Age Differences in Sequential Speech Production: Articulatory and Physiological Factors

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OBJECTIVES: To explore age differences in speech production in relation to orofacial physiology.

DESIGN: Cross-sectional quasi-experimental group study.

SETTING: General community.

PARTICIPANTS: Physically and cognitively healthy volunteers recruited from the community (N = 30), including 15 young (18–39) and 15 older (66–85) adults.

MEASUREMENTS: Accuracy and speech rate were calculated during the production of sequences of syllables containing oral vowels, nasal vowels, or both. Lip and tongue muscular strength, muscular endurance, and tactile sensitivity were also measured.

RESULTS: Older adults had a slower speech rate than younger adults and greater difficulty articulating nasal vowels. Analyses revealed that age-related decline in lip endurance is associated with decline in accuracy during speech production.

CONCLUSION: Older adults are not just slower than younger adults, they also exhibit specific articulatory difficulties. Although many physiological changes in orofacial functions occur in aging, only muscular endurance of the lips is related to age-related differences in speech production. This information is important for the development of speech interventions targeting older adults with speech motor disorders. **J Am Geriatr Soc 2016.**

Key words: articulation; elderly; oral muscular endurance; oral muscular strength

Speech is a complex, intrinsically sequential behavior that requires fine motor control over dozens of muscles in the face, neck, and abdomen. The ability to produce speech movements undergoes important changes with age. Several studies have shown a decrease in speech rate when older adults produce sentences,[1–3] words,[3] and nonwords,[4,5] but in terms of accuracy, results are less consistent. No age differences were found in speech errors during the slow production of tongue twisters[6] and visually triggered syllables.[5] In contrast, older adults are more often misunderstood when they produce words embedded in a carrier phrase,[7] and speech-language pathologists have rated them as less intelligible when they repeat syllables rapidly,[8] suggesting an age-related decline in articulatory precision. The lack of consistency between studies may be related to differences in task complexity. Age-related decline in accuracy was shown for the production of long but not short nonwords[4] and for the production of complex but not simple syllable sequences.[9] It is also possible that certain speech sounds are particularly vulnerable to aging, although to the knowledge of the authors of the current study, no study has compared age differences in the production of specific speech sounds.

Although most studies have focused on the production of oral sounds, it is possible that the production of nasal sounds, which requires fine control over the velum (for velopharyngeal opening and closure) and the coordination of velar movements with tongue and lip movements, is particularly vulnerable to age. Some studies have shown higher nasalance (comparison of nasally and orally emitted acoustic energy) for older adults,[10] suggesting a decline in the control of velar movements, but other studies have shown no aged-related change in this measure,[11,12] in nasal air flow,[13] or in perceived nasality.[14] It therefore remains unclear whether the production of nasal sounds is particularly vulnerable to aging. Physiological decline in the orofacial sphere may also affect speech production. It has been shown that oral tactile sensitivity,[15,16] lip strength,[17] and maximal tongue strength[18,19] decrease with age, but the relationship between physiological changes and speech production has never been tested. The aim of this study was to explore age differences in the effect of motor complexity and orofacial physiology on speech production. It was hypothesized that the production of sequences containing different syllables and sequences containing nasal and oral vowels would be more difficult for older than younger adults, reflecting a decline in speech motor control. It was also expected that a decline in lip and tongue muscular endurance and tactile sensitivity would negatively effect speech production.

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METHODS

Participants

Fifteen cognitively healthy young adults (mean age 27.7 ± 6.8; n = 9 women) and 15 cognitively healthy older adults (mean age 73.9 ± 6.1; n = 7 women) were included in this study. Four additional participants were originally recruited but were excluded because they failed the Geriatric Depression Scale (3 young adults) or reported a diagnosed neuropsychological condition (1 older adult). Participants were native Canadian French speakers with normal or corrected-to-normal vision and no self-reported speech, voice, language, swallowing, psychological, neurological, or neurodegenerative disorder and no diagnosed respiratory disorder; all were nonsmokers. Participants were screened for depression using the Geriatric Depression Scale[20] and for cognitive decline using the Montreal Cognitive Assessment scale.[21] All participants had normal to mild hearing loss for standard pure tone average (PTA: average of threshold at 0.5, 1, and 2 kHz) in each ear as measured using a clinical audiometer (AC40, Interacoustics, Middelfart, Denmark). Participant characteristics are reported in Table 1. The institutional ethical committee of the Institut Universitaire en Santé Mentale de Québec approved the study (#352–2013).

Physiological Measures

Tactile sensitivity of lips and tongue was examined using a standard two-point discrimination procedure (Discriminator, Jamar, Pattersen Medical, Missisauga, Canada).[16] The muscular strength of the tongue and lips was measured using the oral performance instrument over three trials (Iowa Oral Performance Instrument, IOPI Medical LLC, Redmond, WA).[17–19,22] For muscular endurance, participants were asked to squeeze the bulb of the instrument at 50% of their maximum strength for as long as possible. If the participant could not maintain the pressure for at least 2 seconds, the trial was stopped, and the time was noted. Data were missing for two young participants who could not maintain a constant pressure.

Speech Task

Participants were seated in a sound-attenuated room. After a short practice session, syllables were presented visually on a screen. After 1,500 ms, the color of the syllables changed from red to green indicating the start of the trial, which lasted for 5 seconds. A maximal performance task was used, which consisted in repeating the syllables as many times as possible while trying to minimize articulation errors (diadochokinetic rates or DDK). Intertrial intervals ranged from 2 to 3 seconds. Participant responses were recorded. The syllables were manipulated in terms of sequential and articulatory complexity (resonance). For sequential complexity, the stimuli were simple (e.g., /pa/), intermediate (containing two different movements, e.g., / pa ta/), or complex (containing three different movements e.g., /pa ta ka/). For resonance, the sequences were composed of syllables containing only oral vowels (e.g., /pa/) (oral), only nasal vowels (e.g., /pɔ̃/) (nasal condition) or both (e.g., / do tã /) (mixed condition). The order of trials was randomized. Participants completed 96 trials, with 12 trials per condition.

Behavioral Analysis

Two judges transcribed all sequences. When needed, a third judge transcribed the sequence to reach an interjudge agreement of two out of three. The percentage of errors per trial (number of incorrect syllables divided by total number of syllables produced) and speech rate (total number of syllables produced/5 seconds) were computed. Errors included misses, sound exchanges, production of additional syllables, and production of unintelligible syllables.

Statistical Analyses

Speech Task

Statistical analyses were conducted using SPSS version 22 (IBM Corp., Armonk, NY). First, two separate mixed-model analyses of variance (ANOVAs) were run to

Table 1. Participant Characteristics

Characteristic	Young adults (18–39)	Older adults (66–85)
	Mean ± Standard Deviation (Range)	
Age	27.7 ± 6.8 (18–39)	73.9 ± 6.1 (66–85)
Years of education	16.9 ± 2.7 (12–21)	15.1 ± 3.6 (10–22)
Montreal Cognitive Assessment score (maximum 30)	28.7 ± 1.2 (25–30)	27.1 ± 14.9 (25–29)
Depression scale score (maximum 30)	2.1 ± 2.1 (0–8)	1.7 ± 1.6 (0–4)
Handedness (maximum 20)	9.1 ± 14.0 (–18–20)	16.8 ± 7.8 (–10–20)
Right ear PTA, dB	5.8 ± 8.6 (–6–28.7)	13.6 ± 8.4 (–0.3–31.3)
Left ear PTA, dB	2.5 ± 5.4 (–3.7–12.3)	13.1 ± 8.2 (1–24.3)
Muscular strength of the lips, kPa	28.5 ± 3.5 (22–36)	30.1 ± 7.1 (23–45)
Muscular strength of the tongue, kPa	55.1 ± 10.4 (35–68)	53.0 ± 9.7 (37–70)
Muscular endurance of the lips, sec	93.9 ± 27.8 (57–120)	49.1 ± 37.2 (8–120)
Muscular endurance of the tongue, sec	36.7 ± 27.8 (21–74)	35.7 ± 26.8 (7–120)
Tactile sensitivity of the lips, mm[a]	2.7 ± 0.6 (2–4)	3.1 ± 0.8 (2–5)
Tactile sensitivity of the tongue, mm[a]	2.1 ± 0.4 (2–3)	2.5 ± 0.5 (2–3)

[a]Smaller values indicate better tactile discrimination.

PTA = pure tone average.

determine the percentage of errors and speech rate with two within-subject factors (resonance (oral, nasal, mixed) and sequence complexity (intermediate, complex)) and one between-subject factor (group (younger, older)). Because the mixed condition comprised only intermediate and complex trials, simple trials were not included in these first analyses.

Next, two additional ANOVAs were conducted to analyze the percentage of errors and speech rate, with one within-subject factors (sequence complexity (simple, intermediate and complex)) and one between-subject factor (group)). Finally, because the effect of resonance in the simple condition could not be examined through these analyses, two additional ANOVAs were conducted to determine the percentage of errors and speech rate in the simple condition with one within-subject factor (resonance (oral, nasal)) and one between-subject factor (group)). Measures of effect sizes are provided in the form of partial eta squared (η_p^2) for all main effects and interactions. When comparing two means, effect sizes are reported in the form of Cohen d statistics.

Physiological Measures

Unilateral t-tests were used to compare physiological measures between the groups. To examine whether physiological changes mediated age-related changes in speech production performance, mediation analyses were conducted using the PROCESS macro for SPSS (http://www.afhayes.com/).[23,24] Mediation can reveal the mechanisms by which one variable affects another.[5,23,25] In the model illustrated in Figure 1A, the dependent (Y) variables were speech rate and accuracy, the independent (X) variable was the categorical variable age (younger, older), and the mediators (M) were the physiological measures. Sensitivity of the tongue was not used in these analyses because its distribution was dichotomous rather than continuous. Sex was included as a covariate.

RESULTS

Speech Production

The ANOVA conducted on the percentage of errors revealed a significant main effect of sequence complexity ($F_{(1,28)} = 8.85$, $P = .006$, $\eta_p^2 = 0.24$) and resonance ($F_{(2,56)} = 9.86$, $P < .001$. $\eta_p^2 = 0.26$) and interactions between group and resonance ($F_{(2,56)} = 4.04$, $P = .02$, $\eta_p^2 = 0.13$) and between sequence complexity and resonance ($F_{(2,56)} = 3.4$, $P = .04$, $\eta_p^2 = 0.11$). In general, participants were more accurate in producing oral than nasal ($t_{(29)} = -3.17$, $P = .004$, $d = 0.97$) and mixed sequences ($t_{(29)} = -2.90$, $P = .007$, $d = 0.71$). Participants were also more accurate in producing mixed than nasal sequences ($t_{(29)} = -2.54$, $P = .02$, $d = 0.35$). Older participants were less accurate for nasal than oral ($t_{(14)} = -2.81$, $P = .01$, $d = 1.19$) and mixed ($t_{(14)} = 3.06$, $P = .008$, $d = 0.55$)

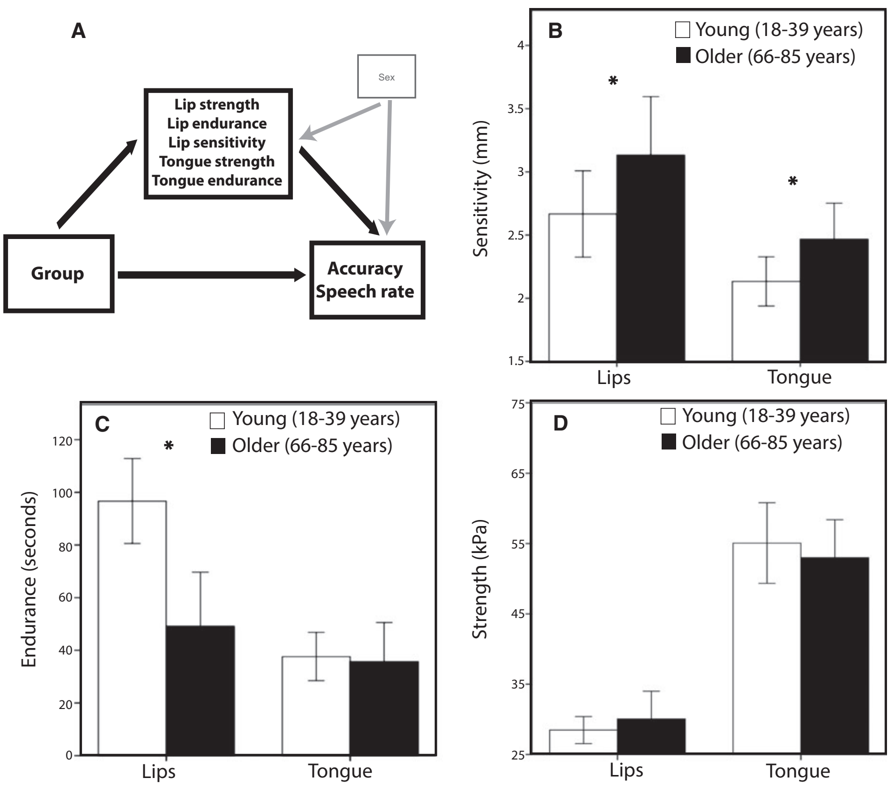

Figure 1. (A) Mediation model that was used to investigate the effect of orofacial physiological measures on speech production in young and older healthy adults. (B) Tactile sensitivity of the lips and tongue (mm) (lower score indicates better sensitivity). (C) Muscular endurance of the lips and tongue (in seconds) (higher scores indicate that a person is capable of maintaining a contraction for a longer period of time). (D) Muscular strength of the lips and tongue (kPa) (higher score indicates that a person is capable of exerting greater force). Measures of sensitivity, endurance, and strength are displayed separately for young and older adults. Asterisks indicate significant differences. Error bars represent standard error of the mean.

sequences (Figure 2a). The younger adults, in contrast, were less accurate in producing mixed than oral sequences ($t_{(14)} = -2.3$, $P = .04$, $d = 0.82$) but not in producing nasal than oral or nasal than mixed sequences. In general, participants were more accurate in producing intermediate than complex sequences ($t_{(29)} = 2.99$, $P = .006$, $d = 0.10$). Furthermore, post hoc tests for the interaction between sequence complexity and resonance revealed that the difference in performance between intermediate and complex was significant for the nasal sequences ($t_{(29)} = -2.83$, $P = .008$, $d = 0.33$) but not for the oral and mixed sequences.

The ANOVA conducted on speech rate revealed main effects of sequence complexity ($F_{(1,28)} = 7.06$, $P = .01$, $\eta_p^2 = 0.2$) and resonance ($F_{(2,56)} = 77.15$, $P < .001$, $\eta_p^2 = 0.73$). In general, participants were faster for the oral than the nasal ($t_{(29)} = 10.24$, $P < .001$, $d = 0.74$) and mixed ($t_{(29)} = 5.63$, $P < .001$, $d = 0.34$) sequences and faster for the mixed than the nasal ($t_{(29)} = -11.07$, $P < .001$, $d = 0.43$) sequence.

The ANOVA (group by sequence complexity) conducted on the percentage of errors revealed a main effect of sequence complexity ($F_{(2,56)} = 11.38$, $P < .001$, $\eta_p^2 = 0.29$). Participants were more accurate in producing simple than intermediate ($t_{(29)} = -2.49$, $P = .02$, $d = 0.44$) and complex sequences ($t_{(29)} = -4.01$, $P < .001$, $d = 0.69$). Participants were also more accurate in producing intermediate than complex sequences ($t_{(29)} = -2.99$, $P = .006$, $d = 0.27$).

For speech rate, the ANOVA revealed main effects of sequence complexity ($F_{(2,56)} = 13.85$, $P < .001$, $\eta_p^2 = 0.33$) and group ($F_{(1,28)} = 4.35$, $P = .046$, $\eta_p^2 = 0.13$). In general, older adults were slower than younger adults (Figure 2B). In both groups, participants were slower for the simple than the intermediate ($t_{(29)} = -3.58$, $P = .001$, $d = 0.38$) and complex ($t_{(29)} = -3.89$, $P = .001$, $d = 0.54$) sequences. Participants were also slower for the intermediate than the complex sequence ($t_{(29)} = -2.69$, $P = .01$, $d = 0.19$).

The ANOVA (group by resonance) conducted on the percentage of errors for the simple sequences revealed no main effect and no interaction. For speech rate, the results revealed a main effect of resonance ($F_{(1,28)} = 49.78$, $P < .001$, $\eta_p^2 = 0.64$), with nasal sequences associated with slower speech rate, as well as a main effect of group ($F_{(1,28)} = 4.75$, $P = .04$, $\eta_p^2 = 0.15$), with younger adults being faster than older adults.

Physiological Aging

T-tests revealed that younger adults had better tactile sensitivity than older adults for the lips ($t_{(28)} = 1.74$, $P = .046$, $d = 0.61$) and tongue ($t_{(28)} = 2.07$, $P = .02$, $d = 0.72$) (Figure 1B). Muscular endurance of the lips was greater for young than older adults ($t_{(27)} = 3.65$, $P < .001$, $d = 1.13$) (Figure 1C). No age effects were found for muscular strength (Figure 1D).

The mediation analysis (Figure 1A) revealed that lip endurance decreased with age ($a = -46.36$, standard error (SE) 12.24, $P = .001$) and was positively associated with overall percentage of errors ($b = 0.11$, SE 0.04, $P = .02$), leading to a significant negative indirect effect of age on percentage of errors (ab = −4.85, SE 3.15, CI = −13.44 to −0.05) through lip endurance. Nevertheless, there was evidence that age was associated with errors independent of lip endurance ($c = 7.71$, SE 2.95, $P = .02$), meaning that the mediating effect of lip endurance on the relationship between age and speech errors was *partial*, a phenomenon that is also referred to as *partial mediation*. No other physiological factor mediated the relationship between age and speech errors.

DISCUSSION

The goal of this study was to explore age differences in speech production by manipulating sequential and articulatory complexity during a maximal performance task and to examine potential relationships between these differences and orofacial physiology. Consistent with the literature, age differences were found in overall speech rate.[1–4,26] As expected, greater sequential complexity was associated with lower accuracy in both groups. A previous study found that sequence complexity affected older adults more than younger adults, although the structure of the syllables used was significantly more complex (containing a consonant cluster and a coda, e.g., /prat/)[9] than the ones that

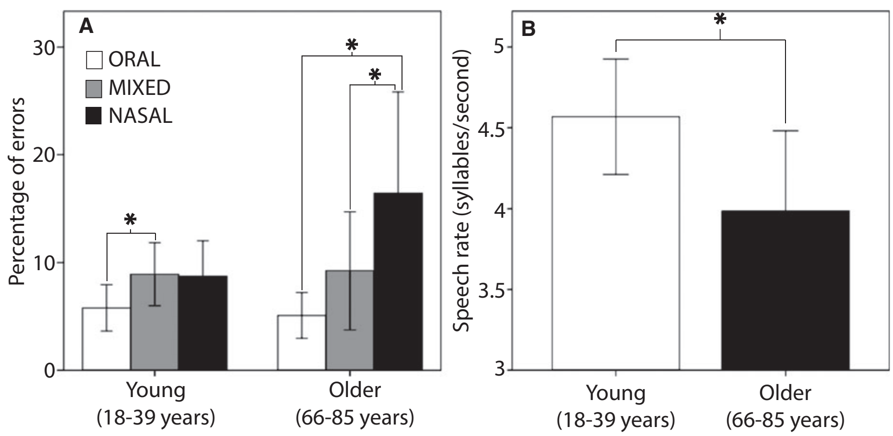

Figure 2. (A) Response accuracy (percentage of errors) and (B) speaking rate (number of syllables per seconds), displayed as a function of articulatory complexity (oral, mixed, nasal) and age (young, older adults). Asterisks indicate significant differences. Error bars represent standard error of the mean.

were used here (no consonant cluster and no coda, e.g., /pa/), which is also consistent with results from another group that showed age effects during the production of long nonwords with complex syllables.[4] The current study found a significant age-related decline in accuracy for the production of nasal vowels, confirming that simple syllables are preserved in aging and demonstrating, for the first time, the vulnerability of nasal vowels. Specifically, difficulty increased along with the total number of nasal vowels, not with the need to alternate between oral and nasal vowels across syllables. Age effects on resonance have been inconsistently reported in the literature,[10–14] but no study had examined articulatory accuracy. In the nasal condition, participants alternated between oral consonants and nasal vowels within syllable boundaries; therefore, they had to move their velum rapidly and precisely. Furthermore, participants needed to synchronize velar movements with lips and tongue movements. Thus, nasal errors may reflect a decline in velar control, a decline in the synchronization process, or both. It also has been suggested that age-related physiological changes affecting the velum can result in neuromuscular weakness.[12] Further studies are needed to uncover the mechanisms underlying the vulnerability of nasal vowels.

Another important finding is that muscular endurance of the lips partially mediated the effect of age on speech production. As expected,[15] tactile sensitivity also declined with age, but it did not affect speech production. No age-related decline in lip or tongue muscular strength was found, consistent with previous studies.[22,27] The present finding is consistent with a study showing no relationship between orofacial strength and speech rate.[18] This result may be because speaking requires only a small amount of muscular strength. The finding of a partial mediation effect of lip endurance on speech production demonstrates that weakness or paralysis of the speech muscles cannot entirely account for decline in speech production, which includes other factors such as age-related decline in speech motor planning and programming. Consistent with this idea, recent studies have shown age-related changes in the structure and function of brain areas involved in speech motor control, including the anterior insula and striatum.[5,28] The speech errors observed in the present study (e.g., substitutions and insertions of phonemes and syllables) and previous studies[4,9] resemble those observed in apraxia of speech, a neuromotor speech disorder whose most notable symptom is difficulty putting sounds and syllables together in the correct order. This disorder has been associated with lesions in the insula and basal ganglia.[29] It is possible that normal decline in brain regions involved in speech motor planning and programming, including the insula and striatum, results in behavioral impairments that share some similarities with (a very mild form of) apraxia of speech. A direct comparison of the behavior and brains of individuals with apraxia of speech and age-matched healthy elderly adults may contribute to understanding the etiology of this complex disorder.

In sum, the present study provides evidence of age differences in speech production despite a few limitations, including cross-sectional design, small sample size, a nonecological task, and lack of a complete evaluation of nonspeech oral motor functions. The speech task was chosen because it is a well-known syllable production task (diadochokinesis) that eliminates the influence of linguistic factors (e.g., semantics) on speech production, thereby measuring "pure" maximal speech performance, although this task is not representative of everyday speech. Studies examining age differences in speech production in more-natural contexts are needed. Finally, a complete evaluation of oral nonspeech motor functions was not conducted, which means that some participants may have had slightly abnormal oral motor functions, although participants did not report any respiratory, speech, language, swallowing or neurodegenerative disorders during the screening interview. Moreover, all participants were able to perform the speech task and the measures of muscular strength and endurance of lips and tongue, which are part of a standard evaluation of nonspeech oral motor functions.[30]

CONCLUSION

These results show that nasal sounds are vulnerable to aging. Even though many physiological changes in orofacial functions occur with aging, only muscular endurance of the lips is related to age-related differences in speech performance, at least during the production of sequences of syllables. Appropriate treatment for older adults with speech difficulties critically depends on the ability to separate normal from pathological processes and on a deep understanding of aging mechanisms, which requires a detailed knowledge of the nature and range of normal aging mechanisms. The present study is a step toward this goal.

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Conflict of Interest: None.

Author Contributions: PT: study design, supervision of data collection and analysis, writing the manuscript. MB-M: study design, data collection and analysis, writing the manuscript.

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REFERENCES

1. Ryan WJ. Acoustic aspects of the aging voice. J Gerontol 1972;27:265–268.
2. Dromey C, Boyce K, Channell R. Effects of age and syntactic complexity on speech motor performance. J Speech Lang Hear Res 2014;57:2142–2151.
3. Smith BL, Wasowicz J, Preston J. Temporal characteristics of the speech of normal elderly adults. J Speech Hear Res 1987;30:522–529.
4. Sadagopan N, Smith A. Age differences in speech motor performance on a novel speech task. J Speech Lang Hear Res 2013;56:1552–1566.
5. Tremblay P, Deschamps I. Structural brain aging and speech production: A surface-based brain morphometry study. Brain Struct Funct 2016;221:3275–3299.
6. Vousden JI, Maylor EA. Speech errors across the lifespan. Lang Cogn Process 2006;21:48–77.

7. Shuey EM. Intelligibility of older versus younger adults' CVC productions. J Commun Disord 1989;22:437–444.
8. Parnell MM, Amerman JD. Perception of oral diadochokinetic performances in elderly adults. J Commun Disord 1987;20:339–351.
9. Bilodeau-Mercure M, Kirouac V, Langlois N et al. Movement sequencing in normal aging: Speech, oro-facial, and finger movements. Age (Dordrecht, the Netherlands) 2015;37:9813.
10. D'Haeseleer E, Depypere H, Claeys S, et al. Nasal resonance in middle-aged women: A multiparameter approach. Ann Otol Rhinol Laryngol 2011;120:575–580.
11. Rochet AP, Rochet BL, Sovis EA, et al. Characteristics of nasalance in speakers of western Canadian English and French. J Speech Lang Pathol Audiol 1998;22:94–103.
12. Hutchinson JM, Robinson KL, Nerbonne MA. Patterns of nasalance in a sample of normal gerontologic subjects. J Commun Disord 1978;11:469–481.
13. Hoit JD, Watson PJ, Hixon KE, et al. Age and velopharyngeal function during speech production. J Speech Hear Res 1994;37:295–302.
14. Amerman JD, Parnell MM. Auditory impressions of the speech of normal elderly adults. Br J Disord Commun 1990;25:35–43.
15. Calhoun KH, Gibson B, Hartley L, et al. Age-related changes in oral sensation. Laryngoscope 1992;102:109–116.
16. Heft MW, Robinson ME. Age differences in orofacial sensory thresholds. J Dent Res 2010;89:1102–1105.
17. Wohlert AB, Smith A. Spatiotemporal stability of lip movements in older adult speakers. J Speech Lang Hear Res 1998;41:41–50.
18. Neel AT, Palmer PM. Is tongue strength an important influence on rate of articulation in diadochokinetic and reading tasks? J Speech Lang Hear Res 2012;55:235–246.
19. Crow HC, Ship JA. Tongue strength and endurance in different aged individuals. J Gerontol A Biol Sci Med Sci 1996;51:M247–M250.
20. Yesavage JA, Brink TL, Rose TL, et al. Development and validation of a geriatric depression screening scale: A preliminary report. J Psychiatr Res 1982;17:37–49.
21. Nasreddine ZS, Phillips NA, Bedirian V, et al. The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. J Am Geriatr Soc 2005;53:695–699.
22. Vitorino J. Effect of age on tongue strength and endurance scores of healthy Portuguese speakers. Int J Speech Lang Pathol 2010;12:237–243.
23. Preacher KJ, Hayes AF. SPSS and SAS procedures for estimating indirect effects in simple mediation models. Behav Res Methods Instrum Comput 2004;36:717–731.
24. Hayes AF. Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach. New York: The Guilford Press, 2013.
25. Bilodeau-Mercure M, Lortie CL, Sato M, et al. The neurobiology of speech perception decline in aging. Brain Struct Funct 2015;220:979–997.
26. Salthouse TA. The processing-speed theory of adult age differences in cognition. Psychol Rev 1996;103:403–428.
27. Clark HM, Solomon NP. Age and sex differences in orofacial strength. Dysphagia 2012;27:2–9.
28. Tremblay P, Dick AS, Small SL. Functional and structural aging of the speech sensorimotor neural system: Functional magnetic resonance imaging evidence. Neurobiol Aging 2013;34:1935–1951.
29. Ogar J, Slama H, Dronkers N, et al. Apraxia of speech: An overview. Neurocase 2005;11:427–432.
30. Kent RD. Perceptual sensorimotor examination for motor speech disorders. In: McNeil MR, editor. Clinical Management of Sensorimotor Speech Disorders. New York: Thieme, 2009, pp 19–29.