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Speech Production in Healthy Older Adults With or Without Amateur Singing Experience

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ABSTRACT

Purpose: Amateur singing is a universal, accessible, and enjoyable musical activity that may have positive impacts on human communication. However, evidence of an impact of singing on speech articulation is still scarce, yet understanding the effects of vocal training on speech production could provide a model for treating people with speech deficits. The aim of this study was to examine speech production in younger and older adults with or without amateur singing experience.
Method: Thirty-eight amateur singers (aged 20–87 years, 23 women and 15 men) and 40 nonmusician active controls (aged 23–88 years, 19 women and 21 men) were recruited. A set of tasks were used to evaluate the oral motor sphere: two voice production tasks, a passage reading task, and a modified diadochokinetic (DDK) rates task performed at a natural rhythm and as quickly as possible.
Results: Our results show that older age was associated with lower reading rate, lower articulation rate, and articulation rate variability in the DDK task, as well as reduced accuracy for the phonologically complex stimuli. Most importantly, our results show an advantage for singers over cognitively active nonsingers in terms of articulatory accuracy in the most challenging situations.
Conclusion: This result suggests extended maximal performance capacities in amateur singers perhaps resulting from the articulatory efforts required during singing.
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Perhaps no behavior is more essential to happiness, life quality, and self-esteem during the later years of life than the ability to communicate with others. While higher level components of language production such as conceptual preparation and vocabulary remain relatively stable over time, the motor stages of language production, namely, voice production and articulation, undergo significant changes with age, with important interindividual variability. Specifically, aging has been associated with physiological changes in the larynx (Bloch & Behrman, 2001; Filho et al., 2003; Honjo & Isshiki, 1980; Kersing & Jennekens, 2004; Pontes et al., 2005), the vocal tract (Liu et al., 2021; Pontes et al., 2006; Rother et al., 2002), and the respiratory system (Lalley, 2013; Linville, 1996; Zeleznik, 2003). Associated decline includes reduced vocal stability (e.g., Lortie et al., 2015; Wilcox & Horii, 1980) and loudness (Baker et al., 2001), an increase in the duration and variability of speech utterances during syllable and sentence repetition (e.g., Morris & Brown, 1987; Smith et al., 1987), syllable reading (Tremblay & Deschamps, 2016; Tremblay et al., 2017, 2018), and nonword repetition (Sadagopan & Smith, 2013). Others have reported a decline in articulation rate in diadochokinetic (DDK) tasks (Bilodeau-Mercure & Tremblay, 2016; Jacewicz et al., 2010; Padovani et al., 2009). In addition to timing-related decline, studies have reported a decline in articulation accuracy in nonword repetition (Sadagopan & Smith, 2013) and in syllable, nonword, and sentence reading (Bilodeau-Mercure et al., 2015; Gollan & Goldrick, 2018; Tremblay et al., 2018). A recent analysis of the "Up"

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corpus (Gahl et al., 2014), which features a group of people aged between 21 and 49 years, filmed at 7-year intervals, over a period of 56 years (Apted, 1977, 1984, 1991, 1998), reported a shift in vowel space toward the periphery with age (Gahl & Baayen, 2019). Specifically, the authors reported lower first formants with age for vowels /i I ɔ ʊ u/ and higher second formants with age for vowels /i I e æ u/.

In summary, the motor stages of language production undergo important transformations with age. This is perhaps not surprising given that articulation is a rather spectacular flow of precise movements of the vocal folds, lips, tongue, and other structures that require precise timing and coordination with the respiratory system. Yet, some of these changes can render communication-mediated activities more difficult and have a negative impact on self-esteem and social participation.

While aging itself is an irreversible process, a key question is whether changes in speech production are avoidable, or at least mitigable. Can certain activities that engage the vocal system, such as amateur singing, have a positive impact on voice and articulation in older adults? The mental exercise hypothesis proposes the general notion that lifestyle factors can affect cognitive functioning and reduce cognitive decline in aging (Simons et al., 2016). One set of hypotheses, developed by Timothy Salthouse, provides a framework to study the mechanisms underlying the relationship between cognitive aging and lifestyle factors (Salthouse, 2006; Salthouse et al., 1990). The first hypothesis, coined the differential preservation hypothesis, proposes that, in younger age, those with high and low cognitive activity do not differ. With age, however, only highly active adults maintain a youth-like performance. This hypothesis predicts that group differences will increase with age, with highly active adults showing maintained or improved performance over time and less active adults showing a decrease in performance over time. The second hypothesis, coined the preserved differentiation hypothesis (Salthouse, 2006; Salthouse et al., 1990), stipulates that the difference in performance is preserved over the life span. This hypothesis predicts that highly active individuals maintain a stable advantage over less active individuals throughout their life span. Together, these hypotheses provide a useful framework to interpret results that address the question of the mental exercise hypothesis. This framework can be used to study the association between musical activities, such as singing, and cognitive aging (Alain et al., 2014), including spoken language production.

Why singing? Amateur singing is a universal, accessible, and enjoyable musical activity that relies on the vocal system. Over the centuries, numerous authors have been interested in the relationship between music and language (for a review, see Besson et al., 2011; Turker & Reiterer, 2021). Because singing, like language production, involves lexical access, phonological encoding, voice production, and articulation, it is possible that singing has an enduring effect on different stages of language production. Consistent with this notion, several studies have shown that singers outperform nonsingers in tasks requiring lexical access (Fu et al., 2018) and verbal working memory (Fu et al., 2018; Pongan et al., 2017; Tremblay & Perron, 2023). The notion of the impact of singing on speech skills is consistent with the overlap, precision, emotion, repetition, attention (OPERA) hypothesis (Patel, 2011, 2012, 2014), which proposes that musical activities affect speech skills by driving plasticity within neural circuitry shared between musical activities and speech processes. Consistent with OPERA, a recent meta-analysis showed that musical activities are associated with enhanced speech processing in noise capacity (Maillard et al., 2023). However, much less is known about how musical activities can affect other aspects of communication, especially spoken language production. Yet, understanding the effects of vocal training on speech and voice production could provide a model for treating people with speech and voice deficits. Further, at the theoretical level, the notion that singing could impact articulation is consistent with the Integrative Model (IM) of Speech Motor Control (Ballard et al., 2003), which proposes that speech and nonspeech orofacial functions are controlled through domain-general brain networks and that working on one behavior (e.g., singing) might have beneficial effects on another (e.g., speaking). Because singing and speaking share the same apparatus, which includes the respiratory system, the vocal tract, and the articulators (tongue, soft palate, and lips), learning to sing could enhance vocal flexibility and provide singers with the possibility to exploit a larger articulation space than nonsingers. Given that singers can be considered vocal athletes, one could hypothesize that, over time, continuous singing training would have an impact on the motor system, affecting voice and speech patterns. This could be considered evidence of relatively near transfer (Barnett & Ceci, 2002). While near-transfer takes place between relatively closely related domains (e.g., using two models of the same device), far transfer occurs when the domains are weakly related (e.g., transfer from music to mathematics; Bigand & Tillmann, 2022).

Consistent with these notions, experimental evidence also shows that singers can operate on a wider range of vocal intensities and frequencies (e.g., Story, 2004). Importantly, several studies have shown a positive effect of singing on the aging voice, including better stability in the frequency domain (Prakup, 2012), which is associated with lower perceived harshness, better stability in the amplitude domain (Lortie et al., 2017), longer maximum phonation time (MPT; Maruthy & Ravibabu, 2015), and less perceived voice disorder (Stager et al., 2020). However, other studies failed to find a benefit of singing on the aging voice (Berghs et al., 2013; Brown et al., 1990). In summary, there is limited consistency about the specific benefit of singing on the aging voice (for a review, see Tremblay & Veilleux, 2018).

Regarding articulation, previous research has examined jaw opening, speech timing, speech imitation, intonation, and vocal tract adjustments of trained singers and untrained singers during speech and singing. A recent meta-analysis has shown that a singing-based speech-language intervention, the Melodic Intonation Therapy (Albert et al., 1973; Sparks et al., 1974), is associated with speech improvements in participants with motor speech disorders (Zumbansen & Tremblay, 2018). In healthy adults, it was found that novice and experienced singers do not differ in terms of jaw opening patterns during speaking (Austin, 2007). Regarding timing and intonation, Brown et al. (2000) found no difference in sentence duration and number of syllables per second between trained singers and nonsingers. There was, however, a difference in intonation variability, with male (but not female) singers using significantly greater variation in intonation in comparison to the male nonsingers when reading the sentence. In terms of vocal tract adjustments, measured as voice onset times (VOTs), the results are somewhat conflicting. McCrea and Morris (2005) found significantly longer VOTs in trained compared to untrained singers during both singing and sung speech. However, in a follow-up study, McCrea and Morris (2007a) found the reverse pattern, with longer VOTs in trained singers compared to untrained singers during speaking, but shorter VOTs during singing. In a third study from the same group, no differences were found between trained and untrained singers (McCrea & Morris, 2007b). Interestingly, singing ability has been found to predict speech imitation abilities in a nonnative or an unknown language (Christiner & Reiterer, 2013; Coumel et al., 2019). In summary, available evidence is inconclusive in terms of the relation between singing and articulation. One cannot discard the possibility that singing, because it often compromises intelligibility in lieu of musical phrasing, especially as pitch rises, may not have a beneficial impact on speech production. However, the data are currently too sparse to warrant this conclusion.

The hypothesis that singing could influence speaking is inconsistent with the task-dependent model (TDM; Bunton, 2008; Weismer, 2006; Ziegler, 2002), a linguistically oriented account of speech production, which proposes that the neural system that controls speech production is dedicated and specialized. According to the TDM, other actions involving the speech apparatus such as laughing and singing are controlled by distinct motor control systems. This account therefore predicts no learning transfer from singing to speaking. In line with this account, and despite similarities between singing and speaking, there are some important differences between these two behaviors, including vocal intensity, consonant–vowel ratio, and intelligibility. While speech strives to be most intelligible, singing often sacrifices intelligibility for aesthetic/melodic purposes (Collister & Huron, 2008; Deme, 2014; Gregg & Scherer, 2006; Story, 2004), as well as to reach certain notes. Another notable difference between speaking and singing concerns coarticulation. While pervasive in speech, coarticulation is reduced in singing, which can be detrimental to intelligibility (Deme, 2014). The TDM stipulates that the lack of shared neural resources prevents nonspeech activities from transferring to speech (Maas, 2017). The TDM thus predicts no articulation benefits for singers. Partly consistent with this notion, in a previous study from our group, we found only limited evidence of a positive impact of singing on vowel articulation and speech rate in a standardized passage reading task (Marczyk et al., 2022). Specifically, singing practice was associated with the size of vowel space in female speakers but not with vowel clarity in either female or male speakers. It is possible, however, that different types of analyses, especially those focusing on intelligibility rather than acoustics, or different communication contexts (i.e., more difficult task) could yield different results. The scarcity of data on the subject does not warrant strong conclusion regarding a potentially beneficial impact of singing on speech production, in terms of speaking rate or accuracy. An additional knowledge gap concerns the relationship between speaking rate and accuracy. Speech motor actions are performed remarkably quickly, yet they require a high degree of precision, meaning that speed and accuracy could be in conflict during speech production, especially in challenging contexts. Fitts' law (Fitts & Peterson, 1964) refers to the observation that the accuracy of spatially constrained, target-directed movements diminishes when speed becomes excessive. While speed–accuracy trade-offs (SATs) have been shown in multiple motor behavior including walking, manual pointing, and reaching (e.g., Dean et al., 2007; Drury & Woolley, 1995), evidence is limited for speech production. Kuberski and Gafos (2021) have shown evidence of a SAT in tongue movements during a simple syllable production task. Similarly, Lammert et al. (2018) have shown evidence of SAT during speech production, though with significant interspeaker variability. While the reason for this variability is currently unknown, it is possible that singers learn to maintain accuracy while speaking fast, which could suggest a decrease in this relationship in this population; this, however, has not been investigated.

The aim of this study was to examine different components of speech production in younger and older adults with or without amateur singing experience using a battery of tests that included voice production tasks, a standardized passage reading, and a maximal performance task (DDK rates task). The maximal performance task is needed to reveal potential effects of singing that would not be apparent in nonchallenging speaking contexts, such as reading a passage. To examine the effect of speaking rate, we compared the DDK task when performed at a natural rhythm and when performed as fast as possible. To gain new insights about the contexts that may affect performance the most in older talkers, we used words and nonwords manipulated in terms of their phonological complexity and spoken frequency, two factors that affect speech production performance (Indefrey & Levelt, 1999; Levelt, 1999; Levelt et al., 1999). Moreover, there is evidence suggesting that phonological processing during speech production could be impaired in aging (Burke, 1999). Importantly, singers in this study were compared to active controls, that is, to people that were cognitively active to rule out potential unspecific effects associated with singing. Our first hypothesis was that older adults would be slower, more variable, and less accurate than younger adults, in the challenging conditions (DDK) but not the simpler task (reading), and that their voice quality and MPT would be worse. We also expected to find more conflict between accuracy and speaking rate in the DDK task in older adults, measured as a steeper SAT with age. The second hypothesis was that these age effects would be more limited in singers, reflecting a protective effect of singing on voice and speech production, and consistent with the differential preservation hypothesis and with the IM of Speech Motor Control.

Method

Participants

The participants were 78 healthy adults (M_{age} = 58.35 ± 18; 20–88 years, 44 women and 34 men) recruited through e-mails, posters, Facebook posts, Facebook ads, and flyers distributed at Université Laval, in the general community, and to choirs and music harmonies in the Québec City area as part of the PICCOLO project (from the French "Projet de recherche sur les effets de la **Pra**tique d'un **I**nstrument ou du **C**hant sur la **CO**gnition, le **L**angage et l'**O**rganisation cérébrale"). The study was approved by the Comité d'éthique de la recherche sectoriel en neurosciences et santé mentale, Institut Universitaire en Santé Mentale de Québec (#2019–1733). All participants provided informed consent. The general inclusion criteria were to be right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971); native speakers of Québec French; to have normal or corrected-to-normal vision; no self-reported speech, voice, or respiratory disorder; and no diagnosed language, hearing, or psychological disorder and no neurological or neurodegenerative disorder. Participants' depression symptoms were assessed using the 15-item version of the Geriatric Depression Scale (GDS; Yesavage et al., 1982). No participant exhibited signs of major depression. The GDS was not used as exclusion criteria. General cognitive functioning was assessed using the Montréal Cognitive Assessment (MoCA; Nasreddine et al., 2005). One singer (67 years) was excluded from the study after recruitment due to the diagnosis of a respiratory disorder, leading to a final sample of 78.

The final sample was divided into two groups: 38 amateur singers (M_{age} = 56.56 ± 18.68; 20–87 years, 24 women and 14 men) and 40 nonmusician controls (M_{age} = 61.41 ± 16.67; 23–88 years, 20 women and 20 men) involved in cognitive–motor activities (active control group; see Table 1). To be included, participants had to practice their activity (musical or cognitive–motor) for at least 5 years at the amateur level (at least 3 hr/week). Professional singers were excluded. Singers could not practice other musical activities (e.g., instrument playing, dancing, figure skating, artistic gymnastic) or cognitive–motor activities for more than half of the time spent singing each week, with a maximum of less than 3 hr weekly over the past 5 years. Participants from the control group could not be involved in any musical activities for more than half of the time spent practicing their cognitive–motor activity each week, with a maximum of less than 3 hr weekly over the past 5 years. Cognitive–motor activities performed by the control group included golf, knitting, billiards, yoga, curling, strategy and precision video games, pétanque, bowling, tai chi, and sewing. Some participants practiced more than one activity. Though the control group is more diverse in the activity practiced than the singers, everyone in this group was active but practiced only activities that are not musical, meaning that any group differences that are found can be associated with the musical component of singing rather than its more general cognitive or fine motor components. This is an important test to contribute to identifying the "active ingredients," if any, that drive potential musicians' advantage. Individual singers' characteristics are provided in Supplemental Material S1.

To ensure that the groups were comparable, we ran a series of *t* tests to compare them in terms of biological sex, age, education, language experience, general cognitive functioning (MoCA), depression symptoms (GDS), self-reported physical health, dementia risk factor (the detail of this score, which is based on Livingston et al. [2020], is

Table 1. Description of the participants

	Singers *N* = 38 (14 men and 24 women)				Controls *N* = 40 (20 men and 20 women)				*t* test	
Characteristic	***M***	***SD***	**Min**	**Max**	***M***	***SD***	**Min**	**Max**	***t***	***p***
Age	55.80	19.07	20.00	87.00	61.03	16.60	23.00	88.00	1.29	.20
Education (years)[a]	14.80	2.21	11.00	18.00	15.08	2.69	10.00	23.00	–0.50	.62
GDS[b] (/15)	0.95	1.57	0.00	7.00	0.92	1.55	0.00	7.00	0.08	.93
MoCA[c] (/30)	27.42	1.60	25.00	30.00	28.00	1.69	24.00	30.00	–1.54	.13
nLNG score[d]	0.91	0.18	0.53	1.59	0.93	0.21	0.53	1.38	–0.43	.67
Group activities[e]	1.35	2.97	0.00	15.00	1.52	2.44	0.00	10.50	–0.29	.77
Social activities[f]	4.03	3.52	0.00	12.00	3.56	2.46	0.00	8.75	0.69	.49
Self-reported health[g]	5.21	0.85	3.00	7.00	5.24	1.10	3.00	7.00	–0.14	.89
Risk of dementia[h]	9.56	6.55	0.00	28.39	9.22	7.37	0.00	29.82	0.22	.83
Right-ear PTA[i]	19.04	15.05	–4.17	59.17	19.45	13.13	–0.83	54.17	–0.13	.90
Left-ear PTA[i]	19.46	15.37	–3.33	70.83	19.61	13.88	0.00	53.33	–0.04	.96
Better-ear PTA[j]	16.71	13.28	–4.17	50.00	17.57	12.84	–0.83	53.33	–0.29	.77
Interaural difference[k]	–0.42	8.30	–24.17	34.17	–0.15	5.10	–10.83	10.00	–0.17	.87
Age of onset[l]	25.38	18.78	5.00	62.00	25.32	18.30	3.00	69.00	0.01	.99
Experience (years)[m]	26.04	17.05	8.00	80.00	28.23	15.89	5.08	72.00	–0.59	.56
Experience (ratio)[n]	0.48	0.24	0.11	0.92	0.47	0.21	0.08	0.83	0.25	.80
Practice experience[o]	0.28	0.44	0.02	2.49	0.18	0.19	0.02	0.71	1.34	.19
Intensity of practice[p]	9.81	8.30	1.00	40.00	9.88	8.26	1.38	45.60	–0.04	.97

Note. *N* = number of participants per group; GDS = Geriatric Depression Scale; MoCA = Montréal Cognitive Assessment; PTA = pure-tone average; nLNG score = normalized language score; CEGEP = Collège d'enseignement general et professionnel; DRF = dementia risk factor; AO = age of onset;. AAr = ratio of practice.

[a]Number of years of education standardized: elementary = 6; high school = 11; CEGEP (general) = 13; CEGEP (technique) = 14; undergraduate = 16; master = 18 (includes medical doctors); PhD = 21; Medical doctors with specialization = 23. [b]The GDS includes 15 yes/no questions. Each "negative" answer is worth 1 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 1 point, whereas a "yes" answer is worth no point. Participants with scores between 0 and 3 are considered normal, whereas scores between 4 and 10 indicate a light depression, and scores between 10 and 15 indicate a severe depression. No participant scored above 7. [c]Higher scores indicate better cognitive functions. [d]The combined self-assessed capacity in each known language divided by the average score across all participants. The higher the number, the more the language capacity. [e]Group activities = number of hours of organized group activities per week (e.g., bingo, book clubs). [f]Social activities = number of hours of informal social activities per week (e.g., family reunions or visit to a friend). [g]Self-reported health = self-reported physical health status on a scale of 0–7 (0 being lowest physical health level). [h]Risk of dementia = to control for the risk of dementia among our sample, we developed a DRF based on the 2020 *Lancet* Commission for dementia prevention, intervention, and care (Livingston et al., 2020). Livingston et al. (2020) have identified 12 potentially modifiable risk factors for dementia that could reduce dementia prevalence by 40% if eliminated. Nine of these factors were measured in our sample, corresponding to a maximum risk reduction of 31%. These included low education, hearing loss, traumatic brain injury, depression, social isolation, Type 2 diabetes, physical inactivity, alcohol consumption, and obesity. The details of the calculation are provided in Supplemental Material S2. [i]Left- and right-ear PTA = PTA thresholds measured in decibels at 0.5, 1, 2, 3, 4, and 6 kHz for each ear. [j]Better ear PTA = PTA thresholds at 0.5, 1, 2, 3, 4, and 6 kHz for the better ear measured in decibels (dB). [k]Interaural difference = difference between the left- and right-ear PTAs. [l]Age of onset = age at which singers or control participants began to practice their activity. [m]Experience (years) = total years of active practice of signing or of a cognitive–motor activity. [n]Experience (ratio) = ratio of years of experience and age. [o]The practice experience score combines the AO and the AAr of the main activity. It consists of the multiplicative inverse of the subtraction between the age of onset and the product of the age of onset and the ratio of practice (1/(AO – (AO – AAr))). A higher score indicates that a person started practicing early and has practiced for a large proportion of his life. [p]Intensity of practice = mean number of hours of singing or practicing a cognitive–motor activity each week over the past 5 years.

provided in Supplemental Material S2), and pure-tone hearing. We also compared the groups in terms of the number of years of active practice of their activity (singing or cognitive–motor activities); ratio of practice (ratio between years of practice and age); intensity of activity over the past 5 years (calculated as the mean number of hours spent singing or practicing a cognitive–motor activity each week); and age of onset and overall experience, which consists of the multiplicative inverse of the subtraction between the age of onset and the product of the age of onset and the ratio of practice (1/(AO − (AO − AAr))). A higher score indicates that a person started practicing early and has practiced for a large proportion of their life. Finally, we also compared the groups for their amount of time invested in social activities, either formal or informal. Table 1 provides a summary of participants' characteristics.

Note that the PICCOLO project also includes a group of instrumentalists. This group was not analyzed here because this study focuses on speech motor control and there is no reason to believe that instrumentalists would be any different from controls in that regard.

Procedure

The experiment took place at the Speech and Hearing Neuroscience Laboratory in Québec City, Canada. The visit had a duration of approximately 3 hr and included several breaks. It included an audiometric assessment, a cognitive assessment, language measurements (picture naming, verbal fluency), speech perception in noise, and magnetic resonance imaging measurements. These measures are not reported here because the focus on this article is on motor control. As such, we analyzed a DDK task, a passage reading, and voice production tasks.

Audiometric Evaluation

Pure-tone thresholds in dB HL were measured with a calibrated clinical audiometer (AC40; Interacoustics) connected to TDH-39 headphones in a sound-treated room. The following frequencies were assessed in each ear separately: 0.5, 1, 2, 3, 4, and 6 kHz. These measurements were used to compute a better ear (i.e., lowest thresholds between the two ears) pure-tone average (PTA). The average better ear PTA was 17.50 dB HL. The groups did not differ in better ear PTA (p = .88), or interaural difference (p = .85; see Table 1). Because normal age-related hearing impairment in adults can affect speech production performance, hearing (better ear average across all frequencies) was included as a covariate in all statistical analyses.

Speech and Voice Recordings

All recordings were performed under identical conditions in a double-walled sound-attenuated room. Participants were seated in a comfortable armchair. Speech samples were recorded using a high-quality head-worn microphone (Microflex Beta 53) connected to a Quartet USB audio interface (Apogee Electronics) that fed into an iMac computer. The recordings were made using the Sound Studio 4 software (Felt Tip Inc.) at a sampling signal of 48 kHz and 24 bits of quantization. All data were analyzed with Praat (Boersma & Weenink, 2011) and R (R Core Team, 2019).

Voice production. Two voice production tasks were used: a sustained vowel production task and a maximal phonation task. Participants were given three trials for each task.

First, participants were asked to produce a sustained vowel /a/ at comfortable frequency and amplitude levels, that is, under "normal talking voice" condition for 5 s. The participants produced the vowel at a "comfortable everyday pitch," that is, a pitch level not associated with subjective muscular tension or discomfort during phonation. All vowels were produced as steadily as possible, with no amplitude or frequency variation. Original voice samples were visually inspected to identify passages with artifacts such as extraneous noise, laughter, or coughing. These passages were excluded from the analysis. The analysis was then performed in two steps. First, the vowels were automatically segmented. A Praat script was applied to automatically extract three measures of voice quality: relative jitter (%), shimmer (dB), and harmonics-to-noise ratio (HNR) in dB (Feinberg, 2021).

For the MPT task, participants were asked to hold a vowel /a/ for as long as possible at a comfortable level. All vowels were produced as steadily as possible, with no amplitude or frequency variation. The resulting voice samples were inspected to identify passages with artifacts such as extraneous noise, laughter, or coughing. These passages were excluded from the analysis. Next, the vowels were automatically segmented, and a script was applied to extract the duration of each vowel.

Passage reading. To obtain an estimate of speaking rate in reading, participants were requested to read a 2-min passage, *La bise et le soleil* (International Phonetic Association, 1999), which is a standardized reading passage in French of about 100 words commonly used in phonetic experiments to study normal or pathological speech (Roy et al., 2012). They first read the passage silently, and then they read it aloud in a relatively natural way (i.e., no acting) at their habitual pitch and amplitude levels. For each participant, articulatory rate, expressed in syllables per second, was measured for sequences of at least four syllables spoken without silent pauses (to exclude single-word sequences). The passage is included in Supplemental Material S3.

DDK test. A DDK task was used to evaluate articulation performance. DDK is a maximal performance task that consists of repeating single syllables (e.g., /pa/), or sequences of syllables (e.g., /pa ta/, /pa ta ka/), as quickly and as accurately as possible for 5 s, while trying to minimize articulation errors. The syllabic sequences were created through three manipulations: a frequency manipulation, a lexical manipulation (words vs. nonwords), and a phonological complexity manipulation ($2 \times 2 \times 2 = 8$ experimental conditions). The frequency manipulation consisted of comparing stimuli composed of syllables with low-spoken frequency measured from the SyllabO+ database (Bédard et al., 2016). The average frequency for the low-frequency condition was 79.5; it was 93.5 for the high-frequency condition. The phonological complexity manipulation consisted of comparing stimuli composed of simple CV (C = consonant; V = vowel) syllables containing only one consonant and one vowel (CV; e.g., /bi-jou/ "jewel") to stimuli composed of complex syllables (CCV, CVC, or CCVC) containing two or three consonants and one vowel (e.g., /plas-tique/ "plastic"). Each stimulus (word or nonword) was formed of two syllables. Inside a word or nonword, the vowels did not repeat. If there was an articulatory movement, it was from front to back. This was done to make the stimuli challenging and comparable, especially across type (words and nonwords).

The DDK task was first performed at a natural pace, to establish a baseline speech rate, and then twice at maximal pace, for a total of three repetitions per stimulus (one natural and two fast), each lasting 5 s. Participants completed a total of 24 trials (approximately 12 min). The list of stimuli is provided in Supplemental Material S4. At the beginning of each trial, instructions were provided on the screen. To ensure that stimuli were registered properly, they were presented both visually, on the screen, and through a loudspeaker. If the stimulus was misunderstood, the participant was asked to repeat the trial.

The DDK recordings were transcribed manually. The recordings were then automatically aligned and segmented using the EasyAlign Praat plugin (http://latlcui.unige.ch/phonetique/easyalign.php). A macrosegmentation at the utterance level was first performed to identify words and syllables, which was followed by a grapheme-to-phoneme conversion and a final phone segmentation. The automated alignment was corrected manually when needed. Custom semi-automatic Praat scripts were developed to segment participants' responses and identify each syllable nucleus, determined by the detection of the maximum amplitude in the syllable interval, on a new Praat tier. Next, vocalic peak intensity was extracted and used to calculate the articulation rate (number of syllables per second) and articulation rate stability. The recordings were then listened, and articulation and phonation mistakes were noted. A syllable was considered failed when, compared with the target, it presented an elision (suppression), addition, inversion, or substitution of phonemes. Three percent of all trials were not analyzed because the participant appeared to have misunderstood the target and produced the wrong syllables throughout the series. These were considered perceptual rather than articulation errors. Forty-three percent of the assessments were verified by a second judge (A. A.) as part of the training process. The remaining transcriptions were assessed by one judge (L. G.). The average interjudge agreement was 97.48%. This agreement was calculated for each syllable.

Analyses of the DDK data focused on accuracy, articulation rate, and articulation rate stability. A word or nonword was considered accurate if it included all the expected sounds and no additional sound and if all sounds were deemed intelligible by the rater. Peak vocalic intensity was used to calculate the articulation rate and articulation rate stability. Articulation rate was defined as the number of syllables produced correctly per second without considering silent pause intervals. Articulation rate stability was operationalized as the normalized vocalic Pairwise Variability Index (nPVI), which measures articulatory rhythm based on 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. In addition, we examined the relationship between speed and accuracy (SAT).

Statistical Analyses

All data were analyzed using R studio (Version 4.0.3; R Core R Core Team, 2019). First, the data were inspected using density plots and by calculating kurtosis and skewness to ensure that the distributions were normally or relatively normally distributed (using the −1 and 1 interval as the cutoff). Next, data were analyzed using a linear mixed model (LMM) approach. In all analyses, the between-subject–fixed factors were Group (singers, controls) and Age (continuous). There were a total of eight dependent variables: accuracy (DDK), speaking rate (DDK), speaking rate variability (nPVI), reading rate (passage reading), maximal phonation time (MPT; maximal phonation task), jitter, shimmer, and HNR (sustained vowel production). To control for potentially confounding age-related factors, GDS, MoCA, dementia risk factor, sex, better ear PTA, and a normalized language score (nLNG score) were included as covariates. Each LMM was fit using the buildmer package (Version 1.9; Voeten, 2020) and the lme4 package (Version 1.1.23; Bates et al., 2015). The buildmer package starts with the full model specified and determines the order of the fixed and random effects in the model that best explain the variance (Barr, 2013). The full model for the voice and passage reading analysis was: Group × Age + Sex + BE + MoCA + GDS + RD + nLNG score + (1 | Participant) + (1 | Group). For the DDK analyses, the full model was: Group × Age + Type × Age + Type × Group + Type × Age × Group + Speed × Age + Speed × Group + Speed × Age × Group + Complexity × Age + Complexity × Group + Complexity × Age × Group + Frequency × Age + Frequency × Group + Frequency × Age × Group + Sex + BE + MoCA + GDS + RD + nLNG score + (1 | Participant) + (1 | Group). The effects were systematically reduced with backward stepwise elimination based on likelihood ratio tests to arrive at the final converging model with the best fit. LMM results were extracted using the sjPlot packages for R (Lüdecke, 2021) for reporting model results (marginal means). The normality of the residuals of each model was inspected using Q–Q plots.

In addition to the main analyses (LMMs), SATs were also examined to determine if the relationship between accuracy and articulation rate was moderated by group and age. Interactions were probed using the Interactions and JTools packages for R and the Johnson–Neyman interval approach.

Results

For the sake of clarity and concision, given the large number of dependent variables, we focus on the effects that relate to group and age for each dependent variable, as well as the main effects of the experimental manipulations (for the DDK task: stimulus type, stimulus complexity, stimulus frequency, speed). However, the full results are reported in Tables 2 (phonation), 3 (passage reading), and 4 (DDK), and additional illustrations are provided in Supplemental Materials S5 (phonation), S6 (passage reading), and S7–S9 (DDK).

MPT

The mean MPT (marginal means) was 14.5 s (SE = 0.791) for the controls and 14.1 s (SE = 0.834) for the singers. The Q–Q plot revealed that the residuals followed a normal distribution. The main LMM analyses revealed only a main effect of sex, with longer MPT for men regardless of their age and group (men: M = 15.7, SE = 0.995; women: M = 12.9, SE = 0.729; see Supplemental Material S5). There was no difference between singers and nonsingers. The results are detailed in Table 2A.

Voice Quality

The mean relative jitter (marginal means) was 0.0046% (SE = 0.0001) for the controls and 0.004% (SE = 0.0001) for the singers. The main LMM analyses revealed only a main effect of sex, with slightly higher jitter values for men regardless of their age and group (men: M = 0.0047, SE = 0.000151; women: M = 0.00407, SE = 0.000131). There was no difference between singers and nonsingers. The results are detailed in Table 2B and illustrated in Supplemental Material S5.

The mean shimmer (marginal means) was 0.0323 dB (SE = 0.0011) for the controls and 0.0305 dB (SE = 0.0011) for the singers. The Q–Q plot revealed that the residuals followed a relatively normal distribution. The main LMM analyses revealed only a main effect of sex, with slightly higher shimmer values for men regardless of their age and group (men: M = 0.0353, SE = 0.0012; women: M = 0.0275, SE = 0.001). There was no difference between singers and nonsingers. The results are detailed in Table 2C and illustrated in Supplemental Material S5.

The mean HNR (marginal means) was 21.1 (SE = 0.301) for the controls and 22.2 (SE = 0.302) for the singers. The Q–Q plot revealed that the residuals followed a relatively normal distribution. The main LMM analyses revealed only a main effect of sex, with slightly lower HNR values for men regardless of their age and group (men: M = 20.3, SE = 0.521; women: M = 23, SE = 0.449). There was no difference between singers and nonsingers. The results are detailed in Table 2D and illustrated in Supplemental Material S5.

Passage Reading

The average articulation rate (marginal means) was 5.02 syllables per second (SE = 0.07) for the controls and 4.98 syllables per second (SE = 0.078) for the singers. The Q–Q plot revealed that the residuals followed a normal distribution. The main LMM analyses revealed a negative age effect, with lower rate associated with older age (see Figure 1). There were also significant effects of the nLNG score and the MoCA score: Higher rate was associated with higher MoCA and higher language scores (see Supplemental Material S6). There was no difference between singers and nonsingers. The results are detailed in Table 3.

DDK: SAT

First, we examined the SAT and whether it was affected by group and by age. The analysis revealed a negative relationship between accuracy and rate for all ages, which was steeper in the youngest talkers (see Figure 2).

Table 2. Result for the voice production tasks.

	A. MPT					B. Jitter (%)					C. Shimmer (dB)					D. HNR				
Predictors	**β**	***b***	***SE***	**CI**	***p***	**β**	***b***	***SE***	**CI**	***p***	**β**	***b***	***SE***	**CI**	***p***	**β**	***b***	***SE***	**CI**	***p***
(Intercept)	0.17	15.7	0.88	13.96 to 17.45	**< .001**	0.1688	0.0047	0.0002	0.0043 to 0.0051	**< .001**	0.32	0.31	0.01	0.29 to 0.33	**< .001**	–0.46	20.27	0.52	19.25 to 21.30	**< .001**
Sex [Female]	0.22	–2.8	1.15	–5.06 to –0.54	**.015**	–0.2844	–0.0005	0.0003	–0.0010 to –0.0000	**.041**	–0.53	–0.06	0.01	–0.09 to –0.03	**< .001**	0.79	2.77	0.69	1.42 to 4.13	**< .001**
Random effects																				
σ^2	4.69															2.69				
τ_{00}	21.80_{SID}															7.78_{SID}				
ICC	0.82															0.74				
N	74_{SID}					0										75_{SID}				
Observations	218					214					213					225				
Marginal R^2/ Conditional R^2	.067 / .835					.020 / .015					.068 / .064					.153 / .782				
AIC	1,157					–2,081					–359					1,037				

Note. Bold text indicates significance. MPT = maximum phonation time; HNR = harmonics-to-noise ratio; b = unstandardized estimate, β = standardized estimate; *SE* = standard error of the standardized estimate; CI = confidence interval of the standardized estimate; ICC = intraclass correlation coefficient; AIC = Akaike information criterion.

Table 3. Result for the passage reading (rate).

Predictors	β	*b*	*SE*	CI	*p*
(Intercept)	0.000	3.15	1.18	0.79 to 5.50	**.01**
Age	−0.46	−0.02	0	−0.02 to −0.01	**< .001**
MoCA	0.23	0.08	0.04	0.01 to 0.16	**.027**
nLNG score	0.18	0.56	0.28	0.00 to 1.11	**.049**
Observations	78				
R^2 / R^2 adjusted	.394 / .369				
AIC	112.292				

Note. Bold text indicates significance. β = standardized estimate; *b* = unstandardized estimate, *SE* = standard error of the standardized estimate; CI = confidence interval of the standardized estimate; MoCA = Montréal Cognitive Assessment; nLNG score = normalized language score; AIC = Akaike information criterion.

The Johnson–Neyman interval approach was used to probe this interaction. For the controls, this negative relationship was significant at all ages (slope of the relationship when age is 40.39 years: $b = -10.41$, $SE = 0.67$, $p \leq .001$; when age is 58.29 years: $b = -8.61$, $SE = 0.59$, $p \leq .001$; when age is 76.13 years: $b = -6.83$, $SE = 0.93$, $p \leq .001$). The pattern was the same for the singers (slope of the relationship when age is 40.39 years: $b = -9.72$, $SE = 0.83$, $p \leq .001$; when age is 58.29 years: $b = -8.53$, $SE = 0.58$, $p \leq .001$; when age is 76.13 years: $b = -7.35$, $SE = 0.81$, $p \leq .001$). Because of the significant relationship between accuracy and rate, rate was included as a covariate in the analysis of accuracy and accuracy was included as a covariate in the analysis of rate.

DDK: Accuracy

The overall accuracy across all conditions (marginal means) was 69% ($SE = 1.31$) for the controls and 72.7% (SE =1.37) for the singers. The Q–Q plot revealed that the residuals followed a normal distribution. The main LMM analyses revealed that stimulus type, frequency, and speed affected accuracy. Accuracy was lower for nonwords compared to words, lower for rare compared to frequent stimuli, and lower for the fast compared to the normal rate condition (see Supplemental Material S7 and Figure 3). The effect of rate was significant, with accuracy decreasing with increased speaking rate. Finally, women were significantly more accurate compared to men (see Supplemental Material S7 and Figure 4).

While there was no main effect of group, the analysis revealed several two-way interactions: Age × Phonological Complexity, Age × Speed, Group × Phonological Complexity, and Group × Speed. The interaction between Age and Phonological Complexity revealed the expected negative (detrimental) association between age and accuracy in the complex condition ($b = -0.28$, $SE = 0.06$, $p \leq .001$) with no association in the simple condition ($b = 0.02$, $SE = 0.06$, $p = .67$; see Figure 3A). The interaction between Age and Speed on accuracy revealed a positive association between age and accuracy in the fast condition ($b = 0.22$, $SE = 0.06$, $p \leq .0005$) and no relationship in the normal condition ($b = 0.02$, $SE = 0.06$, $p = .67$; see Figure 3B). The interaction between Group and Phonological Complexity on accuracy revealed a stronger advantage for singers in the complex condition (estimated marginal mean [EMM] = −6.03, $SE = 2.06$, $p = .0043$, $d = -0.439$), compared to the simple condition (EMM = −1.49, $SE = 2.06$, $p = .49$, $d = -0.11$; see Figure 3C). The interaction between Group and Speed on accuracy revealed an advantage for singers in the fast condition (EMM = −5.74, $SE = 2.06$, $p = .006$, $d = -0.419$) but not in the normal condition (EMM = −1.78, $SE = 2.06$, $p = .39$, $d = -0.129$; see Figure 3D). The results are detailed in Table 4A.

DDK: Articulation Rate

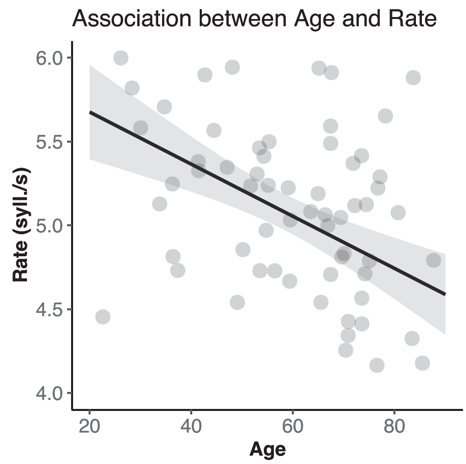
The overall articulation rate across all conditions (marginal means) was 4.16 syllables per second ($SE = 0.028$) for the controls and 4.18 syllables per second ($SE = 0.03$) for the singers. In the normal condition, the average rate across groups was 3.06 ($SE = 0.035$); in the fast condition, it was 5.28 ($SE = 0.035$). The Q–Q plot revealed that the residuals followed a relatively normal distribution. The main LMM analyses revealed that stimulus type, complexity, frequency, and speed affected articulation rate: Rate was lower for nonwords compared to words, lower for complex compared to simple stimuli, lower for rare compared to frequent stimuli, and lower for the normal compared to the fast rate condition. These results are illustrated in Supplemental Material S8. Several participant-related covariates also affected rate: accuracy (higher accuracy associated with lower speaking rate), MoCA (higher MoCA associated with higher speaking rate), GDS (higher GDS score associated with lower speaking rate), sex (men > women), language score (higher score associated with higher rate), and dementia

Table 4. Results for the DDK task.

	A. Accuracy					B. Rate					C. nPVI				
Predictors	**β**	***b***	***SE***	**CI**	***p***	**β**	***b***	***SE***	**CI**	***p***	**β**	***b***	***SE***	**CI**	***p***
(Intercept)	0.91	101.55	4.49	92.75 to 110.36	**< .001**	−0.4	2.39	0.51	1.39 to 3.39	**< .001**	0.36	25.78	24.54	−22.37 to 73.93	.294
Speed [F]	−1.21	−41.97	3.48	−48.80 to −35.15	**< .001**	1.43	3.08	0.15	2.78 to 3.37	**< .001**	−1.28	−67.63	3.49	−74.48 to −60.79	**< .001**
Complexity [C]	−0.73	−0.51	2.73	−5.86 to 4.84	.853	−0.58	−0.87	0.04	−0.96 to −0.79	**< .001**	0.25	7.27	1.02	5.26 to 9.27	**< .001**
Frequency [R]	−0.37	−9.35	0.79	−10.91 to −7.79	**< .001**	−0.21	−0.31	0.04	−0.39 to −0.23	**< .001**	−0.09	−10.37	3.49	−17.22 to −3.53	**.003**
Type [NW]	0.11	2.65	0.81	1.07 to 4.23	**.001**	0.22	0.33	0.04	0.25 to 0.41	**< .001**	0.4	11.72	1.02	9.72 to 13.73	**< .001**
Group [S]	−0.02	−0.49	2.2	−4.82 to 3.83	.824	−0.03	−0.05	0.06	−0.17 to 0.06	.377					
Age	0.02	0.03	0.06	−0.10 to 0.15	.673	0.03	0	0	−0.00 to 0.01	.245	−0.28	−0.46	0.08	−0.62 to −0.29	**< .001**
Speed [F] × Group [S]	0.16	3.97	1.58	0.87 to 7.06	**.012**	0.1	0.16	0.08	−0.00 to 0.31	.05					
Complexity [C] × Group [S]	0.18	4.53	1.58	1.44 to 7.63	**.004**										
Complexity[C] × Age	−0.22	−0.31	0.04	−0.39 to −0.22	**< .001**										
Speed [F] × Age	0.14	0.2	0.05	0.11 to 0.29	**< .001**	−0.19	−0.02	0	−0.02 to −0.01	**< .001**	0.32	0.52	0.06	0.41 to 0.63	**< .001**
Frequency [R] × Age											0.08	0.14	0.06	0.02 to 0.25	**.018**
Rate	−0.13	−2.14	0.64	−3.39 to −0.89	**.001**										
Accuracy						−0.13	−0.01	0	−0.01 to −0.01	**< .001**					
Sex [Female]	0.21	5.22	1.92	1.46 to 8.99	**.007**	−0.08	−0.12	0.04	−0.20 to −0.03	**.007**					
MoCA						0.05	0.04	0.01	0.01 to 0.07	**.003**	0.14	2.43	0.8	0.86 to 3.99	**.002**
nLNG score						0.04	0.31	0.11	0.11 to 0.52	**.003**					
RD						0.05	0.01	0	0.01 to 0.02	**< .001**					
GDS						−0.03	-0.03	0.01	−0.06 to −0.00	**.034**					
Random effects															
σ^2	188.25										322.63				
τ_{00}	55.55 $_{SID}$										86.69$_{SID}$				
ICC	0.23										0.21				
N	78 $_{SID}$										78$_{SID}$				
Observations	1,240					1,240					1,239				
Marginal R^2/ Conditional R^2	.615 / .703					.788 / .785					.525 / .626				
AIC	10,159.636					2,629.951					10,816.134				

Note. Bold text indicates significance. DDK = diadochokinetic rates task; nPVI = normalized vocalic Pairwise Variability Index; *b* = unstandardized estimate, β = standardized estimate; *SE* = standard error of the standardized estimate; CI = confidence interval of the standardized estimate; F = fast; C = complex; R = rare; NW = nonword; S = singers; MoCA = Montréal Cognitive Assessment; nLNG score = normalized language score; RD = risk of dementia; GDS = Geriatric Depression Scale; ICC = intraclass correlation coefficient; AIC = Akaike information criterion.

Figure 1. Estimated marginal means for reading rate. Each dot represents one participant. The shade around the regression line represents the 95% confidence interval of the regression line. syll. = syllables.



risk factor (higher risk associated with higher rate). These results are illustrated in Supplemental Material S8.

While there was no main effect of group, the analyses revealed an interaction between Age and Speed: In the fast condition, there was a negative association between age and rate ($b = -0.0129$, $SE = 0.002$, $p \leq .001$), while in the normal rate condition, there was no association ($b = 0.0047$, $SE = 0.0028$, $p = .0937$; see Figure 4A). The results are detailed in Table 4B.

DDK: Stability (nPVI)

The overall nPVI across all conditions (marginal means) was 56.5 ($SE = 1.69$) for the controls and 55.3 ($SE = 1.73$) for the singers, reflecting the high difficulty level of the task (high scores indicate high speaking variability, i.e., more temporally irregular speech). The Q–Q plot revealed that the residuals followed a relatively normal distribution. The main LMM analyses revealed that stimulus type, stimulus complexity, stimulus frequency, and speed affected nPVI: nPVI was higher for words compared to nonwords, higher for complex compared to simple stimuli, higher for frequent compared to rare stimuli, and higher for the normal compared to the fast condition. There was also an effect of MoCA (higher MoCA associated with higher speaking variability). While there was no main effect of group, the analyses revealed a main effect of age as well as interactions between Age and Speed, and Age and Frequency. Further analysis indicated that variability decreased with age in the normal condition ($b = -0.46$, $SE = 0.08$, $p \leq .001$), while it increased with age in the fast condition ($b = 0.06$; $SE = 0.08$, $p = .47$; see Figure 4B). In other words, the difference in speech rate variability between the normal and fast condition was reduced in older compared to younger adults. For frequency, the analyses revealed that variability decreased with age for the frequent syllables ($b = -0.46$, $SE = 0.08$, $p \leq .001$) as well as for the rare syllables, though at a lower rate ($b = -0.32$, $SE = 0.08$, $p \leq .001$; see Figure 4C). In other words, in older adults, the

Figure 2. Results of the speed–accuracy trade-off analysis. (A) The scatter plot displays the relationship between articulation rate and accuracy as a function of age (separated in three levels: average age, younger than the average by 1 *SD*, and older than the average by 1 *SD*) for the controls. The shade around the regression line represents the 95% confidence interval of the regression line. Each dot represents one data point. (B) The scatter plot displays the relationship between articulation rate and accuracy as a function of age for the singers. syll. = syllables.

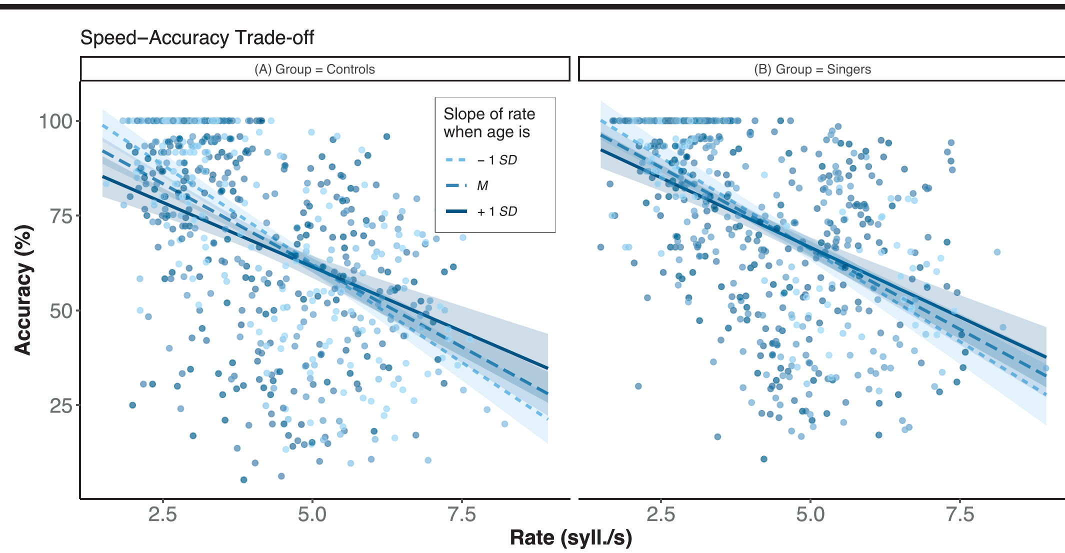
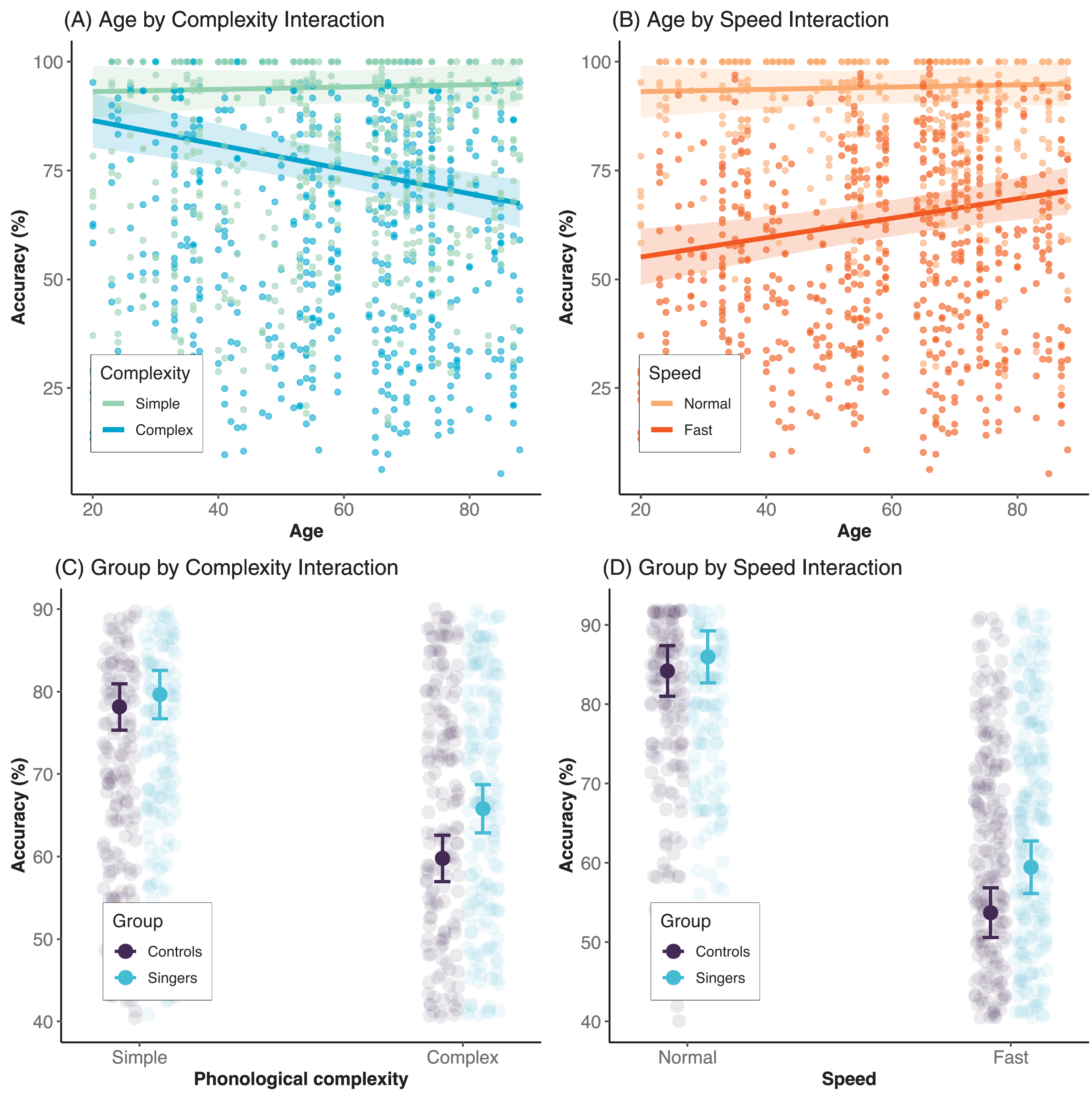


Figure 3. Estimated marginal means for accuracy. (A) The scatter plot displays the significant interaction between Age and Complexity. Each dot represents one data point. The shade around the regression line represents the 95% confidence interval of the regression line. (B) The scatter plot displays the significant interaction between Age and Speed. (C) The plots display the significant interaction between Group and Complexity. The line represents the confidence interval of the mean. (D) The plots display the significant interaction between Group and Speed.

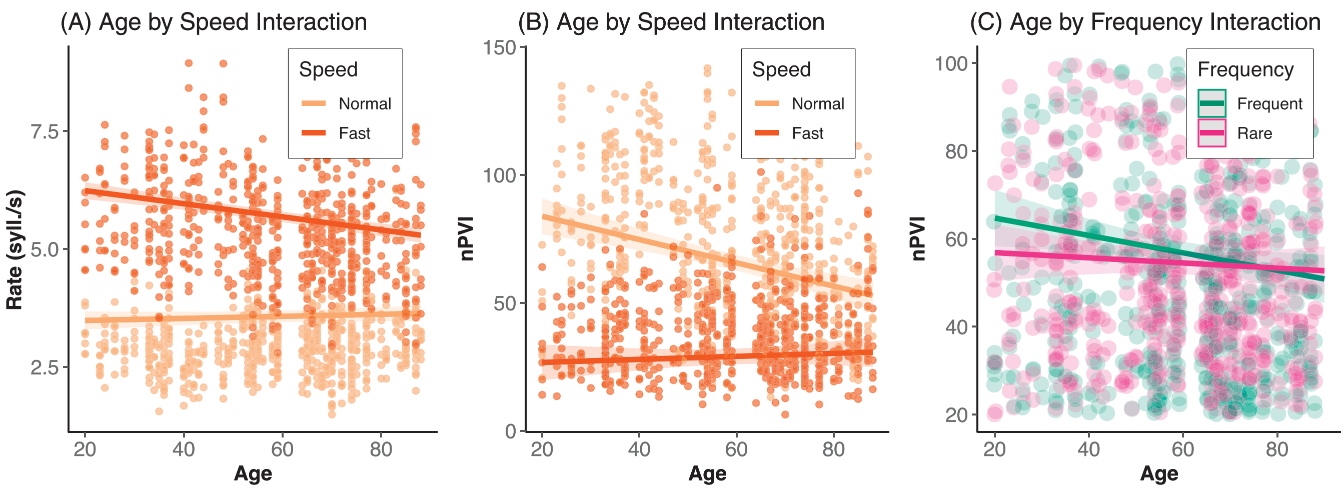


variability difference between the frequent and rare stimuli was reduced compared to younger adults. The results for nPVI are detailed in Table 4C.

Discussion

Despite the key role that verbal communication plays in social interactions throughout the entire lifes pan, several important questions remain regarding the way the speech motor system evolves with age. Because decline in language production can negatively affect self-esteem as well as the perception of others (Ryan & Johnston, 1987; Ryan et al., 1994), with potential consequences on communication-mediated activities and the extent and quality of social participation, understanding the manner and extent to which speech production evolves with age, and whether these changes are avoidable, is crucial. In this study, we tackled these questions by investigating voice and speech production in younger and older adults with or without amateur singing experience using a maximal performance approach. Within the frameworks of the

Figure 4. Results for the temporal variables (rate and nPVI). (A) The scatter plot displays the significant interaction between Speed and Age on Rate. The shade around the regression line represents the 95% confidence interval of the regression line. Each dot represents one data point. (B) The scatter plot displays the significant interaction between Speed and Age on nPVI. (C) The scatter plot displays the significant interaction between Frequency and Age on nPVI. nPVI = normalized vocalic Pairwise Variability Index; syll. = syllables.



mental exercise hypothesis (Simons et al., 2016) and the IM of speech production (Ballard et al., 2003), we hypothesized that older adults would be slower and less accurate than younger adults, especially in the fast DDK task, and that these effects would be more limited in singers compared to nonsingers, reflecting a protective effect of singing on speech production. Our results show that older age was associated with lower articulation rate and lower articulation rate stability when speaking at a fast pace, as well as reduced accuracy for the phonologically complex stimuli in the DDK task. Importantly, our results show an advantage for singers in terms of articulatory accuracy in the most challenging situations. These results are discussed below.

While our study is cross-sectional and as such not causal and can, therefore, only speculate about associations found between singing and speech performance, it nevertheless makes a strong case regarding this association, thanks to (a) a relatively large sample that allowed us to conduct a thorough and sophisticated statistical analysis (LMMs with a rigorous model selection process) that included multiple explanatory factors and covariates (this approach is in contrast with most studies of aging and singing that do not include covariates in their analyses, rendering it difficult to explain effects or lack thereof) and (b) an active control group that was well characterized; typically, in the literature, control groups are undefined and poorly characterized. Finally, another strength of the present work is the use of a modified DDK task, which allowed us to examine the impact of speech, phonological complexity, stimulus type, and frequency effects on speech performance in aging singers and nonsingers.

Age Effects

Our main hypothesis, which was partly verified, was that normal aging would be associated with differences in voice quality, MPT, and articulation accuracy and rate, especially in the challenging task (DDK), consistent with prior studies (e.g., Tremblay et al., 2018, 2019), even after controlling for hearing, education, mood, and linguistic background. The finding of reduced accuracy (DDK) and speech rate (passage and DDK) with age is suggestive of a decline in the planning and execution of speech movements, most likely resulting from brain senescence (i.e., declining motor control capacities). Though it is possible that peripheral factors, such as muscle strength, could play a part in these age differences, in a prior study we showed that age-related decline in speech production performance was only marginally related to such factors (Bilodeau-Mercure & Tremblay, 2016).

In this study, speed was the variable that most affected performance in aging. In the normal speaking rate condition, older adults performed similarly as did younger. When asked to speak as fast as they could, however, older adults were slower but more accurate. This is consistent with the notion that a slower speaking rate favors articulation quality (e.g., Ferguson & Kewley-Port, 2002; Meunier & Espesser, 2012). While our analysis of the SAT demonstrates a reduction of this well-established relationship with age, it was still very much significant in the older adults. Speaking rate in the reading task was also negatively affected by age. It appears, therefore, that slower speech may reflect a compensatory mechanism to maintain communication efficiency with declining resources, consistent with the selection–optimization–compensation model of aging, which suggests that older adults adjust their objectives and develop compensation strategies to optimize outcomes (M. M. Baltes & Carstensen, 1996; P. B. Baltes & Lindenberger, 1997; P. B. Baltes et al., 1999). Interestingly, the difference in speech rate and speech regularity between the normal and fast condition was reduced in older compared to younger adults, and so was the difference in regularity between the frequent and rare stimuli. Overall, our results suggest that speech may become more regular in aging. This could also reflect a change in strategy, whereby regularity rather than rate is favored.

In contrast to speech production (passage and DDK), there was no effect of age on the voice measures in any of the group, suggesting some preservation of vocal quality and of the ability to sustain phonation (MPT) with age in our sample, potentially reflecting the good health status of our participants. The only effects that were found were related to the sex of the participants, with female participants exhibiting relatively lower instability in the frequency and amplitude domains, as well as higher HNR, suggesting better voice quality in the women in our sample. While previous studies have not found differences in voice quality in men and women, some of those have very small samples (Teixeiraa & Fernandesa, 2014); others with larger samples have documented several differences between men and women (Santos et al., 2021). Men, however, had higher MPT, consistent with the literature (Hirano et al., 1968; Ptacek & Sander, 1963a, 1963b). In summary, in this study, age effects were more important on speech than voice production, after controlling for multiple factors including mood, hearing, and cognitive levels.

Singers' Advantage

Assuming some degree of shared cerebral control between speech production and singing, and based on the IM (Ballard et al., 2003) and on the cognitive reserve hypothesis (Stern, 2002, 2003, 2009), we predicted that amateur singers would exhibit some advantages on speech production compared to a group of cognitively active nonsingers. Specifically, we expected that age effects on speech production would be more limited in singers, reflecting a protective effect of singing. Within the framework developed by Salthouse, a benefit was defined as a Group × Age interaction, whereby the benefit would emerge, or be stronger, in older adults (Salthouse, 1990, 2006). Our results do not support this account, since no such interaction was found in any metric analyzed. We also found very limited overall group differences, meaning that most group differences were found in specific contexts (i.e., expressed as interactions between Group and Speed, or Complexity). This study, therefore, makes a unique contribution to the literature by demonstrating that, contrary to our prediction, there was only limited evidence in support of the differential preservation hypothesis; that is, the association between age and speech production was largely similar in singers and nonsingers. Hence, singing, in this study, was not associated with a difference in the rate of decline of speech production with normal aging. Our results, therefore, suggest that the differential preservation hypothesis may not be an appropriate model to explain the relationship between singing and the aging of speech production. Instead, our results suggest that the differences between singers and nonsingers are stable throughout the adult life span, consistent with Salthouse's preserved difference hypothesis—that is, the notion that the difference between singers and nonsingers is unaffected by age. This suggests that at any age, adult singers will perform significantly better than nonsingers on specific speech-related tasks, which still offer some advantage as they age.

As mentioned, we found evidence of an advantage for singers that was independent of singers' age. Specifically, articulation accuracy was better maintained in singers in challenging conditions, meaning that singers made fewer mistakes. That is to say, when asked to speak as fast as possible and when asked to produce phonologically complex utterances, singers were more accurate than controls. These findings are important, as maintaining accuracy is key to maintaining intelligibility and, in turn, communication efficiency, in older age. This result suggests extended maximal performance capacities in amateur singers perhaps resulting from the articulatory efforts required during singing. There have been relatively few studies investigating the potential impact of singing on speech production. As discussed in the Introduction, these studies have painted a relatively heterogeneous portrait of this relationship in terms of VOT (McCrea & Morris, 2005, 2007a, 2007b), timing, and intonation (F0) variability (Brown et al., 2000). One issue with previous studies was their use of simple speech tasks. In a previous study from our group for instance, we examined acoustic markers of intelligibility, specifically vowel distinctiveness, in a completely independent cohort of singers and nonsingers (Marczyk et al., 2022). Our results showed that regular amateur singing was associated with higher tongue movement range along the height dimension in female singers, independently of age, suggesting an articulatory gain. This gain, however, was not associated with increased vowel distinctiveness. In addition, a higher articulation rate was found in younger singers compared to young and older nonsingers and to older singers. In that study, a nonchallenging speech task was used, which consisted in reading a standardized passage. Intelligibility in this simple task, measured in terms of vowel distinctiveness, was not affected by aging, which could explain why we could not find differences between singers and nonsingers in terms of vowel distinctiveness.

Together, these results suggest a benefit—though limited—of singing on speech production. As we discuss in the previous section, healthy older adults have no issue with speech production in simple situations. It is when speaking occurs in more demanding situations that age-related difficulties emerge. We could not find other studies having used challenging speech production tasks to compare singers and nonsingers. Despite this rather scarce evidence, another field of research can provide relevant context against which to interpret our results. Several studies have indeed reported a relationship between musical abilities and second language pronunciation. For instance, Slevc et al. showed that musicality was positively associated with language pronunciation in Japanese adults learning English as a second language after accounting for multiple factors including age of exposure (Slevc & Miyake, 2006). Similarly, a study on Finnish adult speakers showed that participants with higher musical aptitude were able to pronounce English better than the participants with less musical aptitude (Milovanov et al., 2010). A later study suggested that specific musical abilities influence only the pronunciation of specific nonnative (English) phonemes known to be particularly difficult to Japanese speakers (Dolman & Spring, 2014). Relatedly, Christiner and Reiterer showed that singing ability correlate with speech imitation ability—that is, the ability to accurately perceive and reproduce the fine-grained phonetic features produced by a speaker—in preschool children (Christiner & Reiterer, 2018) as well as in adults (Christiner & Reiterer, 2013). Furthermore, exposing young adults to songs in a foreign language was more efficient in terms of learning to pronounce foreign words compared to listening to rhythmic speech (Baills et al., 2021). Together, these studies suggest that musical skills are interconnected with speech production capacity in a nonnative language.

What does all this mean? Given that speaking and singing share overlapping neural networks (e.g., Ozdemir et al., 2006; Schon et al., 2010), the finding of a relationship between the two behaviors, such that improving one behavior (singing) could have a transformative effect on the other (speaking), is perhaps unsurprising. It is possible that being skilled at music entails being skilled at analyzing and discriminating speech sounds, so that musically talented individuals including singers may be better at learning to pronounce foreign phonemes and maintain intelligibility throughout adulthood through self-monitoring. The choice of using an active control group is an important feature of the study. The group differences that were found are unlikely to be associated with unspecific aspects of singing (for instance, the social component of being part of a choir or a potentially better cognitive level). While the control group was more diverse than the singer's group, it contained people that were regularly engaged in nonmusical activities that included a cognitive and a fine motor component. These were the two aspects of singing that we wanted to control for.

Importantly, our results provide some support to the IM (Ballard et al., 2003) according to which speech and nonspeech orofacial functions are controlled through domain-general brain networks. Based on this idea, the model predicts that working on one behavior (e.g., singing) might have beneficial effects on another (e.g., speaking). However, not all aspects of speech were enhanced in singers, which warrants further investigation. The ideal study would be a randomized longitudinal singing training experiment where the nature of the exercises could be documented and controlled to determine the "active ingredients" and their specific impact on various aspects of speech and voice production, in natural as well as in more challenging speaking situations. While this study is cross-sectional, with its inherent selection bias, it provides one of the first accounts of speech production abilities using a controlled experiment in healthy adults with and without singing experience.

Task-Related Effects (DDK)

As was expected, performance in the DDK task was affected by task-related parameters. Words were easier (in terms of accuracy and rate) than nonwords, consistent with the literature (e.g., Faisca et al., 2019; Shuster et al., 2014; Tremblay et al., 2018); phonologically simple syllables were easier than more complex ones; and frequent syllables were easier compared to rare ones. This is expected given that rare syllables must me assembled from phonemes, which is associated with longer vocal reaction times. According to Levelt's model of speech production, only frequent syllables have a stored motor representation (Levelt, 1999; Levelt et al., 1999; Levelt & Wheeldon, 1994).

Furthermore, all performance metrics were influenced by speed: accuracy declined, rate was higher, and nPVI was (unexpectedly) lower. While a decline in accuracy is expected given the increased difficulty associated with fast speech, the finding that higher speed is associated with lower nPVI (therefore more regular speech) was unexpected. In fact, the results for nPVI are generally unexpected: nPVI was higher for words compared to nonwords and for frequent compared to rare stimuli. These findings are difficult to interpret. nPVI can be considered an estimate of segment-to-segment variability from syllable to syllable; it has been associated with disordered timing in clinical populations (Liss et al., 2009; Tjaden & Watling, 2003). nPVI has also been associated with linguistic proficiency in healthy adults, with increased nPVI (thus reduced regularity) in those that are less proficient in a language (Stockmal et al., 2005). It is possible that the greater effort required during the fast condition triggered increased monitoring and led to more regular speech, which could reflect a change in strategy. A similar hypothesis could be laid out to explain the frequency effect; however, phonological complexity showed the expected pattern (more complex stimuli associated with increased irregularity).

Interestingly, the results showed that those with a higher overall cognitive level and with a more extended language background were faster in reading and in the DDK task, regardless of their age or signing experience. Cognitive reserve, either passive (structural) or active (more efficient processing; see, e.g., Stern, 2002, for a review of reserve theories), provides a potential general explanatory mechanism. Briefly, cognitive reserve theories suggest that certain environmental factors can explain and predict an individual's response to brain disease. In the normal aging context, cognitively engaging activities would have an enduring positive effect on the brain, such that the effect of brain senescence would be reduced.

Conclusions

The present results suggest that amateur singing has a positive impact on speech but not voice production accuracy in adulthood. To understand the mechanism of action underlying this relationship, future studies will need to assess musical aptitudes in singers and correlate specific musical skills with various aspects of speech production, including intelligibility, rate, speech imitation skills, accent imitation skills, and many others. While additional research is needed to understand the full extent of the impact of singing on spoken language production—especially randomized controlled experiments—the present results contribute to furthering knowledge on the aging of voice and speech production. This knowledge is needed to develop prevention and mitigation strategies for speech production difficulties in healthy older adults and in those with cognitive decline.

Author Contributions

Pascale Tremblay: Conceptualization (Lead), Data curation (Lead), Formal analysis (Equal), Funding acquisition (Lead), Methodology (Equal), Project administration (Lead), Resources (Lead), Supervision (Lead), Visualization (Lead), Writing – original draft preparation (Lead). **Lydia Gagnon:** Formal analysis (Equal), Investigation (Equal), Writing – review & editing (Supporting). **Johanna-Pascale Roy:** Funding acquisition (Supporting), Methodology (Equal), Software (Lead), Writing – review & editing (Supporting). **Alison Arseneault:** Formal analysis (Equal), Investigation (Equal), Writing – review & editing (Supporting).

Data Availability Statement

The raw data sets generated during this study are not publicly available because participants did not consent to public data sharing. However, the group data is available on Borealis, the Canadian Dataverse Repository: https://doi.org/10.5683/SP3/GHD3HE.

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