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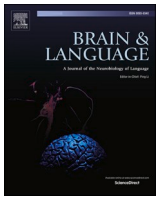

Movement-related cortical potential and speech-induced suppression during speech production in younger and older adults

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ABSTRACT

With age, the speech system undergoes important changes that render speech production more laborious, slower and often less intelligible. And yet, the neural mechanisms that underlie these age-related changes remain unclear. In this EEG study, we examined two important mechanisms in speech motor control: pre-speech movement-related cortical potential (MRCP), which reflects speech motor planning, and speaking-induced suppression (SIS), which indexes auditory predictions of speech motor commands, in 20 healthy young and 20 healthy older adults. Participants undertook a vowel production task which was followed by passive listening of their own recorded vowels. Our results revealed extensive differences in MRCP in older compared to younger adults. Further, while longer latencies were observed in older adults on N1 and P2, in contrast, the SIS was preserved. The observed reduced MRCP appears as a potential explanatory mechanism for the known age-related slowing of speech production, while preserved SIS suggests intact motor-to-auditory integration.

1. Introduction

The act of speaking is one of the most complex actions in the vast human motor repertoire, and one that shows evidence of decline with aging. During speech production, not only do we need to plan incredibly precise and fast sequences of (co-) contractions in hundreds of muscles located in the lips, tongue, velum, vocal folds and respiratory system, but we also need to monitor the flow of resulting sensory (acoustic and somatosensory) feedback, comparing incoming with predicted feedback.

With age, several components of the speech system undergo important changes—anatomical, physiological and functional—which, in turn, can result in age-related difficulties. Specifically, the passage of time alters the physiology of the vocal tract (Liu et al., 2021; Pontes et al., 2006; Rother et al., 2002), the larynx (Bloch & Behrman, 2001; Honjo & Isshiki, 1980; Kersing & Jennekens, 2004; Pontes et al., 2005; Ximenes Filho et al., 2003), and the respiratory system (Lalley, 2013; Linville, 1996; Zeleznik, 2003). Associated changes include reduced vocal stability (e.g. Lortie et al., 2015; Wilcox & Horii, 1980), reduced loudness (Baker et al., 2001), slower and more variable speech (e.g. Bilodeau-Mercure & Tremblay, 2016; Jacewicz et al., 2009; Morris & Brown, 1987; Padovani et al., 2009; Sadagopan & Smith, 2013; Smith et al., 1987b; Tremblay & Deschamps, 2016; Tremblay et al., 2018; Tremblay et al., 2017) as well as a decline in accuracy across a range of speech tasks (Bilodeau-Mercure et al., 2015; Gollan & Goldrick, 2018; Sadagopan & Smith, 2013; Tremblay et al., 2018; Tremblay et al., 2023). Despite this body of documented age-related differences, the neural mechanisms that underlie these differences remain largely unknown. Magnetic resonance imaging (MRI) studies have shown age differences in BOLD MRI signal in several sensorimotor and executive control areas including the primary motor cortex, the pars opercularis of the inferior frontal gyrus (IFG) and the cingulate cortex (Tremblay et al., 2017). MRI has also revealed age-dependent relationships between cortical thickness and speech responses (reaction time and response duration) in several areas including the insular cortex, supratemporal cortex, inferior frontal sulcus and bilateral caudate (Tremblay & Deschamps, 2016). Together, these results suggest broad age-related changes to the speech motor system but also beyond.

Another approach to examining speech production mechanisms in aging is to record electroencephalography (EEG), which could reveal physiological differences in the neural networks supporting speech production. In young adults, EEG studies have revealed that speech

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production is characterized by two important mechanisms: movement-related cortical potential (MRCP) and speaking-induced suppression (SIS) (Sato, 2022; Wang et al., 2014). MRCP (also referred to as readiness Potential [RP] or Bereitschaftspotential [BP] for self-paced movement) is a slow negative deflection occuring on central electrodes around 1000 ms prior to the onset of a self-paced movement (Kornhuber & Deecke, 1965; Libet et al., 1983), reaching the maximum negativity near movement onset (Tremblay et al., 2008), and followed by a positive rebound (Birbaumer et al., 1990; Pereira et al., 2017). MRCPs, preceding both speech and oral non-speech movement production, are related to movement planning and are thought to reflect "*the accumulation and coordination of neural computations related to action planning and preparing sensory systems for their expected consequences*" (Wang et al., 2014). Using EEG, Johari et al. showed that vowels generated following unpredictable cues are associated with longer RT and greater premotor activity in older compared to younger adults, while no difference was found in the predictable condition (Johari et al., 2019). The authors interpreted this age-related increase in brain response as reflecting the recruitment of additional neural resources to compensate for the decline of cognitive and sensorimotor mechanisms during speech motor timing processing. In a follow-up publication using the same experimental paradigm, Johari showed that, compared to younger adults, older adults exhibited slower reaction time and increased event-related desynchronization (ERD) of the alpha and beta bands before and after speech production (Johari & Behroozmand, 2020). These results suggest age differences in pre-movement EEG activity reflecting declining motor control.

In addition to MRCP, another important mechanism for speech production is speaking-induced suppression or SIS, a well-established phenomenon characterized by a suppression of auditory evoked responses to self-produced speech (e.g., Curio et al., 2000; Ford & Mathalon, 2004; Ford et al., 2001; Heinks-Maldonado et al., 2006; Houde et al., 2002; Niziolek & Guenther, 2013; Numminen et al., 1999; Sato, 2022; Sato & Shiller, 2018; Ventura et al., 2009). SIS is revealed by comparing auditory neural responses to speaking vs. passive listening. Specifically, it is measured on N1 (and corresponding M100) auditory evoked potential (AEP) originating mainly from the supratemporal plane of the auditory cortex (Naatanen & Picton, 1987; Woods, 1995). SIS is thought to index auditory predictions of speech motor commands by means of efference copy and corollary discharge and to reflect a partial neural cancellation of the incoming sensory feedback to self-generated speech, as well as the computation of an error signal, allowing talkers to adjust their speech motor output toward the auditory sensory target when there is a mismatch between predicted and actual auditory feedback. Hence, during speaking, when feedback matches prediction, auditory responses are reduced compared to passive listening to playback of the same acoustic signal. The SIS appears therefore as a core mechanism underlying speech motor control.

This mechanism—the SIS—appears to be vulnerable to aging, at least in those with disorders affecting speech production such as Parkinson disease (PD) and Alzheimer disease (AD). It is well documented that individuals with PD do not perceive the sound of their own voice in the same way as healthy individuals, while their general listening capacities are unaltered (Fox & Ramig, 1997; Ho et al., 2000). This may suggest dysfunctions in the integration of auditory and/or somatosensory information with motor commands during speech production. Consistent with this notion, one study has shown that individuals with PD have a reduced SIS (Railo et al., 2020), though another group did not report such a reduced SIS in PD (Huang et al., 2016), but nevertheless reported neurophysiological differences in PD patients' responses to their voice, with larger P2 auditory evoked response. Further, one study has shown that SIS is reduced in patients with Alzheimer disease (Kim et al., 2023). Despite evidence for a defective SIS mechanism in AD and PD, little is known about the way SIS evolves over the lifespan, and whether a deficient SIS mechanism could underscore the known impacts of aging on speech production.

The goal of the present study was therefore to examine the normal aging of sensorimotor processing during speech production, focusing on MRCP, SIS and N1/P2 to shed new lights on the origin of age-related speech production difficulties. To this end, we compared the neurophysiological response to a simple self-paced vowel production task and a vowel perception task in healthy young and older adults. Given the scarcity of studies examining the electrophysiological basis of speech production in aging, the present study is in part exploratory. However, based on prior work from Johari et al., we expected that MRCP would be higher in older adults, as a potential explanatory mechanism for the known age-related slowing of speech production. Regarding the SIS, given the evidence for a defective SIS mechanism in abnormal aging (AD and PD), we wanted to examine whether this mechanism shows signs of abnormality in normal aging, as a potentially explicative factor for normal age-related speech production decline.

2. Methods

2.1. Participants

Forty right-handed French-speaking healthy adults participated in the study after giving informed consent. Participants were divided into a younger and an older group. The data from the younger group were published in Sato (Sato, 2022) and included 20 adults (12 females), with a mean age of 27 ± 6 years (20–39 years) and an average of 16 ± 2 years of education (range: 11–20 years). The older group included 20 adults (12 females), with a mean age of 71 ± 5 years (61–78 years) and an average of 15 ± 3 years of education (range: 9–20 years). All participants reported normal or corrected-to-normal vision and were allowed to wear their glasses or corrective lenses during the experiment. Participants reported no history of hearing, speaking, language, neurological and/or neuropsychological disorders. The cognitive functioning of all participants was evaluated using the Montreal Cognitive Assessment scale (MoCA) (Nasreddine et al., 2003; Nasreddine et al., 2005). Participants' characteristics are detailed in Table 1. The study took place on site and with the agreement of the "Centre d'Expérimentation sur la Parole" (Aix-Marseille University, France), the protocol being carried out in accordance with the ethical standards of the Declaration of Helsinki (World Medical, 2013) and participants paid for the time spent in the study.

2.2. Experimental procedures

The experimental protocol was adapted from a well-defined vocal production and perception EEG protocol for studying corollary discharge (Ford et al., 2010) and was described in Sato (Sato, 2022) for the younger group. The experiment was carried out in a dimly lit sound-attenuated room and consisted of a speech production and perception task during which EEG was recorded, as well as a Multimodal Speech Identification Task.

2.2.1. Speech Production and Perception Task

Participants were asked to produce vowels in a self-paced manner for 3 min, while listening to their auditory feedback through earphones (speech production condition). Following the production condition, subjects passively listened to a recording of their speech production (speech perception condition). To limit adaptation effects, three vowels were used: /a/, /ø/ and /e/. The vowels differed in terms of height and/or roundedness phonetic features: the French /a/ vowel is produced with the jaw opened and the lips unrounded, the French /ø/ vowel is produced with the jaw mid-opened and the lips rounded, and French the /e/ vowel is produced with the jaw mid-opened and the lips unrounded and stretched back.

In the production condition, participants were asked to randomly produce one vowel every second or every other second until asked to stop after 3 min. To limit adaptation effects, they were also asked not to produce the same vowel consecutively (e.g., /a/-/a/) and not to repeat

Table 1
Participants' characteristics.

	Younger adults				Older adults				*t*-test	
Characteristics	**M**	**SD**	**min**	**max**	**M**	**SD**	**min**	**max**	**t**	**p**
Age in years	*26.75*	5.71	20.00	39.0	70.53	5.03	61.18	78.44	25.72	**≤.001**
Education in years	*15.95*	2.35	11.00	20.0	14.90	3.35	9.00	20.00	1.1465	0.2596
MoCA (/30)	*28.95*	1.23	26.00	30.0	27.15	1.66	23.00	30.00	3.8867	**≤.001**

Note. M = Mean; SD = . Standard deviation of the mean. Bold font is used to identify significant effects and interactions.

the same sequence of vowels through the entire recording (e.g., /a/-/ø/-/e/-/a/-/ø/-/e/…). Acoustic recordings are described in Sato (2022) for the younger group. During the production condition, participants' verbal responses were recorded using a condenser shotgun microphone (NTG-2, Røde, Sydney, Australia) located approximately 25 cm from the mouth, with audio digitizing done at 48 kHz. To minimize the effects of bone conduction, the acoustic signal level played back through earphones (T205, JBL, Northridge, USA) was 10 dB greater than the signal at the microphone (calibrated prior to testing using a 1000 Hz pure tone). During the speech perception condition, the set up for the presentation of auditory stimuli was identical to the setup for the production condition. The microphone and earphones were connected to a computer (Zbook 15 Workstation, Hewlett-Packard, Palo Alto, USA) equipped with 32 GB RAM through a USB audio interface (iO2, Alesis, Cumberland, USA). In addition, in both conditions, the acoustic signal sent to the earphones was duplicated and sent to the EEG Biosemi system equipped with an auxiliary connector for isolated sensors and synchronized with EEG recordings to determine offline the acoustical triggers for the EEG analyses (refer to the next section).

After being familiarized with EEG muscle artefacts (eye movements, eye blinks, articulatory movements), participants were asked to produce vowels in a natural manner but with minimal force/tension in the lip and jaw muscles. This was aided further by the instruction to produce vowels with a constant/natural intensity and duration, as well as to maintain a neutral open mouth posture between each vowel. For the perception condition, participants were asked to passively listen to the recording of their own vowels.

A short training session was performed prior to beginning the EEG data collection to ensure that no artifact was present in the EEG signal and to confirm that participants understood the task. The production condition was followed by a short break, then the perception condition was started.

2.3. EEG recordings

EEG recordings were described in Sato (2022) for the younger group. In all tasks, EEG data were continuously recorded using the Biosemi Active Two AD-box EEG system operating at a 512 Hz sampling rate. Since MRCP and N1/P2 AEPs have maximal response over fronto-central sites (Naatanen & Picton, 1987; Scherg & von Cramon, 1986; Shibasaki et al., 1980), and as recommended by Ford et al. (2010), EEG were collected from F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2 fronto-central scalp electrodes (Electro-Cap International, INC), according to the international 10–20 system. Two additional electrodes served as ground electrodes (Common Mode Sense [CMS] active and Driven Right Leg [DRL] passive electrodes). Horizontal (HEOG) and vertical (VEOG) eye movements were recorded using electrodes positioned at the outer canthus of each eye and above the left eye. In addition, two external reference electrodes were attached over the left and the right mastoid bones. Before the experiment, the impedance of all electrodes was adjusted to get low offset voltages (the impedance of each electrode was kept below 10 uV) and stable DC.

2.3.1. Multimodal Speech Identification Task

Following EEG recording, participants performed a behavioural speeded forced-choice vowel identification task. This task was included to determine participants' auditory and visual speech abilities. The stimuli consisted of auditory, visual and audiovisual /a/, /ø/ and /e/ vowels recorded by a native French female speaker in a similar set-up as the one used in the EEG experiment. Multiple utterances of each vowel were recorded using a microphone (NTG-2, Røde, Sydney, Australia) located approximately 25 cm from the mouth, and a digital video camera (C922, Logitech, Lausanne, Switzerland) located approximately 50 cm from the head. Audio digitizing was done at 48 kHz. Video digitizing was done at 30 frames per second with a resolution of 1080 × 1920 pixels. Using Adobe Premiere (Adobe systems, San Jose, USA) and Praat (Boersma & Weenink, 2011), one set of clearly articulated /a/, /ø/ and /e/ tokens were selected and edited based on acoustic and visual properties. All stimuli were 833 ms long (25 frames) with a mean vowel duration of 362 ms (± 18 SD), a mean vowel onset of 349 ms (± 13 SD) and a mean intensity of 81 dB (± 1 SD). For each of the three audiovisual stimuli, auditory-only and visual-only stimuli were built by either replacing all visual frames by the first still neutral image or by removing the acoustic signal.

On each trial, participants were asked to identify one vowel (/a/, /ø/ or /e/) as quickly as possible by pressing one of three keys on a keyboard with their right hand. No feedback was provided. The response key designation was fully counterbalanced across both groups and participants. This task consisted of 45 trials (3 modalities x 3 vowels x 5 trials) presented in a fully randomized order, including 15 trials per modality.

2.4. Analyses

2.4.1. Multimodal Speech Identification Task

In the multimodal speech identification task, the percentage of correct responses and median RTs (calculated from the acoustic onset of each vowel) were calculated for each participant and each condition. ANOVAs were performed separately on these measures with the modality (Audio, Visual and Audio-Visual) as a within-participant factor and the group (younger, older) as a between-participant factor. The MoCA score and the sex were included as covariates.

2.4.2. Speech Production and Perception Task

Acoustic analyses were described in Sato (2022) for the younger group. Acoustic analyses were performed using version 5.3 of the Praat software (Boersma & Weenink, 2011). For each participant, a semi-manual procedure was first performed to determine the onset and offset of the ~5000 vowels recorded vowels. Using the Speech Corpus Toolkit for Praat (Lennes, 2017), pauses between each vowel were automatically identified, based on minimal duration and low intensity energy parameters. Vowel boundaries were then fine-tuned manually based on waveform and spectrogram information. In addition, onsets and offsets were defined according to a continuous voicing period, without pause, based on the lowest frequency part of the wide-band spectrogram (i.e. < 300–400 Hz). All vowels were listened to and labelled by one author (MS). Low quality vowels (e.g., including hesitations, transient silent phonatory periods, diphtongues) and/or including acoustic/electrical noise were removed from the acoustic and EEG analyses (on average, 5.5%±3 SD and 4.1%±2 SD) for the younger and older groups, without significant difference between the tasks, F (1,38) = 1.1). On average, after low quality vowel rejection, the number of analyzed vowels per participants was 120±8 (/a/: 39; /ø/: 41; /e/:

40) for the 20 younger participants and 132±6(/a/: 43; /ø/: 45; /e/: 44) for the 20 older participants (see Table 3). Vowel onsets were saved as triggers, which were later used for EEG analysis (with vowel onsets matched with the acoustic signal recorded in the analog channel of EEG data (see Ford et al., 2010)).

For each vowel, the maximum peak intensity was calculated using parabolic interpolation. The fundamental frequency (f_0), the first three formant frequencies (F_1, F_2 and F_3) and the intensity were averaged from a period defined as ±25 ms of the maximum peak intensity (Duckworth et al., 2011; Kent & Vorperian, 2018). f_0 was estimated using an auto-correlation procedure with a pitch range of 150–300 Hz for females and 75–200 Hz for males. F_1, F_2 and F_3 were estimated using LPC analysis (Linear Predictive Coding, Burg method), with LPC parameters adjusted on a per-subject basis to avoid/minimize the occurrence of spurious formant values. The intensity was computed using the mean energy averaging method.

For each participant and each vowel, the number of occurrences, the number of repetitions (i.e., sequences of the same vowel), the median inter-trial duration, mean vowel duration, mean intensity, and mean f_0, F_1, F_2, F_3 were computed. To identify potential group difference in intra-individual variability, SEM was computed on the inter-trial duration, vowel duration, intensity, f_0, F_1, F_2, F_3. Finally, the F_1-F_2-F_3 triangular /a/-/ø/-/e/ vowel space area (defined as the Pythagorean sum of the areas of the respective projections on the three principal planes) was calculated, as a quantitative index of articulatory working space (for a review, see Kent & Vorperian, 2018).

Two-way repeated-measure ANOVAs were performed separately on these measures with the vowel (/a/, /ø/, /e/) as a within-participant factor and with the age group (younger, older) as a between-participant factor. In addition, a one-way ANOVA was performed on F_1-F_2-F_3 triangular vowel space area with the age group (younger, older) as a between-participant factor.

2.4.3. EEG Data Analyzes

EEG analyses were described in Sato (2022) for the younger group. EEG data were processed using the EEGLAB software version 2020 (Delorme & Makeig, 2004) running on Matlab (Mathworks, Natick, USA; version R2019a). For each participant, EEG data were first re-referenced to the average of left and right mastoids, and band-pass filtered using a two-way least square FIR filtering (1–30 Hz). Residual sinusoidal noise from scalp channels was further estimated and removed using the EEGLAB CleanLine plug-in (version 2012). Scalp channels were then automatically inspected, and bad channels interpolated using the EEGLAB Clean_rawdata plug-in (version 0.34). On all channels, eye blinks, eye movements, speech-related movements and other motion artefacts were detected and removed using the EEGLAB Artifact Subspace Reconstruction plug-in (version 0.13). Based on a sliding-window principal component analysis, this algorithm rejected high-variance bad data periods by determining thresholds based on clean segments of EEG data.

To evaluate the movement-related cortical potential (MRCP) while taking into account its influence on AEPs, two analyses based on a distinct epoching procedure were performed. The first analysis was designed to evaluate N1/P2 AEPs subtracting the temporally contingent influence of MRCP on AEPS. To this end, EEG data were segmented from −100 ms to 300 ms relative to the acoustic onset and corrected relative to a −100 ms to 0 ms baseline. The second analysis was designed to examine the time-course of MRCP and to calculate N1/P2 AEPs in relation to a baseline assumed to be similar across all tasks. Since RP has been shown to occur approximately 300 ms before vowel production (Wang et al., 2014), EEG data were here segmented from −1000 ms to 300 ms relative to the acoustic onset and corrected relative to a −1000 ms to −900 ms baseline.

2.5. First epoching procedure [-100 ms to 300 ms]

EEG data from /a/, /ø/ and /e/ vowels were averaged together and segmented into 400 ms epochs (from −100 ms to 300 ms relative to the acoustic onset), corrected from a −100 ms to 0 ms baseline. Epochs with an amplitude change exceeding ±100 uV at any channels were removed, and EEG data were averaged over the nine F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2 fronto-central electrodes. On average, the entire preprocessing pipeline rejected 23% of epochs and left 90 epochs per task for the younger group and rejected 25% of epochs and left 99 epochs per task for the older group (for details, see Supplementary Table 2.1).

For each participant, N1/P2 amplitude and latency were first computed on the EEG waveform averaged over the two tasks, from a fixed temporal window of 40–120 ms for N1 and of 120–240 ms for P2. In the younger group, clear and homogeneous N1 and P2 AEPs were observed for all but two participants, who were removed from the EEG analyses. For one of these two participants, no N1/P2 AEPs were observed in the EEG waveform, while, for the second participant, both the latency and amplitude were ±2 SD away from the mean). In the older group, one participant was removed from the EEG analyses, with no P2 AEPs observed in the EEG waveform. On the remaining participants, for each participant and each task, N1 and P2 amplitudes and latencies were automatically computed based on two fixed temporal windows defined as ±30 ms of the N1 and P2 peak latencies previously calculated from the individual waveform averaged over the four tasks (Ganesh et al., 2014; Treille et al., 2014).

Additionally, we also calculated a SIS value directly by subtracting the amplitude of the N1 during speech production from the amplitude of N1 during speech perception.

Two-way repeated-measure ANOVAs were performed separately on the number of rejected trials and on N1 and P2 amplitudes and latencies, with Task (perception, production) as a within-participant factor and age group (younger, older) as a between-participant factor. Sex and MoCA scores were included as covariates to control for potential confounds. Statistical analyses were conducted with r studio version 2023.09.0+463. A final one-way ANOVA examined SIS with age group (younger, older) as a between-participant factor, and Sex and MoCA scores as covariates to control for potential confounds.

2.6. Second epoching procedure [-1000 ms to 300 ms]

As for the first analysis, EEG data from /a/, /ø/ and /e/ vowels were averaged together but segmented into 1300 ms epochs (from −1000 ms to 300 ms relative to the acoustic onset of the vowels), corrected using a baseline ranging from a −1000 ms to −900 ms. Epochs with an amplitude change exceeding ±100 uV at any channels were removed, and EEG data were averaged over the nine F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2 fronto-central electrodes. On average, the preprocessing pipeline rejected 34% of epochs for the younger adults, leaving 77 epochs per task, and 37% for the older group, leaving 84 epochs per task (for details, see Supplementary Table 3.1).

For each participant and each task, the mean amplitude of the successive 100 ms periods from −900 ms to 0 ms prior to the acoustic onset were calculated to examine the time course of MRCP. N1 and P2 amplitudes and latencies were computed based on two fixed temporal windows defined as ±30 ms of the N1 and P2 peak latencies calculated from the individual waveform averaged over the two tasks.

Additionally, we also calculated a SIS value directly by subtracting the amplitude of the N1 during speech production from the amplitude of N1 during speech perception.

A three-way repeated-measure ANOVA was performed on the time course of MRCP with Interval ([-900 ms to −800 ms]…[-100 ms to 0 ms]) and Task (perception, production) as within-participant factors and Age Group (younger, older) as a between-participant factor. Two-way repeated-measure ANOVAs were performed separately on N1 and

P2 amplitudes and latencies, with Task (perception, production) as a within-participant factor and age group (younger, older) as a between-participant factor. Sex and MoCA scores were included as covariates to control for potential confounds.

A final one-way ANOVA examined SIS with age group (younger, older) as a between-participant factor, and Sex and MoCA scores as covariates to control for potential confounds.

3. Results

3.1. Multimodal Speech Identification Task

Overall accuracy was high in the multimodal speech identification task (~96%). For the younger adults, accuracy was 98.2%, while it was 93.4% for older adults. The full results are presented in Table 2A and Fig. 1A. The analysis showed a significant effect of Modality, a main effect of Group, and an interaction between Group and Modality. Post-hoc analyses revealed that accuracy in the Audio Modality was significantly higher than in the Visual Modality (b =.0383, SE =.0155, p =.0394). The interaction revealed that accuracy was lower for the older compared to younger adults but only in the Visual Modality (b = 0.0940, SE = 0.0234, p =.0001).

The average median RT was 649 ms. For the younger adults, it was 606 ms (SE =22.1) while it was 689 ms (SE =22.1) for older adults. The full results are presented in Table 2B and Fig. 1B. The analysis showed significant main effects of Modality and Group, with older adults having longer RT overall. Post-hoc analyses revealed that RTs were longer than in the Visual compared to the Audio Modality (b = 105, SE = 34.8, p =.0084); and in the Visual compared to the Audio-Visual Modality (b = 138, SE = 34.8, p =.0004).

3.2. Speech production and perception task

Analyses of the acoustic recordings confirmed that the production task was correctly performed by all participants. Group differences were found on several dependent variables: number of occurrences, number of repetitions, inter-trial interval, vowel duration, F0, F2 and F3. There was no interaction between Group and Vowel on any of the dependent variables. As detailed in Table 3 and illustrated in Fig. 2, older adults produced more utterances and more repetitions; they produced longer vowels at a faster pace and had lower F0, F2 and F3 but similar intensity. Their vowel space was similar. The full statistical results are provided as Supplementary Material 1.

3.3. EEG signal

3.3.1. First epoching procedure [-100 ms to 300 ms]

A similar number of trials was observed across tasks, with on average 125 trials per task (refer to Supplementary Table 2.1). The ANOVA revealed a task difference in N1 and P2 amplitude, with reduced amplitude in the production compared to the perception tasks, indicative of a SIS. Further, Group differences were found on both N1 and P2 latency with longer latency for older compared to younger adults. Descriptive statistics and statistical results for the group effect are provided in Table 4; the full statistical results are reported in Supplementary Table 2.2 and illustrated in Figs. 3 and 4 (top row).

3.3.2. Second epoching procedure [-1000 ms to 300 ms]

Compared to the first analysis, due to longer epochs, the EEG signal included more artefacts. A similar number of trials was observed across tasks (refer to supplementary Table 3.1).

Visual inspection of the data revealed clear MRCPs during vowel production for both younger and older adults (Fig. 5). MRCPs were characterized by a slow negative deflection on fronto-central sites from 800 ms to 300 ms prior to the vocalic onset. The ANOVA revealed main effects of Task, Group and Interval. As expected, amplitude was more negative in the production compared to perception tasks. A significant Interval x Task interaction was also observed, with a more negative amplitude in the production compared to perception tasks from −800 ms to −200 ms. The main effect of Group revealed that the amplitude of MRCP was more negative in older compared to the younger participants. The Group by Task interaction revealed that older adults exhibited more negative amplitude in the production task compared to younger adults. The main results are reported in Table 5 and the full ANOVA results are reported in Supplementary Tabe 3.2.

Turning now to AEP, as detailed in Table 5 and Supplementary Material 3 and illustrated in Fig. 4 (bottom row), the ANOVA revealed a task difference in N1 amplitude, with reduced amplitude in the production compared to the perception tasks (on average, −2.4 μV vs. −4.9 μV, respectively). For P2, there was no main effect of Group or Task and no interaction. As for latencies, Group differences were found on both N1 and P2. N1 and P2 latencies were longer for the older compared to younger groups.

3.4. SIS

A final analysis compared the amplitude of the SIS on N1 (N1 amplitude $_{perception}$—N1 amplitude $_{production}$) across groups using a one-way ANOVA, separately for the first and second epoching procedures. As shown in Fig. 4E and J, the analysis revealed a significantly reduced SIS in older adults in the second epoching procedure. Table 6 provides the details of the analyses.

4. Discussion

With age, the motor stages of speech production evolve naturally. As a consequence, a person's age is easily guessed from their speech (e.g., Lortie et al., 2018). Given that articulation consists of a rapid flow of very precise movements of the lips, tongue, soft palate and vocal folds, which must be coordinated with respiration, age-related changes in speech production appear unavoidable. Because decline in speech production can negatively impact communication-mediated activities such as family gatherings, understanding the manner and extent to which speech production evolves with age is crucial to develop mitigation and prevention strategies. Yet, while age differences in speech production are well documented, the underlying mechanisms remain elusive. This

Table 2
ANOVA results for the multimodal speech identification task.

	A. Accuracy						B. RT					
Term	df	SS	MS	F	*p*	η 2	df	SS	MS	F	*p*	η 2
Modality	2	0.04	0.02	3.61	**0.03**	0.05	2	416,800	208,400	8.61	**<.001**	0.12
Group	1	0.05	0.05	10.54	**0.00**	0.08	1	234,700	234,700	9.70	**0.00**	0.07
Modality: Group	2	0.03	0.02	3.29	**0.04**	0.05	2	7529	3765	0.16	0.86	0.00
MoCA	1	0.01	0.01	1.02	0.31	0.01	1	1412	1412	0.06	0.81	0.00
Sex	1	0.00	0.00	0.86	0.36	0.01	1	14,649	14,649	0.61	0.44	0.00
Residuals	112	0.539	0.005				112	2,710,000	24,197			

Note. SS = Sum of squares; MS = Mean squares. Bold font is used to identify significant effects and interactions.

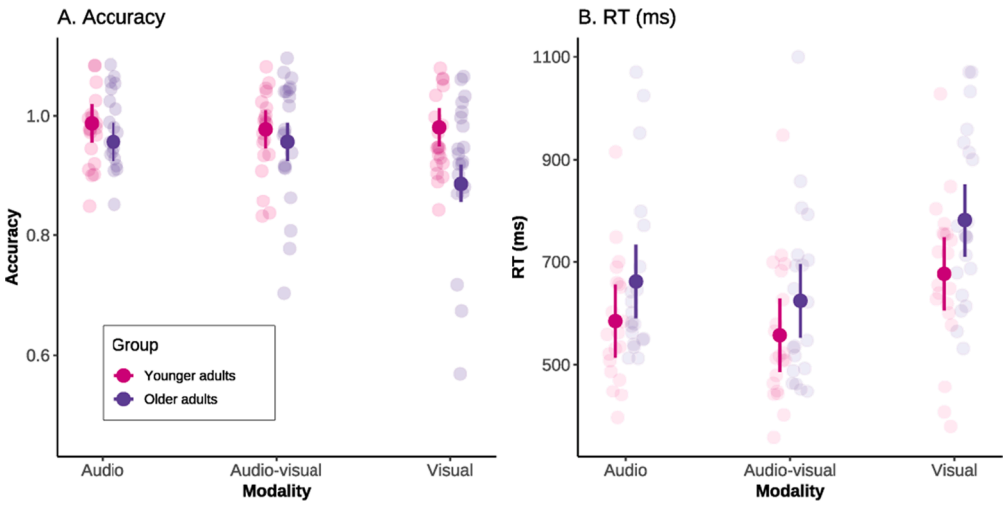

Fig. 1. Mean accuracy and RTs in the behavioural experiment for each of the Modality: auditory, audiovisual and visual; shown separately for the younger and older groups. Each dot represents one participant. The error bars represent standard errors of the mean.

Table 3
Mean vocal behaviours, acoustic values, and individual variability for /a/, /ø/ and /e/ vowels for the younger and older groups (based on ~ 5000 occurrences); SEM are provided in parentheses.

Measurement	Younger Group			Older Group			Group difference	
	/a/	/ø/	/e/	/a/	/ø/	/e/	F	P
Number of utterances	39 (3)	41 (3)	40 (3)	43 (2)	45 (2)	44(2)	3.95	**0.05**
Number of repetitions	1 (1)	1 (0)	1 (1)	3 (1)	4 (1)	3 (1)	12.15	**0.001**
Inter-trial interval (ms)	1470 (103)	1494 (107)	1483 (103)	1318 (62)	1321 (65)	1310 (67)	5.86	**0.02**
Vowel duration (ms)	216 (12)	227 (12)	220 (12)	273 (18)	289 (19)	280 (18)	22.59	**<.001**
Intensity (dB)	69 (1)	70 (1)	70 (1)	72 (1)	72 (1)	72 (1)	3.5	0.06
f_0 (Hz)	171 (10)	174 (11)	174 (11)	135 (9)	140 (9)	139 (9)	80.86	**<.001**
F_1 (Hz)	704 (32)	406 (17)	399 (16)	693 (31)	371 (13)	359 (9)	3.23	0.08
F_2 (Hz)	1388 (34)	1545 (35)	2208 (53)	1286 (38)	1492 (36)	2133 (59)	7.27	**0.01**
F_3 (Hz)	2702 (55)	2545 (47)	2893 (41)	2639 (72)	2448 (56)	2811 (70)	4.49	**0.04**
F_1-F_2-F_3 vowel space area (Hz^2)	151,449 (17558)			174,454 (25448)			0.68	0.41

study therefore aimed to examine the normal aging of the motor stages of speech production, focusing on MRCP, AEPs and SIS to shed new lights on cortical speech mechanisms. To this end, we compared neural responses evoked by speech production to those evoked by playback of the same utterances in healthy young and older adults. Taken together, our results indicate that male and female speakers retain good vowel production abilities across the lifespan, but that MRCP and AEPs, but not SIS, showed clear age-related differences.

Our hypothesis, which was verified, was that normal aging would be associated with differences in speech rate —in the form of longer vowel duration—consistent with prior studies (e.g. Marczyk et al., 2022; Tremblay et al., 2018; Tremblay et al., 2019), even after controlling for sex and cognitive level. However, detailed acoustic analyses of the corpus of vowels produced by the participants did not reveal strong age-related differences in non-temporal metrics. The distribution of F1, F2 and F3 formant values was consistent with those previously reported for French vowels (Calliope, 1989). Importantly, there was no group difference in vowel space despite some differences in F2 and F3. This is consistent with a recent study that examined vowel production in heathy aging (Marczyk et al., 2022). In contrast, in a recent analysis of the "Up" corpus (Gahl et al., 2014)—which is based on a series of documentary films featuring a group of adults aged between 21 and 49 years, filmed at seven-year intervals, over a period of 56 years (Apted, 1977, 1984, 1991, 1998)—a shift in vowel space towards the periphery was found from young to middle-aged adulthood (Gahl & Baayen, 2019). However, since no data were available on old adults, it is possible that these changes represent maturation of the system rather than age-related decline. Together, these findings suggest that articulatory space is relatively stable in aging and that it may not represent the mechanism that would explain age-related changes in intelligibility.

4.1. *Effect of age on MRCP*

Our analyses revealed a slow negative deflection on fronto-central sites occurring 800 ms to 300 ms prior to vowel production, during the preparatory phase of speech production, followed by a positive rebound from 200 ms to 0 ms prior to the vocalic onset. This time-course is in line with the literature on MRCPs/RPs and their reported temporal profiles for non-speech actions (Birbaumer et al., 1990; Kornhuber & Deecke, 1965; Libet et al., 1983). A similar pre-speech negative deflection has been shown in several studies in young adults during speaking (den Hollander et al., 2019; Jouen et al., 2021; Lancheros et al., 2020; Tremblay et al., 2008; Wang et al., 2014). Wang et al. localized this deflection to the posterior ventrolateral frontal lobe bilaterally (Wang et al., 2014), including the inferior frontal gyrus (IFG) and the posterior sensorimotor mouth area. Importantly, pre-speech IFG activity during the 300 ms before speaking was associated with SIS (see below) while, on the contrary, pre-speech activity in the sensorimotor mouth area was not related to N1 suppression, suggesting that it may represent the instantiation of the motor command itself rather than an efference copy or corollary discharge.

Despite a similar overall profile in younger and older adults, MRCPs differed significantly for the older compared to younger adults, suggesting age-related differences in speech motor planning and motor control. The amplitude of the negative deflection was significantly stronger in older adults during the preparatory phase of speech

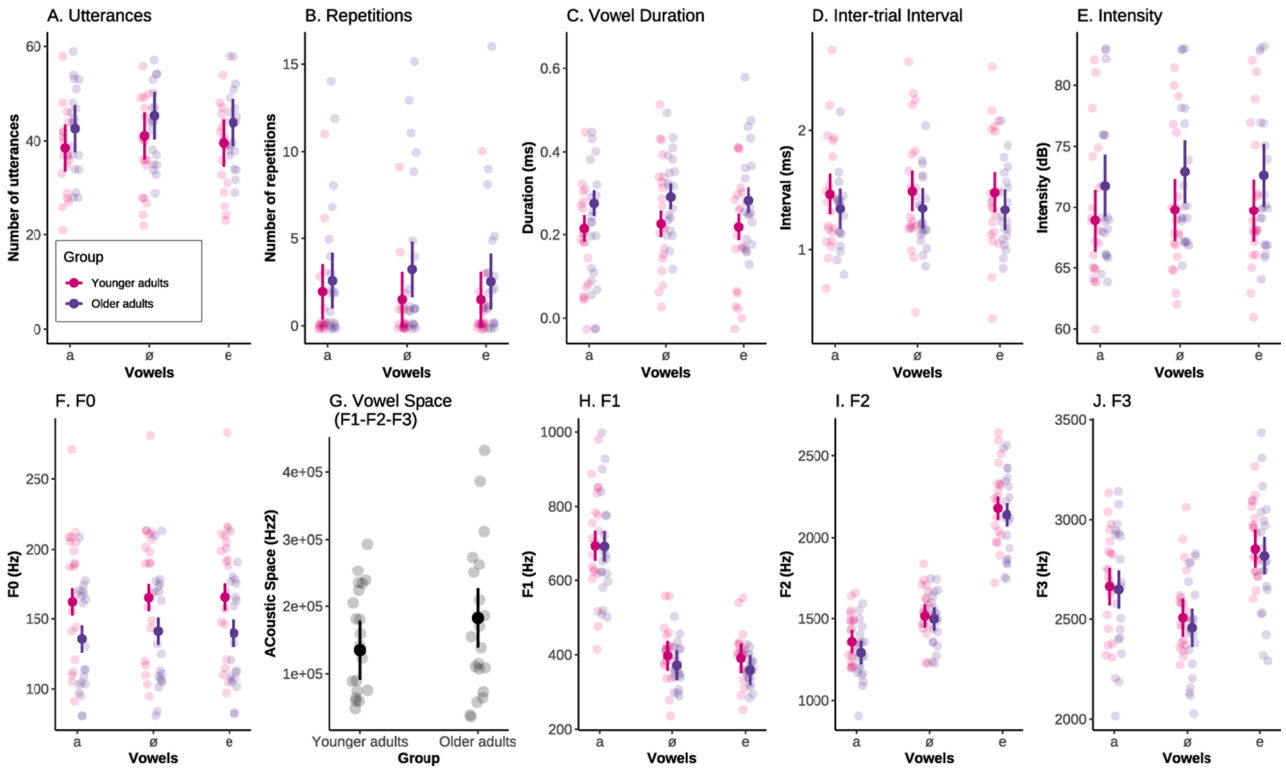

Fig. 2. Mean vocal behaviours and acoustic values for /a/, /ø/ and /e/ vowels for the younger and older groups (based on ~ 5000 occurrences). Each dot represents one participant; the error bars represent the standard error of the mean.

Table 4
Mean (SEM) N1/P2 raw amplitudes and latencies for the first epoching procedure [-100 ms to 300 ms].

	Younger group		Older Group		Group difference	
	Production	**Perception**	**Production**	**Perception**	**F**	**P**
Amplitudes (μV)						
N1	−3.35 (0.43)	−5.37 (0.59)	−3.40 (0.60)	−4.83 (0.48)	0.21	0.65
P2	2.12 (0.56)	3.42 (0.63)	1.32 (0.83)	3.24 (0.44)	0.6	0.44
Latencies (ms)						
N1	84 (3)	85 (3)	98 (4)	92 (2)	10.9	**<.001**
P2	173 (7)	173 (3)	202 (9)	202 (5)	21.23	**<.001**

production from 800 ms to 200 ms prior to the vocalic onset. Our results build from prior work from Johari et al. which showed that unpredictable (but not predictable) externally triggered are associated with greater premotor ERP activity in older compared to younger adults (Johari et al., 2019). In a follow-up publication Johari showed that, compared to younger adults, older adults exhibited increased event-related desynchronization in the alpha and beta bands before and after the speech production (Johari & Behroozmand, 2020). Interestingly, in our study, vowel production was self-paced, which is known to engage stronger event-related desynchronization compared to externally triggered speech movements (Tremblay et al., 2008). Together, these findings suggest that the control of speech motor timing is altered in older adults because of less efficient neural processing, indexed by amplified premotor neural activation. This is consistent with the finding of age-related differences in the timing of the responses in the present study, with longer vowels and shorter inter-trial intervals, but also with a large body of evidence suggesting that the temporal characteristics of speech production are compromised in aging (e.g., Bilodeau-Mercure et al., 2015; Bilodeau-Mercure & Tremblay, 2016; Jacewicz et al., 2009; Marczyk et al., 2022; Morris & Brown, 1987; Padovani et al., 2009; Sadagopan & Smith, 2013; Smith et al., 1987a; Tremblay & Deschamps, 2016; Tremblay et al., 2018; Tremblay et al., 2017).

This finding is also consistent with evidence from brain imaging studies, which have shown that the cortical and subcortical systems supporting speech production change with age (Shuster et al., 2014; Sörös et al., 2011; Tremblay et al., 2013), including the striatum, a region involved in the preparation and execution of speech, the insular cortex, a region best known for its role in multimodal integration and executive control, and the supramarginal gyrus, known for its role in phonological encoding. A recent MRI study showed that structural decline in these different regions is associated with the production of longer syllable sequences in older adults (Tremblay & Deschamps, 2016). Differences in the activity of the primary motor cortex, measured using fMRI, have been shown to correlate with changes in the duration of speech responses (Tremblay et al., 2017).

In sum, the present results suggest that the neural preparation of self-paced vowels, despite the simplicity of the task, requires additional neural resources in older adults, which contributes to the body of evidence showing that normal aging affects the timing of speech. While our groups differed in terms of their MoCA score, all analyses included the MoCA as a covariate. It is therefore unlikely that a difference in cognitive level can account for the present findings. Additional research is needed to understand which specific mechanisms are affected by brain aging, such as phonetic encoding, motor sequencing and speech

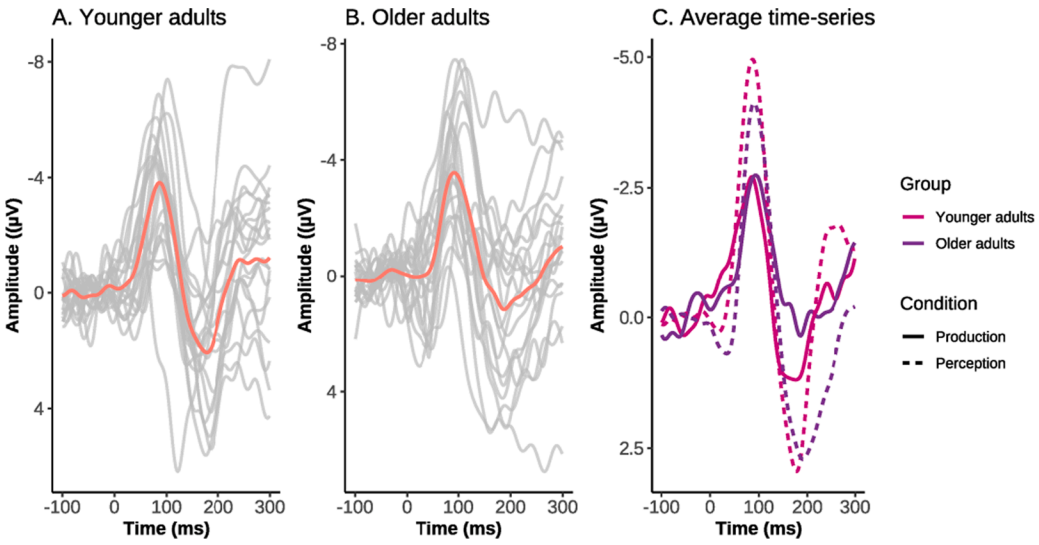

Fig. 3. A and B: Individual EEG waveforms for the younger and older groups on fronto-central electrodes averaged over the two tasks from the [-100 ms to 300 ms] epoching procedure (the orange lines represented the average of all participants). C. Average EEG waveform for each task for the younger and older groups.

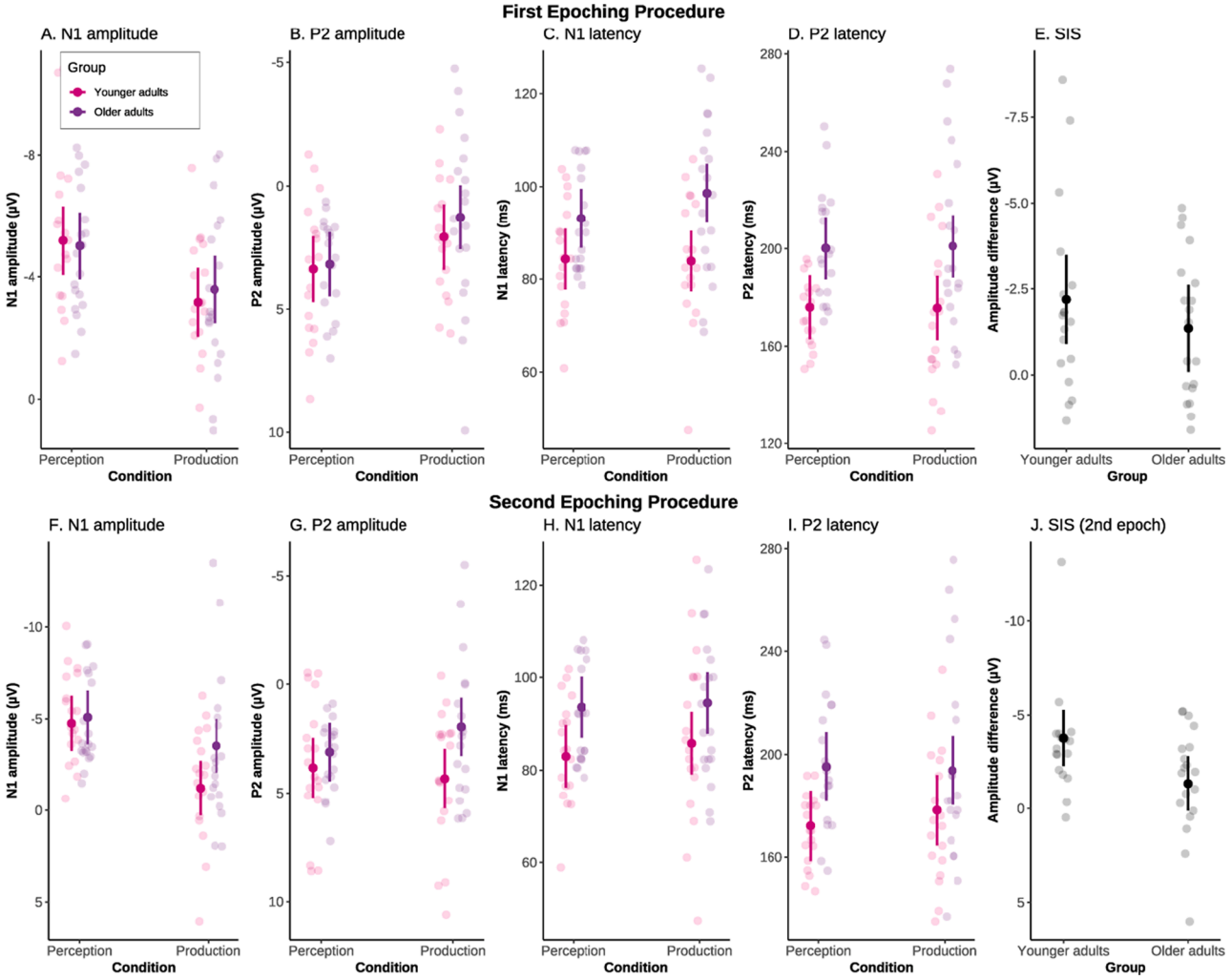

Fig. 4. AEP. Top row: first epoching procedure. A-D: Mean N1 and P2 AEP amplitudes and latencies for the younger and older groups. E. SIS amplitude. Bottom row: second epoching procedure. F-I: Mean N1 and P2 AEP amplitudes and latencies for the younger and older groups.. J. SIS amplitude. Each dot represents one participant; the error bars represent the standard error of the mean.

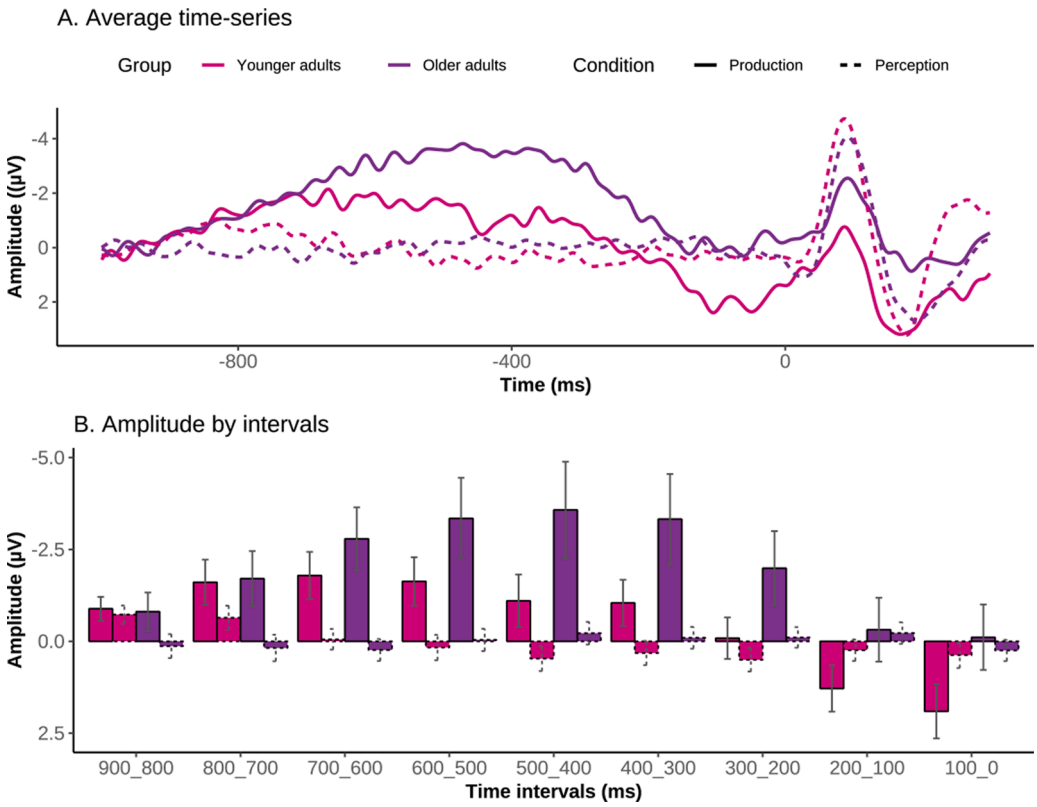

Fig. 5. A. Average EEG waveform for each task on fronto-central electrodes for the younger and older groups from the second epoching procedure [-1000 ms to 300 ms]. B. Mean amplitude of MRCPs. Each dot represents one participant; the error bars represent the standard error of the mean.

Table 5
MRCP mean (SEM) amplitudes and N1/P2 amplitudes and latencies for the second epoching procedure [-1000 ms to 300 ms].

	Younger Group		Older Group		Group difference	
	Production	**Perception**	**Production**	**Perception**	**F**	**P**
Amplitudes (μV)						
−900–800 ms	−0.88 (0.32)	−0.73 (0.25)	−0.81 (0.51)	0.13 (0.32)	13.03	**<.001**
−800–700 ms	−1.61 (0.62)	−0.64 (0.33)	−1.71 (0.73)	0.18 (0.35)		
−700–600 ms	−1.79 (0.65)	−0.05 (0.28)	−2.79 (0.83)	0.24 (0.29)		
−600–500 ms	−1.63 (0.66)	0.17 (0.35)	−3.34 (1.08)	−0.04 (0.30)		
−500–400 ms	−1.10 (0.72)	0.47 (0.34)	−3.57 (1.28)	−0.22 (0.30)		
−400–300 ms	−1.04 (0.63)	0.32 (0.33)	−3.32 (1.20)	−0.09 (0.29)		
−300–200 ms	−0.08 (0.57)	0.51 (0.32)	−1.99 (0.98)	−0.11 (0.27)		
−200–100 ms	1.29 (0.63)	0.24 (0.29)	−0.31 (0.85)	−0.22 (0.29)		
−100 0 ms	1.91 (0.74)	0.38 (0.35)	−0.11 (0.87)	0.25 (0.28)		
N1	−1.58 (0.72)	−5.11 (0.57)	−3.20 (0.91)	−4.75 (0.53)	0.8	0.38
P2	4.22 (0.74)	3.72 (0.69)	2.17 (0.75)	3.33 (0.37)	3.5	0.07
Latencies (ms)						
N1	87 (4)	84 (3)	92 (3)	92 (2)	3.83	**0.05**
P2	176 (6)	170 (3)	195 (9)	197 (6)	12.14	**0.001**

Table 6
ANOVA results for the SIS analysis.

Term	**A. First Epoching Procedure**						**B. Second Epoching Procedure**					
	df	**SS**	**MS**	**F**	**p**	**η 2**	**df**	**SS**	**MS**	**F**	**p**	**η 2**
Group	1	3.229	3.229	0.527	0.473	0.015	1	36.419	36.419	4.462	**0.042**	0.116
Sex	1	10.11	10.11	1.651	0.208	0.047	1	2.662	2.662	0.326	0.572	0.009
MoCA	1	1.177	1.177	0.192	0.664	0.005	1	4.49	4.49	0.55	0.463	0.014
Residuals	33	202.07	6.123				33	269.319	8.161			

initiation in groups of older adults matched for cognitive and hearing levels.

4.2. *Effect of age on AEPs and SIS*

Overall, longer latencies were observed in older adults on N1 and P2 AEPs in both epoching procedures. This suggests slower neural

processing time for either encoding or processing and appears consistent with the longer RTs observed in the multimodal speech identification task.

Our results show a classic SIS effect on N1 amplitude, with a reduced response in the production task compared to the perception task, consistent with previous EEG/MEG studies on efference copy and corollary discharge during speech production (e.g., Curio et al., 2000; Ford & Mathalon, 2004; Ford et al., 2001; Heinks-Maldonado et al., 2006; Houde et al., 2002; Niziolek et al., 2013; Numminen et al., 1999; Sato & Shiller, 2018; Ventura et al., 2009; Wang et al., 2014). Contrary to our hypothesis, age differences in SIS were modest: we found that SIS magnitude was reduced in older adults in the second epoching procedure, that is, when AEPs were calculated in relation to a baseline outside the temporal windows of MRCP. However, when considering/subtracting the temporally contingent influence of MRCP on AEPs in the first epoching procedure, SIS effect was evident for both groups and did not show group differences. Together with our analysis of the MRCP, these findings suggest that SIS is relatively resilient to age and does not play a major part in the difficulties experienced with older adults, whose difficulties would result from less efficient motor preparation rather than motor-to-auditory integration.

4.3. Conclusions

The present study adds new and important information about the aging of speech production mechanisms, by showing that pre-speech MRCP—which reflects motor planning of the upcoming response—differs extensively between healthy younger and older adults during a simple self-paced vowel production task and that, in contrast, SIS—which indexes auditory predictions of speech motor commands—appears to be relatively preserved. Additional studies should strive to isolate and localize the speech planning processes that are affected by aging more precisely, using either EEG source localization procedures or magnetic resonance imaging. This information is crucial to the development of prevention or mitigation strategies such as excitatory brain stimulation methods to enhance declining speech-related processes, which could lead to enhanced communication in older adults and, in turn, preserved quality of life.

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Data availability statement

In accordance with Open Practices, all data (raw and processed), code, analysis pipelines, materials and results are available in the project OSF repository at https://osf.io/g32zq/

CRediT authorship contribution statement

Pascale Tremblay: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Marc Sato:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2024.105415.

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