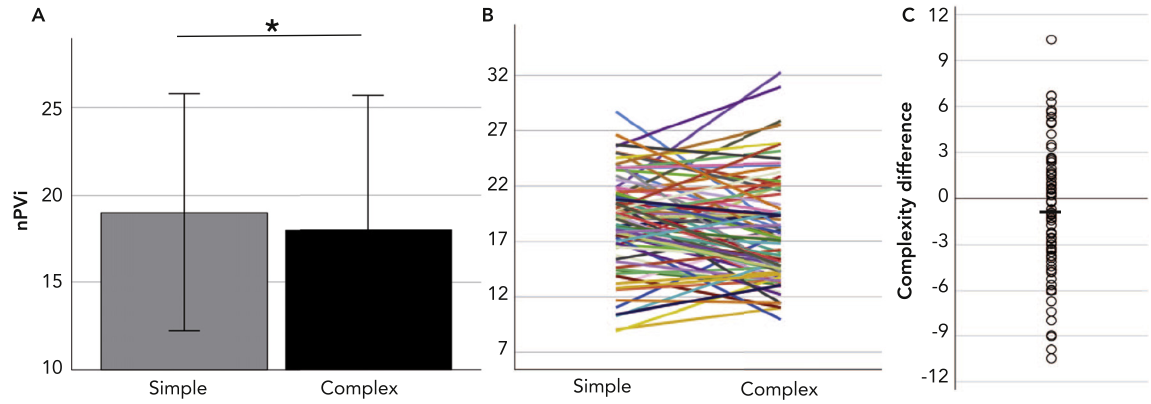

Fig. 2. Phonological complexity effect on nPVI. A. The bar chart shows the group nPVI separately for the simple and complex syllables. Error bars in the graph represent the standard deviation of the mean; the asterisk indicates statistical significance ($p < .05$). B. The line chart illustrates individual nPVI data for each level of the phonological complexity variable. Each line represents one subject. C. The scatter plot represents differences in nPVI (complex – simple) for each subject. Positive values indicate higher instability associated with higher complexity. The median difference is represented as a thick black line.

moderator was the continuous variable age. GDS scores were entered in the model as a covariate because of their influence on articulation rate. When considering only complex syllables, a significant positive relationship was found between articulation rate and nPVI ($\beta = 6.33$, $p = .0068$), whereby higher articulation rate was associated with higher variability. This relationship was moderated by age (r^2 change $= -0.046$, $p = .029$). The pick-a-point approach (Bauer and Curran, 2005) was used to probe this interaction. As shown in Fig. 6, in older adults, there was no relationship between articulation rate and stability: variability was always high. In middle-aged and younger adults, higher rate resulted in higher variability. When the same analysis was conducted on the average of all conditions or on the longest sequences only, the effects were identical but there was no moderation (average: r^2 change $= 0.02$, $p = .187$; 3-syllable sequences: r^2 change $= 0.028$, $p = .08$). Next, we analyzed the relationship between error rate and articulation rate. Results showed that the relationship between articulation rate and error rate just failed to reach significance ($\beta = 6.64$, $p = .073$). There was no moderating effect of age on the relationship between articulation rate and error rate (r^2 change $= -0.0013$, $p = .71$).

4. Discussion

Speaking is a key component of the personal and professional interactions that form the core of the human experience throughout the entire lifespan. Decline in language production can negatively affect self-perceptions as well as the perception of others (Ryan and Johnston, 1987; Ryan et al., 1994), and, in turn, have a negative impact on social participation and life quality. Understanding the manner and extent to which speaking evolves with age is therefore an important scientific endeavour. The main objective of this study was to test hypotheses about the nature of the changes that occur in speech production to help clarify underlying neurobiological mechanisms. Our main hypothesis was that normal aging would be associated with changes in speech performance, in the form of changes in speech timing, reflecting a motor deficit, and reduced accuracy, reflecting a difficulty at the level of phonological planning, independent of hearing, depression and general cognitive level. This hypothesis was verified.

4.1. Aging and speech timing

Our results show that articulation rate stability (nPVI) is affected by both phonological and sequential complexity, and that it decreases with age in healthy adults with no known motor disorder. Articulation rate stability reflects a person's ability to maintain a constant articulation rate during syllable repetition. Disruption in this ability could result from a difficulty occurring in two different systems: phonological (i.e. selecting the correct phonemes) or motor (i.e. compiling articulatory plans). The finding of disrupted temporal properties of speech in aging is consistent with previous studies showing an age-related decrease in speed in DDK tasks (Bilodeau-Mercure and Tremblay, 2016; Jacewicz et al., 2010; Meurer et al., 2004; Padovani et al., 2009; Watanabe et al.,

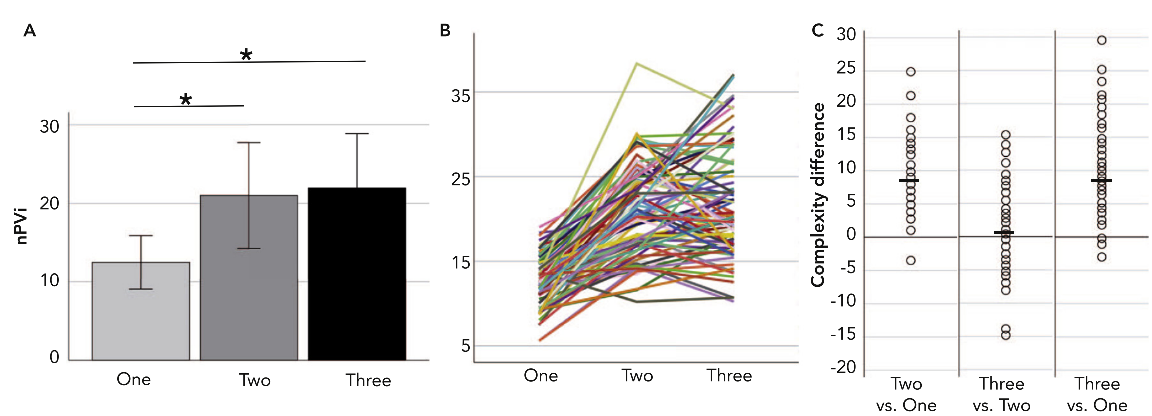

Fig. 3. Sequential complexity effect on nPVI. A. The bar chart shows the group nPVI separately for the one-, two- and three-syllable sequences. Error bars in the graph represent the standard deviation of the mean; asterisks indicate statistical significance ($p < .05$). B. The line chart illustrates individual nPVI at each level of the sequential complexity factor. Each line represents one subject. C. The scatter plot represents differences in nPVI for each subject. Positive values indicate higher instability associated with increased complexity. The median difference for each contrast is represented as a thick black line.

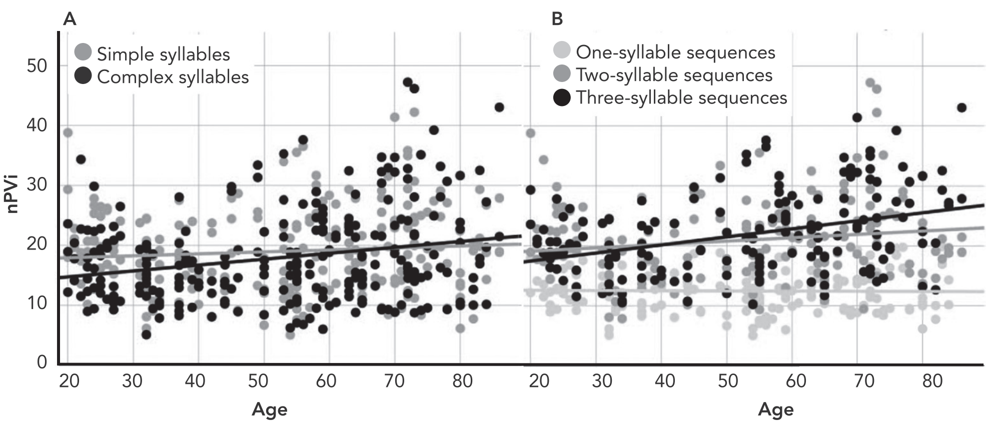

Fig. 4. Age effects on nPVI. The bar chart shows nPVI on the y-axis as a function of age. A. Interaction between age and phonological complexity on nPVI. Individual data points are displayed for the simple and complex syllables. B. Interaction between age and sequential complexity on nPVI. Individual data points are displayed for each level of the sequential complexity variable.

2017), but also in sentence reading (Jacewicz et al., 2009; Jacewicz et al., 2010), sentence repetition (Wohlert and Smith, 1998) and conversational speech (Searl et al., 2002). There is also evidence in the literature for an age-related increase in speech duration (Morris and Brown, 1987; Sadagopan and Smith, 2013; Tremblay and Deschamps, 2016; Tremblay et al., 2017), as well as increase in variability in consonant duration (Morris and Brown Jr, 1994; Smith et al., 1987).

Importantly, in the present study, temporal disruptions were still present after controlling for three factors that are known to affect speech production: hearing, general cognitive level and depression, which provides strong support to the notion that these age-related changes are not a by-product of decline affecting other neural systems but, instead, reflect changes occurring within the motor speech system. Importantly, however, we found that depression level, but not hearing or general cognitive level, influenced articulation rate. The effects of depression on speech and voice are well documented (e.g. Mundt et al., 2007; Szabadi et al., 1976; Teasdale et al., 1980). Our findings therefore suggest that assessment of articulation rate needs to be interpreted with caution, taking into account patients' mood. Currently, most studies on speech production do not document this, implicitly assuming that speech motor control is independent from emotional state.

Contrary to our prediction, in the current study, the effect of age on articulation rate was not significant. Importantly, the articulation rates that we measured were slower than those reported in previous studies, possibly reflecting an emphasis on accuracy rather than speed, which could account for the lack of a significant age effect. This finding is in contrast with previous DDK studies in older adults (Ben-David and Icht, 2017; Padovani et al., 2009; Pierce et al., 2013). For example, Pierce et al. reported a rate of 6.3 syllables/s for a group of 65–74 years old English speakers and a rate of 5.98 syllables/s for a group of 74–86 years old English speakers, representing a 5.1% decline (Pierce et al., 2013). In the present study, the overall rate for participants aged 65–74 years was 3.71 syllables/s and for those aged 75–93 years it was 3.44 syllables/s, representing a 7.2% decline. Though not significantly different, the general tendency in the present study is in the expected direction. This finding will need to be replicated to determine if an

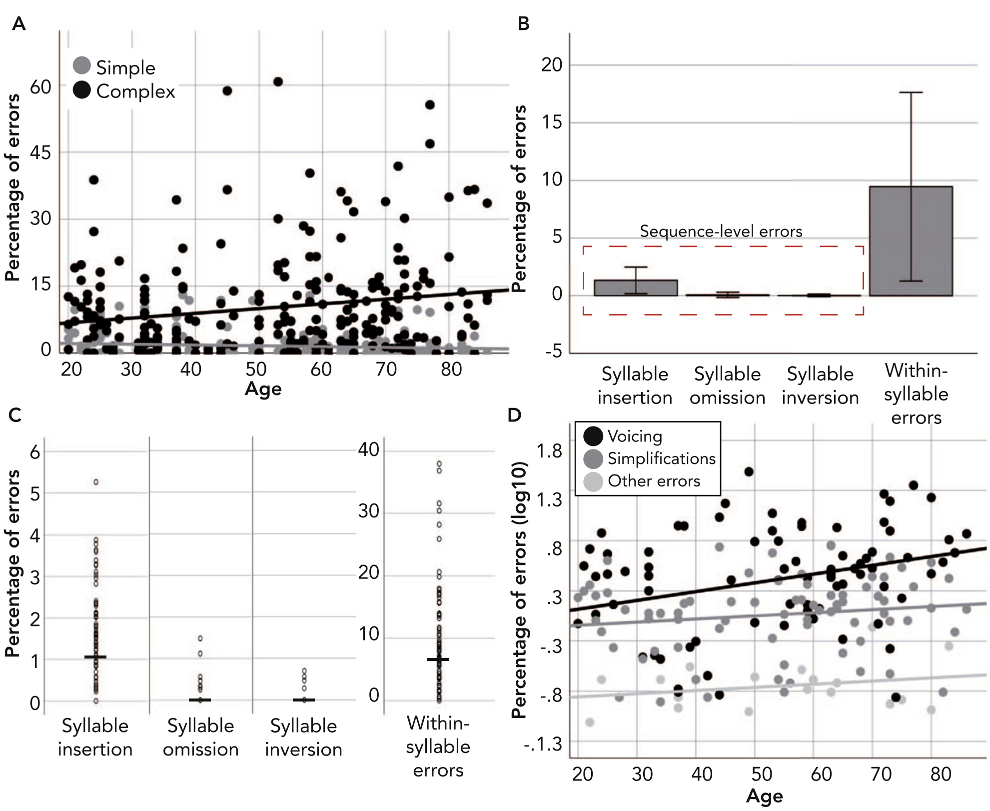

Fig. 5. Percentage of errors. A. The scatter plot shows the interaction between age and phonological complexity on the percentage of syllables with at least one error. B. The bar chart shows error rate (proportion of sequences with at least one error) as a function of the main error types. The error bars represent the standard deviation of the mean. C. Percentage of errors for each subject and each error type. The median percentages of errors are represented as thick black lines. D. Age effects on the log transformed percentage of within-syllable errors. Individual data points are displayed for each error subtype (voicing, simplification and other).

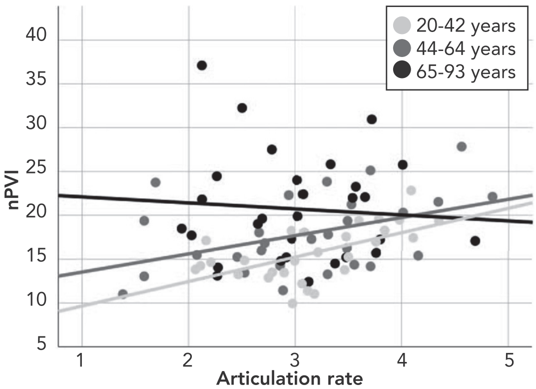

Fig. 6. Result of the moderation analyses. The scatter plot shows the relationship between nPVI (y-axis) and articulation rate (x-axis), at three levels of the age variable shown in different levels of gray.

emphasis on accuracy rather than speed is sufficient to normalize rate – without normalizing rate stability, however. Indeed, a key finding of the present study is that that articulation rate variability may be a more sensitive measure that articulation rate, given that, even at relatively slow rate, variability was still sensitive to age, but also to phonological and sequential complexity. In patients unable to produce fast speech, nPVI may represent a more sensitive measure to assess motor planning and motor control capacities. Given the inherently serial nature of language, the temporal properties of speech have an important impact on speech intelligibility (Kang et al., 2017) and can set apart normal speakers from speakers with neurological disorders such as acquired dysarthria (Liss et al., 2009; Tjaden and Watling, 2003). Inconsistent or an abnormal oral DDK performance in normal aging could therefore indicate disorders of the central nervous system. Consistent with this hypothesis, previous work from our group using magnetic resonance imaging (MRI) has shown that age-related changes in the temporal properties of speech (i.e. movement time) were associated with different activation patterns and structural decline in several brain areas including the primary motor cortex and the striatum (Tremblay and Deschamps, 2016; Tremblay et al., 2017). This suggests that age-related changes in the temporal characteristics of speech results, at least to some extent, from changes occurring within the motor speech system, suggesting that these difficulties reflect disruptions at the level of motor planning or motor control. Additional studies are needed to examine DDK performance in aging in relation with brain structure and function in order to test this hypothesis directly and clarify the specific domain involved (planning or execution or both).

4.2. Aging and speech accuracy

In addition to timing differences, our results also show a significant age-related decline in accuracy for the phonologically complex syllables, in the form of simplification errors occurring in the syllable onset position, consistent with recent studies (e.g. Bilodeau-Mercure et al., 2015; Sadagopan and Smith, 2013). We propose that a disruption in phonological encoding mechanisms, such as proposed by the Transmission Deficit hypothesis (TDH) (Burke et al., 2000), is responsible for the increase rate in simplification errors, and that this is due to neurobiological decline occurring within the dorsal language stream.

Most errors in the present study occurred within the syllable boundary, with very few sequence-level errors such as syllable inversions, elisions or insertions. Most errors affected consonants. While qualitative assessment of the recordings suggests some level of phonetic distortion—articulatory errors—the most common type of error was the simplification of consonant clusters, an error type that is common in aphasia and speech apraxia (e.g. Blumstein, 1973; Galluzzi et al., 2015; Laganaro, 2012). We suggest that this reflects a disruption in phonological planning. This interpretation is grounded in the finding that accuracy was not related to timing, as shown by the moderation analyses, consistent with prior findings using a nonword production task (Tremblay et al., 2018). It has been suggested that, when simplification errors are independent from movement time, they likely originate at the level of phonological selection, which occurs earlier than motor planning (Buchwald and Miozzo, 2012; Galluzzi et al., 2015). According to this view, errors occurring at the articulatory planning level, after successful phonological selection, imply a revision of the selected phonological form, which should lead to a decreased rate. Consistent with this notion, a previous study using structural brain imaging, has shown that speech accuracy, but not duration, was associated with the structure of the supramarginal gyrus (Tremblay and Deschamps, 2016), a region that has been associated with phonological processing and phonological working memory (e.g., Demonet et al., 1994; Paulesu et al., 1993; Price et al., 1997), and which is part of the dorsal language stream (Bohland et al., 2010; Hickok and Poeppel, 2007).

Taken together, these results suggest that phonological disruptions contribute to speech production difficulties in aging, consistent with the TDH (Burke et al., 2000). TDH suggests that normal aging weakens connection strength between phonological nodes. According to this view, following lexical selection, the phonological form of a word is retrieved, which begins with the retrieval of syllabic representations followed by the retrieval of phonological features. This process is particularly vulnerable to disruptions in connection strength because the proposed top-down phonological connections are one-to-one. TDH can account for the tip of the tongue phenomenon (TOT), a momentary inability to retrieve the phonological form of a word that is more common in older than in younger adults (e.g. Brown and Nix, 1996; Burke, 1999; Burke et al., 1991; Rastle and Burke, 1996). Supporting this notion is the finding that older adults experiencing access difficulty benefit from phonemic cues, suggesting a disrupted access to phonological information (e.g. Barresi et al., 2000; Nicholas et al., 1985). TDH proposes that TOTs reflect a phonological retrieval deficit, that is, a deficit in the transmission of priming to phonological nodes representing a target word. TDH also proposes that connection strength is augmented by usage, and therefore that less frequently used phonological forms are more vulnerable to an age-related disruption. We propose here that disruption in phonological encoding mechanisms during language production in aging is related to the increase rate in simplification errors that we observed in complex syllables, which are less frequent in the French language than simple syllables (Bédard et al., 2016), making them particularly vulnerable to a disruption in connection strength, consistent with TDH.

5. Conclusions

The current study suggests that disruptions in speech production in healthy older males and females have a dual origin in the central nervous system, including a decline in the dorsal language stream that results in difficulty with phonological encoding, and a decline within the speech motor system, leading to deficits in the motor implementation of spoken language. These disruptions are independent of hearing, sex and general cognitive level. The present results are therefore, at least in part, congruent with the Transmission Deficit hypothesis (TDH) (Burke et al., 2000). However, TDH focuses on the phonological layer of spoken language production only and does not integrate a speech motor component. The development of more comprehensive theory of spoken language production in aging is key to guide aging research, facilitate differential diagnosis for speech disorders and develop prevention and mitigation strategies aimed at promoting social participation. To achieve these goals, further studies combining careful error analyses, analysis of intelligibility, more detailed cognitive assessments and brain imaging data are needed to test the hypothesis of a dual locus (phonological and motor) by identifying the neural correlates of speech disruptions in aging.

From a clinical standpoint, our results have implications for both the assessment and the treatment of speech disorders in older adults. At the level of assessment, our results support the idea that a modified DDK paradigm with complex syllables is sensitive to changes in speech production in the normal aging population. In particular, our results suggest that rate variability may be the most sensitive measure to extract from such task because of its sensitivity to normal variation, and that documenting error types might also be useful in distinguishing normal from pathological changes. Indeed, in the present study, we show that most errors occurred within the syllable boundaries, and that most of them resulted in a simplified syllabic structure. This provides a baseline against which to compare the productions of people presenting with a complaint or in whom a disorder may be suspected. While DDK assessments are broadly used by speech-language pathologists (Kent and Kim, 2003), because of their simplicity, they could also be used by a variety of clinicians (e.g. family doctors, nurses, psychologists) as a quick and objective tool to assess speech production performance.

At the level of treatment, our results are also useful to guide clinical practice in that they suggest that speech performances decline in aging is associated with disruptions at the level of phonological and motor planning affecting rate variability and accuracy. Clinical interventions for this population should therefore combine phonological tasks (i.e. phoneme discrimination tasks, phoneme sequence repetition) including phonologically complex syllables or words (i.e. those with a consonant cluster in the onset) and principles of motor learning (i.e. controlled practice and feedback conditions) (Maas et al., 2008), to improve speech production performance more effectively.

Acknowledgments

We would like to thank all participants. Thanks also to L-M Deschenes and C. Fontaine-Lavallée for their help with quality control, L. Bourrassa and C.-A. Boudreault for their contribution to data collection and to M. Guitton for the audiological assessments.

The raw data (wave files) and the data used in the analysis reported here are available on the Scholars Portal Dataverse (https://doi.org/10.5683/SP2/RNBELU).

Funding

This work was supported by the Social Sciences and Humanities Research Council of Canada [435-2017-1050 to P.T.]; the Canadian Foundation for Innovation [31408 to P.T.]; the Fonds de Recherche du Québec-Société et Culture [169309 to P.T.]; the Fonds Québécois de la Recherche—Santé [35016 and 27170 to P.T.].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.exger.2019.110695.

References

Bajaj, S., Alkozei, A., Dailey, N.S., Killgore, W.D.S., 2017. Brain aging: uncovering cortical characteristics of healthy aging in young adults. Front. Aging Neurosci. 9, 412. https://doi.org/10.3389/fnagi.2017.00412.

Balsamo, M., Cataldi, F., Carlucci, L., Padulo, C., Fairfield, B., 2018. Assessment of late-life depression via self-report measures: a review. Clin. Interv. Aging 13, 2021–2044. https://doi.org/10.2147/CIA.S178943.

Barresi, B.A., Nicholas, M., Tabor Connor, L., Obler, L.K., Albert, M.L., 2000. Semantic degradation and lexical access in age-related naming failures. Aging Neuropsychol. Cognit. 73 (3), 169–178.

Bauer, D.J., Curran, P.J., 2005. Probing interactions in fixed and multilevel regression: inferential and graphical techniques. Multivar. Behav. Res. 40 (3), 373–400. https://doi.org/10.1207/s15327906mbr4003_5.

Bédard, P., Audet, A.-M., Drouin, P., Roy, J.P., Rivard, J., Tremblay, P., 2016. SyllabO+: a new tool to investigate sublexical phenomena in Québec spoken French. Behavioral Research Methods 49 (5), 1852–1863.

Ben-David, B.M., Icht, M., 2017. Oral-diadochokinetic rates for Hebrew-speaking healthy ageing population: non-word versus real-word repetition. Int J Lang Commun Disord 52 (3), 301–310. https://doi.org/10.1111/1460-6984.12272.

Bilodeau-Mercure, M., Tremblay, P., 2016. Speech production in aging: linguistic and physiological factors. J. Am. Geriatr. Soc. 64 (11), e177–e182. https://doi.org/10.1111/jgs.14491.

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.

Blumstein, S., 1973. A Phonological Investigation of Aphasic Speech. Mouton, The Hague.

Boersma, P., Weenink, D., 2011. Praat: Doing Phonetics by Computer (Version 5.2.10) (Retrieved from). http://www.praat.org/.

Bohland, J.W., Bullock, D., Guenther, F.H., 2010. Neural representations and mechanisms for the performance of simple speech sequences. J. Cogn. Neurosci. 22 (7), 1504–1529. https://doi.org/10.1162/jocn.2009.21306.

Bopp, K.L., Verhaeghen, P., 2005. Aging and verbal memory span: a meta-analysis. J Gerontol B Psychol Sci Soc Sci 60 (5), P223–P233.

Brown, A.S., Nix, L.A., 1996. Age-related changes in the tip-of-the-tongue experience. Am. J. Psychol. 109 (1), 79–91. https://www.ncbi.nlm.nih.gov/pubmed/8714453.

Buchwald, A., Miozzo, M., 2012. Phonological and motor errors in individuals with acquired sound production impairment. J Speech Lang Hear Res 55 (5), S1573–S1586. https://doi.org/10.1044/1092-4388 (2012/11–0200).

Burke, D.M., 1999. Language production and aging. In: Kemper, S., Kliegl, R. (Eds.), Constraints on Language: Aging, Grammar, and Memory. Springer, New York, pp. 3–27.

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? J. Mem. Lang. 30 (5), 542–579.

Burke, D.M., MacKay, D.G., James, L.E., 2000. Theoretical approaches to language and aging. In: Perfect, T., Maylo, E. (Eds.), Models of Cognitive Aging. Oxford University Press, Oxford, England, pp. 204–237.

Demonet, J.F., Price, C., Wise, R., Frackowiak, R.S., 1994. Differential activation of right and left posterior sylvian regions by semantic and phonological tasks: a positron-emission tomography study in normal human subjects. Neurosci. Lett. 182 (1), 25–28 (doi:0304-3940 (94)90196-1 [pii]).

Diaz, M.T., Johnson, M.A., Burke, D.M., Madden, D.J., 2014. Age-related differences in the neural bases of phonological and semantic processes. J. Cogn. Neurosci. 26 (12), 2798–2811. https://doi.org/10.1162/jocn_a_00665.

Duffy, J.R., 1995. Motor Speech Disorders: Substrates, Differential Diagnosis and Management. Mosby, St. Louis, MO.

Duffy, J.R., 2012. Motor Speech Disorders: Substrates, Differential Diagnosis, and Management, 3rd edition. Mosby.

Galluzzi, C., Bureca, I., Guariglia, C., Romani, C., 2015. Phonological simplifications, apraxia of speech and the interaction between phonological and phonetic processing. Neuropsychologia 71, 64–83.

Gollan, T.H., Goldrick, M., 2018. Aging deficits in naturalistic speech production and monitoring revealed through reading aloud. Psychol. Aging. https://doi.org/10.1037/pag0000296.

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.

Hickok, G., 2012. Computational neuroanatomy of speech production. Nat. Rev. Neurosci. 13 (2), 135–145. https://doi.org/10.1038/nrn3158.

Hickok, G., Poeppel, D., 2007. The cortical organization of speech processing. Nat. Rev. Neurosci. 8 (5), 393–402. https://doi.org/10.1038/nrn2113.

Jacewicz, E., Fox, R.A., O'Neill, C., Salmons, J., 2009. Articulation rate across dialect, age, and gender. Lang Var Change 21 (2), 233–256. https://doi.org/10.1017/S0954394509990093.

Jacewicz, E., Fox, R.A., Wei, L., 2010. Between-speaker and within-speaker variation in speech tempo of American English. J Acoust Soc Am 128 (2), 839–850. https://doi.org/10.1121/1.3459842.

Kang, O., Thomson, R.I., Moran, M., 2017. Empirical approaches to measuring the intelligibility of different varieties of English in predicting listener comprehension. Lang. Learn. 68 (1), 115–146. https://doi-org.acces.bibl.ulaval.ca/10.1111/lang.12270.

Kent, R.D., Kim, Y.J., 2003. Toward an acoustic typology of motor speech disorders. Clin Linguist Phon 17 (6), 427–445.

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

Laganaro, M., 2012. Patterns of impairments in AOS and mechanisms of interaction between phonological and phonetic encoding. J Speech Lang Hear Res 55 (5), S1535–S1543. https://doi.org/10.1044/1092-4388. (2012/11–0316).

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. J Speech Lang Hear Res 52 (5), 1334–1352. https://doi.org/10.1044/1092-4388. (2009/08–0208).

Low, L., Grabe, E., Nolan, F., 2000. Quantitative characterizations of speech rhythm: syllable-timing in Singapore English. Lang. Speech 43 (4), 377–401.

Maas, E., Robin, D.A., Austermann Hula, S.N., Freedman, S.E., Wulf, G., Ballard, K.J., Schmidt, R.A., 2008. Principles of motor learning in treatment of motor speech disorders. Am J Speech Lang Pathol 17 (3), 277–298. https://doi.org/10.1044/1058-0360 (2008/025).

Marmor, S., Horvath, K.J., Lim, K.O., Misono, S., 2016. Voice problems and depression among adults in the United States. Laryngoscope 126 (8), 1859–1864. https://doi.org/10.1002/lary.25819.

Meurer, E.M., Wender, M.C., von Eye Corleta, H., Capp, E., 2004. Phono-articulatory variations of women in reproductive age and postmenopausal. J. Voice 18 (3), 369–374. https://doi.org/10.1016/j.jvoice.2003.02.001.

Morris, R., Brown, W.S., 1987. Age-related voice measures among adult women. J. Voice 1 (1), 43.

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

Mundt, J.C., Snyder, P.J., Cannizzaro, M.S., Chappie, K., Geralts, D.S., 2007. Voice acoustic measures of depression severity and treatment response collected via interactive voice response (IVR) technology. J. Neurolinguistics 20 (1), 50–64. https://doi.org/10.1016/j.jneuroling.2006.04.001.

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).

Nicholas, M., Obler, L., Albert, M., Goodglass, H., 1985. Lexical retrieval in healthy aging. Cortex; a journal devoted to the study of the nervous system and behavior 21 (4), 595–606.

Padovani, M., Gielow, I., Behlau, M., 2009. Phonarticulatory diadochokinesis in young and elderly individuals. Arq. Neuropsiquiatr. 67 (1), 58–61.

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.

Paulesu, E., Frith, C.D., Frackowiak, R.S., 1993. The neural correlates of the verbal component of working memory. Nature 362, 342–345. https://doi.org/10.1038/362342a0.

Perkell, J., Guenther, F., Lane, H., Matthies, M.L., Perrier, P., Vick, J., ... Zandipour, M., 2000. A theory of speech motor control and supporting data from speakers with normal hearing and with profound hearing loss. J. Phon. 28, 233–272. https://doi.org/10.1006/jpho.2000.0116.

Perkell, J.S., Lane, H., Denny, M., Matthies, M.L., Tiede, M., Zandipour, M., ... Burton, E., 2007. Time course of speech changes in response to unanticipated short-term changes in hearing state. J Acoust Soc Am 121 (4), 2296–2311.

Pierce, J.E., Cotton, S., Perry, A., 2013. Alternating and sequential motion rates in older adults. Int J Lang Commun Disord 48 (3), 257–264. https://doi.org/10.1111/1460-6984.12001.

Price, C.J., Moore, C.J., Humphreys, G.W., Wise, R.J., 1997. Segregating semantic from phonological processes during Reading. J. Cogn. Neurosci. 9 (6), 727–733. https://doi.org/10.1162/jocn.1997.9.6.727.

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. J. Mem. Lang. 35 (4), 586–605.

Rodda, J., Walker, Z., Carter, J., 2011. Depression in older adults. BMJ 343, d5219. https://doi.org/10.1136/bmj.d5219.

Ryan, E.B., Johnston, D.G., 1987. The influence of communication effectiveness on evaluations of younger and older adult speakers. J. Gerontol. 42 (2), 163–164.

Ryan, E.B., See, S.K., Meneer, W.B., Trovato, D., 1994. Age-based perceptions of conversational skills among younger and older adults. In: Hummert, M.L., Wiemann, J.M., Nussbaum, J.N. (Eds.), Interpersonal Communication in Older Adulthood. Sage Publications, Thousand Oaks, CA, pp. 15–39.

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. https://doi.org/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. https://doi.org/10.1017/S1355617709990385.

Schroeder, P.J., 2014. The effects of age on processing and storage in working memory span tasks and reading comprehension. Exp. Aging Res. 40 (3), 308–331. https://doi.org/10.1080/0361073X.2014.896666.

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

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.

Szabadi, E., Bradshaw, C.M., Besson, J.A., 1976. Elongation of pause-time in speech: a simple, objective measure of motor retardation in depression. Br. J. Psychiatry 129, 592–597.

Teasdale, J.D., Fogarty, S.G., Williams, J.M.G., 1980. Speech rate as a measure of short-term variation in depression. British Journal of Social and Clinical Psychology 19, 271–278.

Tjaden, K., Watling, E., 2003. Characteristics of diadochokinesis in multiple sclerosis and Parkinson's disease. Folia Phoniatr Logop 55 (5), 241–259. https://doi.org/10.1159/000072155.

Tremblay, P., Deschamps, I., 2016. Structural brain aging and speech production: a surface-based brain morphometry study. Brain Struct. Funct. 221 (6), 3275–3299. https://doi.org/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. https://doi.org/10.1002/hbm.23558.

Tremblay, P., Deschamps, I., Bedard, P., Tessier, M.H., Carrier, M., Thibeault, M., 2018. Aging of speech production, from articulatory accuracy to motor timing. Psychol. Aging 33 (7), 1022–1034. https://doi.org/10.1037/pag0000306.

Watanabe, Y., Hirano, H., Arai, H., Morishita, S., Ohara, Y., Edahiro, A., ... Suzuki, T., 2017. Relationship between frailty and oral function in community-dwelling elderly adults. J. Am. Geriatr. Soc. 65 (1), 66–76. https://doi.org/10.1111/jgs.14355.

Watanabe, Y., Arai, H., Hirano, H., Morishita, S., Ohara, Y., Edahiro, A., ... Suzuki, T., 2018. Oral function as an indexing parameter for mild cognitive impairment in older adults. Geriatr Gerontol Int 18 (5), 790–798. https://doi.org/10.1111/ggi.13259.

Weissgerber, T.L., Milic, N.M., Winham, S.J., Garovic, V.D., 2015. Beyond bar and line graphs: time for a new data presentation paradigm. PLoS Biol. 13 (4), e1002128. https://doi.org/10.1371/journal.pbio.1002128.

West, B.T., Welch, K.B., Gałecki, A.T., Gillespie, B.W., 2015. Linear mixed models a practical guide using statistical software (pp. 1 ressource en ligne). Retrieved from. https://www.taylorfrancis.com/books/9781466561021.

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. J. Psychiatr. Res. 17 (1), 37–49.