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A multidimensional characterization of the neurocognitive architecture underlying age-related temporal speech processing

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ABSTRACT

Healthy aging is often associated with speech comprehension difficulties in everyday life situations despite a pure-tone hearing threshold in the normative range. Drawing on this background, we used a multidimensional approach to assess the functional and structural neural correlates underlying age-related temporal speech processing while controlling for pure-tone hearing acuity. Accordingly, we combined structural magnetic resonance imaging and electroencephalography, and collected behavioral data while younger and older adults completed a phonetic categorization and discrimination task with consonant-vowel syllables varying along a voice-onset time continuum. The behavioral results confirmed age-related temporal speech processing singularities which were reflected in a shift of the boundary of the psychometric categorization function, with older adults perceiving more syllable characterized by a short voice-onset time as /ta/ compared to younger adults. Furthermore, despite the absence of any between-group differences in phonetic discrimination abilities, older adults demonstrated longer N100/P200 latencies as well as increased P200 amplitudes while processing the consonant-vowel syllables varying in voice-onset time. Finally, older adults also exhibited a divergent anatomical gray matter infrastructure in bilateral auditory-related and frontal brain regions, as manifested in reduced cortical thickness and surface area. Notably, in the younger adults but not in the older adult cohort, cortical surface area in these two gross anatomical clusters correlated with the categorization of consonant-vowel syllables characterized by a short voice-onset time, suggesting the existence of a critical gray matter threshold that is crucial for consistent mapping of phonetic categories varying along the temporal dimension. Taken together, our results highlight the multifaceted dimensions of age-related temporal speech processing characteristics, and pave the way toward a better understanding of the relationships between hearing, speech and the brain in older age.

1. Introduction

Human behavior is a complex matrix of interacting variables that can best be understood using a multidimensional approach (Bethlehem et al., 2022; Tozzi, 2019). Hence, the combination of manifold behavioral and brain indices might provide fruitful insights into traits and states that go beyond those of single metrics. Healthy aging constitutes a prime example of phenotypic variability that cannot be satisfactorily explained by behavioral or brain parameters in isolation. In fact, although gray and white matter properties usually change with age (Bethlehem et al., 2022; Sele et al., 2020; Taki et al., 2013; Thambisetty et al., 2010), older individuals often demonstrate heterogeneous functional-anatomical, cognitive and behavioral profiles with substantial variations around the mean slopes (Bethlehem et al., 2022; Sele et al., 2020, 2021). Furthermore, a simple correspondence between age-related anatomical changes and behavioral or cognitive functioning is complicated by neurofunctional compensatory mechanisms which are critical for maintaining neural network stability, and are usually manifested in functional hyperactivity (Shafto and Tyler, 2014).

Healthy aging can be associated with both positive and negative connotations (Nieuwenhuis-Mark, 2011). While a decline in executive functions (Shafto and Tyler, 2014), short-term memory and working

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memory (Rhodes and Katz, 2017; Rieckmann et al., 2017) as well as episodic memory (Fjell et al., 2016) seems to be a common denominator of aging, critical language skills like vocabulary and semantic processing have been shown to improve across the lifespan (Shafto and Tyler, 2014). Importantly, older individuals also frequently experience persistent difficulties in understanding speech in noisy environments (Giroud et al., 2021a; Recanzone, 2018; Schmitt et al., 2022; Tremblay et al., 2021), and usually demonstrate lower performance compared to younger cohorts in discriminating temporal (Oron et al., 2019; Strouse et al., 1998; Tremblay et al., 2002; Walton, 2010) and spectral (Bidelman et al., 2014; Chauvette et al., 2022; Isler et al., 2021) speech attributes. Spectral speech perception difficulties have, for example, been documented using vowel (Bidelman et al., 2014; Isler et al., 2021) or fricative discrimination tasks (Giroud et al., 2017), and been linked to altered brain activity and divergent neuroanatomical patterns at both the cortical (Giroud et al., 2019; Isler et al., 2021) and subcortical level (Bidelman et al., 2014; Chauvette et al., 2022). Otherwise, age-related temporal speech perception singularities have commonly been reported in the context of time-compressed speech (Gordonsalant and Fitzgibbons, 1993) and temporal order discrimination tasks (Fogerty et al., 2010, 2012), gap detection tasks (Strouse et al., 1998) as well as in experimental conditions requiring the distinction of consonant-vowel (CV) syllables varying in voice-onset time (VOT) (Oron et al., 2019; Tremblay et al., 2002).

Currently, there is little doubt that speech perception difficulties in OA are often caused by pure-tone hearing loss, which is commonly referred to as presbycusis and manifested, according to an audiogram, in poorer hearing in the high frequency range of the acoustic spectrum (Gates and Mills, 2005). Such a reduction in pure-tone hearing sensitivity is typically observed in approximately one third of the population aged above 65 years (Lin et al., 2011), and may have important repercussions on psychosocial health and quality of life (Gates and Mills, 2005; Heine and Browning, 2002; Pronk et al., 2014) as well as implications for the risk of dementia (Chern and Golub, 2019; Giroud et al., 2021b; Thomson et al., 2017). Although the exact pathophysiology of presbycusis is unclear, there is agreement that this specific kind of hearing disability is related to a deterioration of cochlear hair- and spiral ganglion cells in the inner ear that affects impulse transmission along the ascending auditory pathways (Gates and Mills, 2005). Nevertheless, according to recent findings, such peripheral dysfunctions are not the only possible cause of speech perception difficulties in older individuals (Giroud et al., 2018a, 2019, 2021a). In fact, it is not uncommon that OA report speech perception difficulties in everyday life situations despite pure-tone audiograms in the normative range (Fullgrabe, 2013; Fullgrabe et al., 2014; Hopkins and Moore, 2011; Moore et al., 2014). This perspective is particularly relevant because it suggests a multifactorial genesis of age-related challenges in speech perception which is possibly mediated by both, presbycusis and age-related brain changes (Giroud et al., 2018a; Lin et al., 2014). Importantly, in OA not only clinically relevant hearing loss but also hearing loss in the normative range is often associated with difficulties in processing acoustic signals in the higher frequency spectrum (Humes, 2020).

Auditory-related cortical areas as well as extra-auditory brain regions involved in phonetic decoding, linguistic processes and higher cognitive functions fundamentally contribute to how speech codes are transcribed and analyzed (Friederici, 2002; Hagoort, 2014; Hickok and Poeppel, 2007; Scott and Johnsrude, 2003; Specht, 2014). Hence, at least on a gross neuroanatomical scale, brain areas clustered around the bilateral Sylvian fissure and located in the ventral and dorsal parts of the prefrontal cortex are possible candidates for explaining speech perception difficulties in OA (Hagoort, 2014; Specht, 2014). Even though this specific topic is relatively underexplored, there is at least some evidence indicating a negative relationship between pure-tone hearing loss (Lin et al., 2014; Rosemann and Thiel, 2020) or speech discrimination disabilities (Giroud et al., 2018a; Isler et al., 2021) and different gray matter parameters in the auditory-related cortex and the adjacent superior temporal gyrus (STG) (Eckert et al., 2012; Giroud et al., 2018a; Isler et al., 2021), superior temporal sulcus (STS) (Lin et al., 2014), inferior (IFG) and middle (MFG) frontal gyrus (Rosemann and Thiel, 2020) as well as in the ventrolateral (VLPF) and dorsolateral prefrontal (DLPF) cortex (Giroud et al., 2021a; Rosemann and Thiel, 2020). Furthermore, few studies provided a link between age-related differences in gray matter integrity in multiple auditory-related territories or frontal brain regions and vowel discrimination skills (Isler et al., 2021), prosodic processing (Giroud et al., 2019) as well as phonetic categorization and discrimination abilities (Giroud et al., 2018a). However, most of the previous studies did not use a multidimensional approach to assess the complex interplay between age-related speech discrimination difficulties, cortical gray matter parameters and brain functioning.

The aim of this study was to characterize the neurocognitive matrix underlying age-related temporal speech processing by comparing a sample of YA and OA while at the same time controlling for individual differences in pure-tone hearing loss. With this purpose in mind, we combined EEG and structural brain imaging protocols, and collected behavioral data while YA and OA completed a phonetic categorization and discrimination task. During the phonetic categorization task with voiced and voiceless CV syllables varying in VOT, the participants had to assign prototypical and ambiguous items along a /da/-/ta/ continuum to the respective phonetic categories. In contrast, in the phonetic discrimination task the participants had to judge whether pairs of CV syllables from the same VOT continuum were same or different. Importantly, while administering the phonetic discrimination task, we also collected EEG data and evaluated event-related potentials (ERPs) in response to the first CV syllable of the pairs to assess the timing and strength of neural activity in the bilateral auditory-related cortex. Furthermore, we extracted cortical surface area (CSA) and cortical thickness (CT) parameters from a set of a-priori defined anatomical regions situated around the bilateral Sylvian fissure as well as in the frontal cortex to examine gray matter traits associated with speech discrimination abilities in YA and OA. Finally, we also addressed possible relationships between neuroanatomy, brain function and behavior using correlation analyses.

Based on previous studies (Oron et al., 2019; Strouse et al., 1998; Tremblay et al., 2002; Walton, 2010), we predicted that age-related temporal speech processing difficulties result in a less consistent categorization of items with short VOTs, and are reflected in more frequent /ta/ categorizations in OA compared to YA. This assumption is rooted in the fact that most of these studies found that OA had generally more difficulties than YA in voicing perception (Oron et al., 2019) or in discriminating voice-onset contrasts (Tremblay et al., 2002; Walton, 2010), especially at lower stimulus levels (Strouse et al., 1998). Although most of them did not directly test phonetic categorization, they at least indicated that temporal speech processing difficulties in OA are possibly mediated by a slowing down of neural processing (Oron et al., 2019), by changes in the regulation of excitatory and inhibitory signal transmission (Tremblay et al., 2002), or by a general difficulty in encoding temporal sound attributes (Walton, 2010). Otherwise, the opposite scenario is also conceivable, namely that OA categorize the stimuli more frequently as /da/ than /ta/ because the longer aspiration time has to be recognized in order to assign the CV syllables to the latter category. Moreover, we expected that OA exhibit difficulty in discriminating pairs of CV syllables with small VOT differences compared to YA (Oron et al., 2019; Tremblay et al., 2002), and demonstrate a dysfunctional timing and strength of auditory-evoked ERPs to those syllables (Oron et al., 2019; Tremblay et al., 2003). In this context, we focused on two specific ERPs which are known to be mainly generated in the auditory cortex (Liegeois-Chauvel et al., 1994; Picton et al., 1999; Scherg and von Cramon, 1986), namely the N100 and P200 components. The examination of the timing (i.e., latency) and strength (i.e., amplitude) of these two auditory-evoked responses is particularly fruitful to infer processing time (i.e., latency) as well as to estimate the synchrony and number of neurons (i.e., amplitude) involved in specific aspects of

auditory processing (Boutros et al., 1997; Naatanen and Picton, 1987; Paulraj et al., 2015; Woods, 1995). Based on previous work indicating age-related changes in auditory-evoked ERPs, we predicted that OA would generally demonstrate longer latencies and smaller amplitudes compared to the YA cohort (Harris et al., 2008; Kerr et al., 2011; Kim et al., 2012). Finally, based on structural brain dynamics across the lifespan (Bethlehem et al., 2022), we also postulated overall reduced gray matter parameters in OA compared to YA (Giroud et al., 2018a) as well as an association between brain anatomy and functional-behavioral correlates of phonetic processing. In particular, based on the results, relationships between brain anatomy, EEG and the behavioral data of the phonetic categorization and discrimination tasks were assessed using exploratory correlation analyses without clear assumptions about the direction of the effects. Otherwise, for the anatomical analyses, we focused on a specific set of pre-selected regions-of-interest (ROIs) residing in perisylvian and frontal brain areas which have repeatedly been associated with phonetic processing and categorization (Benson et al., 2006; Binder, 2000; Binder et al., 1997; Blumstein et al., 2005; Elmer et al., 2012; Fuhrmeister and Myers, 2021; Jancke et al., 2002; Zaehle et al., 2008, 2004) as well as with auditory-related cognitive functions (Fedorenko et al., 2012; Hagoort, 2013, 2014; Jurado and Rosselli, 2007; Menon and D'Esposito, 2022). Drawing on this background, we evaluated the bilateral IFG (pars opercularis, triangularis and orbitalis), VLPF and DLPF cortex, planum temporale, planum polare, STG, STS, Heschl's sulcus and the Heschl's gyrus.

2. Materials and methods

2.1. Participants

Seventeen YA (age range = 20–29 years, $M = 24.41$, $SD = 3.12$, 11 female) and 23 OA were recruited for the study. However, due to a technical problem with the response box, the behavioral data of the phonetic categorization and discrimination tasks of 3 OA could not be properly collected. Hence, these 3 individuals were excluded from all analyses, resulting in a sample size of 20 OA (age range = 67–84 years, $M = 72.40$, $SD = 4.97$, 9 female). All participants were consistently right-handed (Annett, 1970), native Swiss German speakers, and did not report past or present neurological, psychological or psychiatric impairments. Furthermore, none of the participants was exposed to a second language before the age of 7 years or played a musical instrument for more than 10 h per week. All participants gave informed written consent in accordance with the procedures of the local ethics committee and the declaration of Helsinki, and were paid for participation.

2.2. Cognitive capabilities

In the present study, we tested a small set of cognitive functions which have been shown to be affected by aging (Shafto and Tyler, 2014), and might have an influence on phonetic processing and discrimination abilities, namely short-term memory and working memory (Elmer et al., 2021, 2017). Short-term and working memory abilities were examined by means of digit span forward and backward tasks consisting of overtly reproducing sequences of digits of increased length (Lehrl et al., 1992).

2.3. Pure-tone audiometry

Pure-tone audiometry was conducted separately for both ears to determine the degree of peripheral hearing loss, and consisted of detecting pure tones presented for 250 ms at 500, 1000, 2000 and 4000 Hz. Thereby we used the same in-house MATLAB-based procedure as described in previous studies of our group (Giroud et al., 2018a; Schmitt et al., 2022). Furthermore, to provide a global assessment of hearing acuity for each participant, we used pure-tone averages (PTA) by computing mean hearing thresholds across the two ears and the octave frequencies in the range of 500–4000 Hz. According to this approach, the pure-tone thresholds were nearly symmetrical for both ears (YA and OA: interaural difference < 11 dB) and clearly below a clinically relevant cut-off level of 25 dB (World Health Organization, WHO) in both groups (mean YA = 1.69, mean OA = 10.55, Fig. 1). Therefore, although OA demonstrated pure-tone hearing loss in the high frequency range, PTA was still in the normative range (Humes, 2020). Due to a technical problem with the software, the audiometric profiles of 4 YA could not be collected and were replaced by the mean value of the respective cohort.

2.4. Auditory stimuli

The purpose of this study was to examine age-related differences in processing temporal speech patterns. Hence, the auditory stimuli consisted of seven CV syllables varying along a synthetic /da/-/ta/ continuum which were used for both the phonetic categorization and discrimination tasks. In a first step, the two prototypical CV syllables /da/ (VOT = 10 ms) and /ta/ (VOT = 70 ms) were recorded from a professional male speaker at a sampling rate of 44.1 kHz (Kuhnis et al., 2013). Afterwards, the consonant (25 ms) and the vowel (309 ms) of the syllable /da/ were separated and reassembled to build the five additional CV syllables of the VOT continuum. In particular, the aspiration period of the syllable /ta/ was cut out, and inserted in between the consonant and the vowel to form CV syllables with a VOT of 20, 30, 40, 50 and 60 ms. All seven CV syllables were normalized to an average intensity of 70 dB using the Audacity software (https://www.audacityteam.org/) (Fig. 2).

2.5. Phonetic categorization task

The participants started the experiment with the phonetic categorization task which was followed by the phonetic discrimination condition. To become familiar with the stimulus material, at the beginning of the experiment the participants were exposed to the two CV syllables with a VOT of 10 and 70 ms which served as prototypical examples for /da/ and /ta/.

To familiarize themselves with the stimuli, the participants could repeat the examples as many times as they wanted. Afterwards, in the main experimental session, the participants were presented with seven CV syllables varying in VOT and instructed to categorize each item as either /da/ or /ta/ by pressing the respective response button (left = /da/, right = /ta/). Each of the seven items was presented four times in a randomized order with a trial duration of 3 s. The presentation of the auditory stimuli and the collection of behavioral responses were controlled by the Presentation software (Version 11.0, Neurobehavioral Systems).

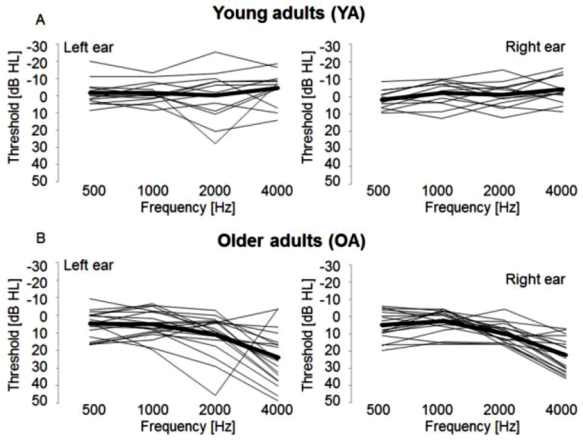

Fig. 1. The pure-tone audiometric profiles in the range of 500–4000 Hz are shown separately for each participant, the two ears and the two groups (A and B). The bold line depicts the mean of the sample.

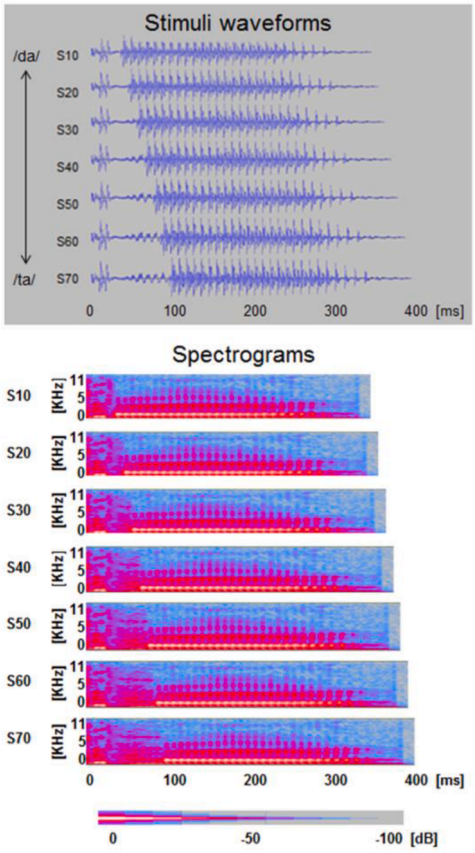

Fig. 2. Waveforms and spectrograms of the consonant-vowel (CV) syllables with a voice-onset time (VOT) of 10 (S10), 20 (S20), 30 (S30), 40 (S40), 50 (S50), 60 (S60) and 70 (S70) ms. In the spectrograms, the y-axis depicts frequency in KHz, with red colors reflecting high and blue colors reflecting low energy.

2.6. Phonetic discrimination task

The phonetic discrimination task consisted of judging whether pairs of CV syllables varying in VOT were same or different (left button = same, right button = different). Furthermore, during this task we also collected EEG data and evaluated the strength and timing of auditory-evoked ERPs to objectify the neural encoding of CV syllables varying in VOT as a function of age. Importantly, unlike previous studies which combined phonetic categorization and discrimination tasks to investigate the phenomenon of categorical perception (Goldstone and Hendrickson, 2010; Kuhl, 2004; Macmillan et al., 1977), here we used a fast mapping procedure to determine participants' minimal VOT separation width. Hence, we did not test all equidistant VOT differences within and across phonetic categories but rather focused on tracking general temporal resolution capabilities by presenting pairs of CV syllables with VOT differences (ΔVOT) of 0 (same), 20, 30, 40, 50 and 60 ms (Fig. 3). The aim of this approach was to examine which VOT separation width is critical for aging, irrespective of the serial position of the CV syllables along the VOT continuum. Thereby, it is noteworthy to mention that we abstained from pairing syllables situated at the left (S10, S20 and S30, Fig. 3) and right (S50, S60 and S70, Fig. 3) end of the continuum because participants are not able to properly distinguish them, possibly due to the so-called magnet effect (Fry et al., 1962; Kuhl, 2004; Lively and Pisoni, 1997). Furthermore, since the distinction of items situated in the proximity of the boundary (S40) is easier, we also avoided to pair syllables at the left or right end of the continuum with the stimulus S40 which was situated in the middle of the sequence.

The first stimulus of the pairs was one of four CV syllables with a VOT

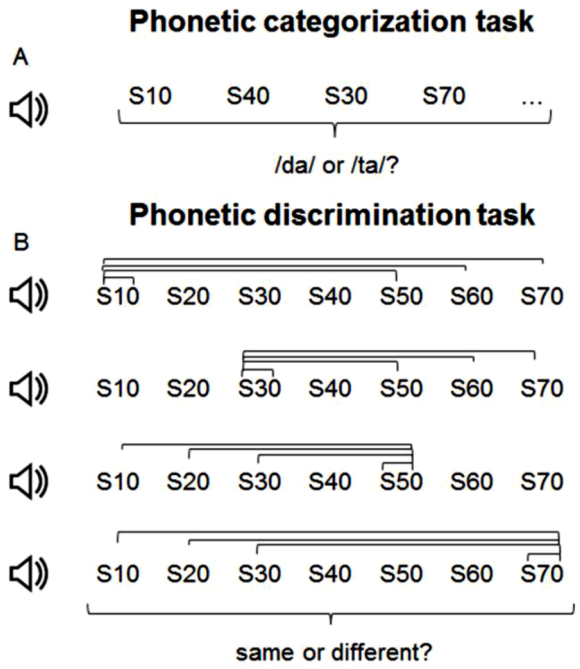

Fig. 3. Experimental design of the phonetic categorization (A) and discrimination (B) task. S10-S70 = consonant-vowel (CV) syllables with a voice-onset time (VOT) in the range of 10–70 ms.

of 10 (/da/), 30, 50 or 70 (/ta/) ms which was followed, after an inter-stimulus interval of 1000 ms, by a second CV syllable. Furthermore, after the presentation of the second stimulus of the pairs we inserted an inter-trial interval in the range of 2000–2200 ms, with a jitter of 0, 100 or 200 ms. The two prototypical items situated at the end of the continuum, namely /da/ (VOT = 10 ms) and /ta/ (VOT = 70 ms), were followed either by the same stimulus or by an item with a ΔVOT of 40, 50 or 60 ms. For example, the prototypical CV syllable /da/ with a VOT of 10 ms was presented twice in a row, or paired with a syllables with a VOT of 50, 60 or 70 ms. In contrast, the two CV syllables located around the midpoint of the continuum and characterized by a VOT of 30 and 50 ms were paired with the same stimulus or with a CV syllable with a ΔVOT of 20, 30 and 40 ms placed on the opposite side of the continuum. For instance, the CV syllable with a VOT of 50 was presented together with his twin stimulus or with an item with a VOT of 10, 20 and 30 ms. The phonetic discrimination task included two blocks with a total of 108 trials (54 same and 54 different) and lasted 12.5 min. The presentation of the auditory stimuli and the collection of behavioral responses were controlled by the Presentation software (Version 11.0, Neurobehavioral Systems). In the present work, we also evaluated the EEG responses to the first stimulus of the pairs characterized by a VOT of 10, 30, 50 and 70 ms.

2.7. EEG data acquisition and processing

During the phonetic discrimination task, the EEG data were recorded with a sampling rate of 512 Hz, and filtered on-line with a bandpass filter of 0.1–100 Hz (https://shorturl.at/abcG4) using a BIOSEMI 128 channel system (ActiveTwo, BioSemi B.V., Amsterdam, Netherlands). Eye movements were monitored with two ocular electrodes placed below the eyes, and electrode impedances were kept below 20 kΩ. All pre-processing steps were performed with the Brain Vision Analyzer software package (Version 2.0.4, BrainProducts, Munich, Germany). In particular, the data were re-referenced off-line to the mean activity of the two mastoid electrodes, band-pass filtered in the range of 0.1–20 Hz using a zero-phase shift Butterworth filter (24 dB/oct, including a band-

stop Notch filter at 50 Hz), and noisy channels were interpolated (i.e., on average 2.7 in YA and 2.9 in OA). In two individuals of the OA group, one interpolated electrode (C3) belonged to the inspected ROIs. Eye blinks and saccades were corrected using an Independent Component Analysis (ICA) (Jung et al., 2000), whereas remaining muscle artefacts were removed from −200 ms before to 200 ms after events using an automatic raw data inspection if a voltage gradient criterion of 50 μV/ms or an amplitude criterion of ±100 μV was exceeded.

Afterwards, brain responses to the first stimulus of the pairs were segmented into units of 1100 ms, baseline corrected from −100 to 0 ms, and averaged for each participant and stimulus type (VOT = 10, 30, 50, and 70 ms). To maximize power and to avoid a different signal-to-noise ratio between the two groups, we refrained from including only correctly answered trials. Hence, all trials that survived the raw data inspection were analyzed (YA: VOT 10 = 90.68%, VOT 30 = 90.36%, VOT 50 = 89.43%, VOT 70 = 90.85%; OA: VOT 10 = 83.05%, VOT 30 = 83%, VOT 50 = 82.87%, VOT 70 = 82.40%). A 2 × 4 ANOVA (2 groups x 4 CV syllables) confirmed that the number of trials entering data analyses did not differ significantly between the two groups (all p values > .25).

For the ERP analyses, we exclusively focused on the N100 and P200 components which have previously been shown to be associated with main sources in primary and secondary auditory regions (Bosnyak et al., 2004; Liegeois-Chauvel et al., 1994; Picton et al., 1999; Scherg and von Cramon, 1986), and evaluated maximal N100/P200 amplitudes (peak amplitudes) and latencies in the pre-selected time windows. Otherwise, we omitted analyses of the P50 component because after having carefully examined the individual waveforms we concluded that the data (particularly from the older participants) were too noisy to allow clear peak detection for all participants. Based on the grand average waveform computed across all participants and stimuli, the N100 component was defined as the first negative deflection in the latency window of 90–230 ms, whereas the P200 component was identified as the second positive deflection in the range of 140–350 ms. The EEG analyses focused on three ROIs situated at anterior (mean of electrodes F3, Fz and F4), central (mean of electrodes C3, Cz, C4) and posterior (mean of electrodes P3, Pz, P4) scalp sites. These ROIs (Elmer et al., 2022, 2021) were selected based on the topographical distribution maps (Fig. 6), on previous studies showing maximal N100 and P200 amplitudes at central electrodes in response to CV syllables (Heimrath et al., 2016; Ott et al., 2011; Zaehle et al., 2007), as well as on previous literature indicating a shift of auditory-related ERPs along the anterior-posterior axis as a function of aging (Pfefferbaum et al., 1980; Sandman and Patterson, 2000).

2.8. Neuroanatomical data acquisition and processing

The structural magnetic resonance imaging (sMRI) sequence was the same as the one used in a previous study of our group (Giroud et al., 2018a). Hence, in the next paragraphs we reiterated the description of the procedure used in this previous work. The structural data were collected using a 3.0 T Philips Ingenia scanner (Philips Medical Systems, Best, The Netherlands) with a 12 channel head-coil. A high resolution T1-weighted anatomical 3D Turbo-Field-Echo (TFE) sequence was measured with echo time (TE) = 3.79 ms, repetition time (TR) = 8.18 ms, field of view (FOV) = 240 × 160 × 240 mm, acquisition matrix = 256 × 256, 160 slices per volume, and isotropic voxel size = 0.94 × 0.94 × 1 mm, flip angle (α) = 90° Cortical surface reconstruction was performed with the FreeSurfer image analysis suite (version 5.1.0.). The software is documented online and freely available (http://freesurfer.net/). Surface-based morphometry (SBM) implemented in the FreeSurfer pipeline involves several preprocessing steps, which have already been extensively described in prior publications (Dale et al., 1999; Dale and Sereno, 1993; Fischl and Dale, 2000; Fischl et al., 2001, 2002, 2004a; Fischl et al., 1999a, 1999b, 2004b; Reuter et al., 2010; Segonne et al., 2004). The pipeline proceeds in a fully automated way, and generates individual cortical surface models with millimeter precision. Furthermore, all brain images were manually checked for segmentation accuracy, but no manual editing of the segmentation was conducted. After preprocessing, FreeSurfer was used to extract CT and CSA at each vertex of the surface. CT is defined as the minimal distance between gray-white matter border and the pial surface at each vertex of the tessellated surface (Fischl and Dale, 2000), whereas CSA is specified as the mean area at the respective vertex. We used the mean of the pial surface area and the gray-white matter surface area as mean CSA to get a more comprehensive measure of the surface. CT has so far been validated using manual segmentations (Cardinale et al., 2014; Kuperberg et al., 2003; Salat et al., 2004) and histological analyses (Rosas et al., 2002), and has been shown to constitute a reliable measure in healthy older adults (Liem et al., 2015). The cortex was parcellated into bilateral ROIs using the aparc.a2009s annotation (Destrieux et al., 2010), which has been utilized previously in similar studies (Meyer et al., 2014).

Based on previous studies showing a contribution of auditory-related and frontal brain areas to phonetic processing, phonetic discrimination (Benson et al., 2006; Binder, 2000; Binder et al., 1997; Blumstein et al., 2005; Elmer et al., 2012; Fuhrmeister and Myers, 2021; Jancke et al., 2002; Zaehle et al., 2008, 2004) and cognitive functions (Fedorenko et al., 2012; Hagoort, 2013, 2014; Jurado and Rosselli, 2007; Menon and D'Esposito, 2022), we selected nine ROIs in each hemisphere, namely the IFG (pars opercularis, triangularis and orbitalis), VLPF cortex, DLPF cortex, planum temporale (PT), planum polare (PP), STG, STS, Heschl's sulcus (HS) and Heschl's gyrus (HG), and compared CSA and CT between the two groups. Importantly, for the anatomical analyses we did not use overlapping ROIs which means that, for example, the IFG ROI was not additionally included in the definition of the VLPF cortex. For reasons of redundancy, we abstained from analyzing cortical volume because this metric is simply the arithmetical product of CSA and CT.

2.9. Statistical analyses

The statistical analyses were performed using the IBM SPSS Statistics 22 software package (SPSS, an IBM company, Armonk, New York, USA). All omnibus comparisons were conducted using analyses of variance (ANOVAs, repeated measures) with specific factors of interest for each model. Significant main and interaction effects were further inspected using post-hoc t-tests (two-tailed) or ANOVAs, and correlation analyses were computed according to Pearson's r (two-tailed). All post-hoc tests and correlation analyses were corrected for multiple comparisons using the Bonferroni procedure. In particular, the psychometric and audiometric data were compared between the two groups using t-tests for independent samples (Bonferroni-corrected). In the phonetic categorization task, the percentage of /da/ assignments and RTs were evaluated using a 2 × 7 ANOVA (2 groups and 7 CV syllables), whereas d-prime values (Stanislaw and Todorov, 1999) and RT data of the phonetic discrimination task were examined by means of a 2 × 6 ANOVA with the factors group and ΔVOT of 0, 20, 30, 40, 50 and 60 ms. The EEG data were analyzed using separate 2 × 4 × 3 ANOVAs (2 groups, 4 CV syllables and 3 ROIs) for maximal (peak) amplitude and latency values of the N100/P200 components. To facilitate the presentation of the EEG results, main effects of ROI as well as stimulus x ROI interactions were not further decomposed because they were not of interest for the study. For the analyses of the phonetic categorization and discrimination tasks as well as for the evaluation of the EEG data, PTA was used as covariate of no interest.

CSA and CT were evaluated using separate ANOVAs for auditory-related and frontal brain regions. The analysis of auditory-related brain regions included the PT, PP, STG, STS, HG, and HS as ROIs, whereas the ANOVA computed with frontal areas consisted of the IFG, VLPF cortex and DLPF cortex. In particular, auditory-related brain regions were analyzed by means of a 2 × 2 × 6 ANOVA with the factors group, hemisphere and ROI. In contrast, for the analysis of the frontal clusters we applied a 2 × 2 × 3 ANOVA (2 groups, 2 hemispheres and 3

ROIs). For all main analyses conducted with the anatomical data PTA and total intracranial volume were used as covariates. In addition, correlation analyses between variables of interest were computed separately for the two groups, and in the OA cohort PTA was used as a covariate (partial correlations).

3. Results

3.1. Pure-tone audiometry and cognitive capabilities

The audiometric profiles (PTAs) were compared between the two groups using a *t*-test for independent samples. According to this procedure, the YA demonstrated a lower PTA compared to the OA ($t_{(35)} = -7.046$, $p < .001$, Fig. 1). Also possible group differences in the digit span forward and backward tests were assessed using *t*-tests for independent samples (Bonferroni-corrected *p* value for 2 tests = .025). However, none of these comparisons reached significance (all *p* values > .33).

3.2. Behavioral data

3.2.1. Phonetic categorization task

In a first step, we computed separate one-sample *t*-tests against chance level (50%) for each group and the 7 CV syllables to define the boundary of the psychometric function (Bonferroni-corrected *p* value for 7 tests = .0071). In the YA group the categorization of the stimulus with a VOT of 30 ms did not differ from chance ($t_{(16)} = 0.187$, $p = .854$, all other stimuli $p < .001$), whereas OA showed chance-level performance for the stimuli with a VOT of 10 ($t_{(19)} = 2.268$, $p = .035$) and 20 ms ($t_{(19)} = -1.221$, $p = .237$, all other *p* values < .001).

The 2 × 7 ANOVA computed with the percentage of /da/ assignments yielded main effects of CV syllable ($F_{(6, 204)} = 29.180$, $p < .001$, partial eta$^2 = 0.462$) and group ($F_{(1, 34)} = 8.431$, $p = .006$, partial eta$^2 = 0.199$) as well as a significant CV syllable x group interaction ($F_{(6, 34)} = 4.590$, $p = .006$, partial eta$^2 = 0.119$, Fig. 4). Post-hoc *t*-tests used to disentangle the main effect of CV syllable (Bonferroni-corrected *p* value for 21 tests = .00238) revealed that the stimuli with a VOT of 10 and 20 ms were more often categorized as /da/ compared to all other items (all *p* values < .001). Furthermore, the CV syllables with a VOT of 60 and 70 ms were more frequently assigned to the category of /ta/ compared to the item with a VOT of 30 ms (all *p* values < .001). Otherwise, the main effect of group originated from an increased number of /da/ classifications in YA compared to OA (mean YA = 38.65%, mean OA = 24.10%). However, according to the significant CV syllable x group interaction which was further inspected by *t*-tests for independent samples (Bonferroni-corrected *p* value for 7 tests = .0071), this effect was mainly driven by the fact that YA more often categorized the stimuli with a VOT of 10 ($t_{(35)} = 2.838$, $p = .006$), 20 ($t_{(35)} = 3.924$, $p < .001$) and 30 ms ($t_{(35)} = 3.843$, $p = .001$) as /da/ compared to OA. The evaluation of the RT data did not reveal significant main effects or interactions (all *p* values > .17). Taken together, these results are in line with the hypothesis that normal aging is associated with a less consistent categorization of items characterized by a short VOT and with a shift of the boundary of the psychometric function, as manifested in more frequent /ta/ categorizations in OA compared to YA.

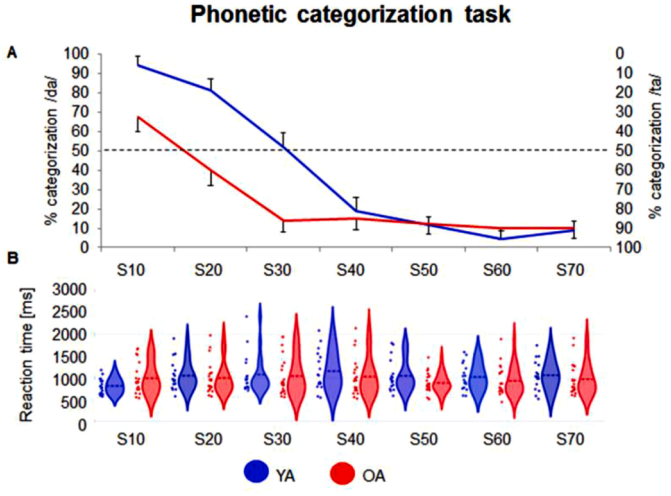

Fig. 4. The upper part (A) shows the mean psychometric function of the younger (YA, blue line) and older (OA, red line) adults in the phonetic categorization task. The labels S10-S70 refer to the seven consonant-vowel (CV) syllables differing in voice-onset time (VOT), whereas the bars depict standard error of the mean. The dashed line represents chance level (50%). The lower part (B) depicts the density distribution of reaction time values with single-subject data and mean. Blue violin plots = younger adults (YA), red violin plots = older adults (OA). The labels S10-S70 refer to the seven stimuli of the phonetic categorization task varying in voice-onset time (VOT) in the range of 10–70 ms.

3.2.2. Phonetic discrimination task

Since the primary target of the phonetic discrimination task was to determine participants' minimal VOT separation width, in the main analysis we computed a 2 × 6 ANOVA with the factors group and ΔVOT (Fig. 5A). The evaluation of d-prime values only revealed a main effect of ΔVOT ($F_{(5, 170)} = 37.902$, $p < .001$, partial eta$^2 = 0.527$). Post-hoc *t*-tests for dependent samples used to infer the origin of the main effect of ΔVOT (Bonferroni-corrected *p* value for 15 tests = .0033) revealed that same stimuli (ΔVOT = 0) were associate with a higher d-prime than stimuli with a ΔVOT of 20 and 30 ms, whereas items with a ΔVOT of 50 and 60 ms were characterized by higher d-prime values than same stimuli (all *p* values < .001). Furthermore, pairs of CV syllables with a larger ΔVOT were generally better discriminated than stimuli with a small ΔVOT (ΔVOT 30, 40, 50, 60 > ΔVOT 20; ΔVOT 40, 50, 60 > ΔVOT 30; ΔVOT 50, 60 > ΔVOT 40; all *p* values < .001).

The 2 × 6 ANOVA computed with RT data (Fig. 5B) only yielded a main effect of ΔVOT ($F_{(5155)} = 7.635$, $p < .001$, partial eta$^2 = 0.198$). Post-hoc *t*-tests for dependent samples (Bonferroni-corrected *p* value for 15 tests = .0033) revealed shorter RTs in response to same stimuli compared to those with a ΔVOT of 20, 30 and 40 ms (all *p* values < .002). In addition, stimuli with a ΔVOT of 50 and 60 ms were discriminated faster than those with a ΔVOT of 20, whereas the items with a ΔVOT of 60 ms resulted in shorter RTs compared to those with a ΔVOT of 30 and 40 ms (all *p* values < .001). In summary, and contrary to our hypothesis, the behavioral data did not reveal an influence of aging on the discrimination of CV syllables varying in VOT.

3.3. Electrophysiological data

3.3.1. N100 component

The evaluation of maximal N100 amplitudes by means of a 2 × 4 × 3 ANOVA (2 groups, 4 CV syllables and 3 ROIs) yielded a main effect of ROI ($F_{(2, 49.429)} = 11.265$, $p < .001$, partial eta$^2 = 0.249$), whereas the analysis of latency data revealed significant CV syllable x group ($F_{(3, 34)} = 4.087$, $p = .009$, partial eta$^2 = 0.107$) as well as CV syllable x ROI x group ($F_{(4.543, 154.466)} = 2.369$, $p = .047$, partial eta$^2 = 0.065$) interaction effects. Separate *t*-tests for dependent sample for the two groups (corrected *p* value for 6 tests = .0083) revealed that the CV syllable x group latency interaction effect originated from the OA group ($t_{(19)} = 3.023$, $p = .007$; YA all *p* values > .12), with longer latencies in response to the stimulus characterized by a VOT of 30 ms (mean = 159 ms) compared to the one with a VOT of 70 ms (prototypical /ta/, mean = 150 ms). Otherwise, the latency-related CV syllable x ROI x group interaction was decomposed using separate 2 × 4 ANOVAs for the 3 ROIs (corrected *p* value for 3 tests = .016), and this procedure revealed significant CV syllable x group interactions at the anterior ($F_{(2.658, 34)} = 4.536$, $p = .007$) and central ($F_{(3, 34)} = 6.812$, $p < .001$) ROIs. These two

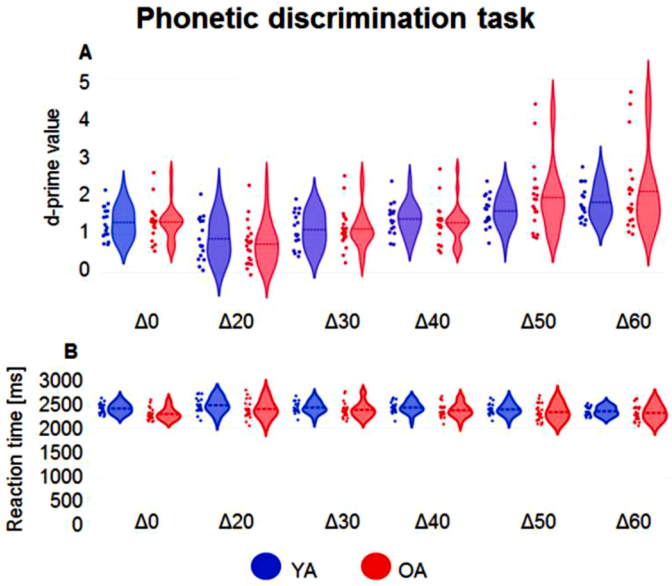

Fig. 5. Density distributions of d-prime scores (A) and reaction time data (B) in the phonetic discrimination task with single-subject values and mean for the younger (YA, blue) and older adults (OA, red). A and B provide an overview of d-prime and reaction time data in response to same stimuli (Δ0) or consonant-vowel (CV) syllables varying in voice-onset time (VOT) in the range or 20–60 ms (Δ20-Δ60).

interactions were further inspected using separate *t*-tests for dependent samples for the two groups at the anterior and central ROIs (corrected *p* value for 6 tests = .0083). The interactions were not broken down using *t*-tests for independent samples because this strategy did not yield significant results that helped to capture their origin. Although the separate evaluation of N100 latencies at the anterior ROI did not survive the correction for multiple comparisons, OA ($t_{(19)} = 2.269$, $p = .035$) but not YA (all *p* values > .215) demonstrated longer latencies in response to the stimulus with a VOT of 30 ms (mean = 161 ms) compared to the one with a VOT of 50 ms (mean = 151 ms). In addition, OA showed a significant latency difference at the central ROI between the stimuli with a VOT of 30 (mean = 159 ms) and 70 ms (mean = 149 ms) that originated from longer latencies in response to the stimulus characterized by a shorter VOT ($t_{(19)} = 3.375$, $p = .003$), whereas this was not the case in the YA group (all *p* values > .025). All results are visible in Figs. 6 and 7.

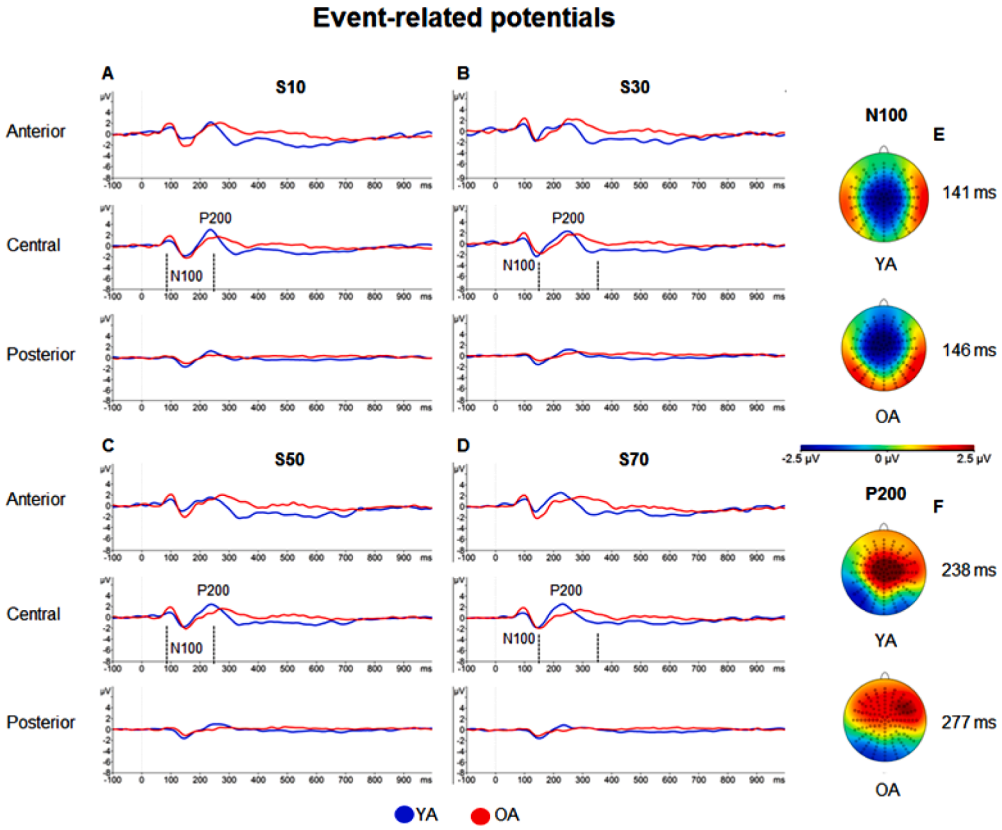

Fig. 6. The ERP traces of the first stimulus of the phonetic discrimination task are shown at the anterior, central and posterior regions-of-interests (ROIs), separately for the younger (YA, blue line) and older adults (OA, red line) as well as for the four consonant-vowel (CV) syllables with a voice-onset time (VOT) of 10 (A), 30 (B), 50 (C) and 70 ms (D). E and F show the topographical voltage distribution maps of the two groups corresponding to the global field power maximum of the grand average across all stimuli (S10, S30, S50, S70) in the time windows (dashed lines) of the N100 (90–230 ms) and P200 (140–350 ms) components.

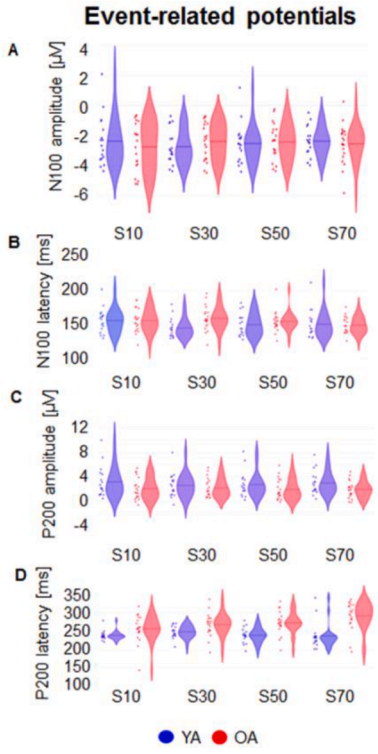

Fig. 7. Single-subject data and violin plots with density distribution and mean. Maximal N100/P200 amplitudes and latencies are shown at the central region-of-interest (ROI), *A* = N100 amplitudes, *B* = N100 latencies, C = P200 amplitudes, *D* = P200 latencies. Blue violin plots = younger adults (YA), red violin plots = older adults (OA).

3.3.2. P200 component

As mentioned above, in a first approach the significant interaction effects with the factor group were further inspected using *t*-tests for independent samples. However, if this strategy was not successful to capture the origin of the interactions of interest, interaction effects were broken down using separate *t*-tests for dependent samples for the two groups. The 2 × 4 × 3 ANOVA (2 groups, 4 CV syllables and 3 ROIs) used to evaluate P200 amplitudes revealed a main effect of ROI ($F_{(1.384,\ 47.055)} = 23.130$, $p < .001$, partial eta$^2 = 0.405$) as well as a significant CV syllable x group interaction effect ($F_{(2.776,\ 34)} = 3.252$, $p = .028$, partial eta$^2 = 0.087$). Even though post-hoc *t*-tests for dependent samples did not survive the correction for multiple comparisons (Bonferroni-corrected *p* value for 6 tests = .0083), OA ($t_{(19)} = 2.458$, $p = .024$) but not YA (all *p* values > .061) demonstrated increased P200 amplitudes in response to the stimulus with a VOT of 30 ms (mean = 2.2 µV) compared to the one with a VOT of 50 ms (mean = 1.9 µV). Otherwise, the 2 × 4 × 3 ANOVA computed with latency data yielded a main effect of CV syllable ($F_{(3,\ 102)} = 3.765$, $p = .013$, partial eta$^2 = 0.100$) as well as a significant CV syllable x group interaction effect ($F_{(3,\ 34)} = 5.072$, $p = .003$, partial eta$^2 = 0.130$). Although post-hoc *t*-tests for dependent samples used to elucidate the main effect of stimulus did not survive the correction for multiple comparisons (Bonferroni-corrected *p* value for 6 tests = .0083), it was related to shorter P200 latencies ($t_{(36)} = -2.431$, $p = .020$) in response to the stimulus with a VOT of 10 ms (prototypical /da/, mean = 247 ms) compared to the one with a VOT of 70 ms (prototypical /ta/, mean = 262 ms). Finally, *t*-tests for independent samples used to inspect the origin of the CV syllable x group interaction (Bonferroni-corrected *p* value for 4 tests = .0125) revealed longer P200 latencies in response to the stimuli with a VOT of 30 ($t_{(35)} = -2.830$, $p = .008$; YA = 242 ms, OA = 267 ms), 50 ($t_{(35)} = -3.078$, $p = .004$; YA = 240 ms, OA = 270 ms) and 70 ms ($t_{(35)} = -4.130$, $p < .001$; YA = 237 ms, OA = 283 ms) in OA compared to YA. All results are visible in Figs. 6 and 7.

3.4. Neuroanatomical data

3.4.1. Auditory-related brain areas: PT, PP, STG, STS, HG and HS

The analysis of CSA by means of a 2 × 2 × 6 ANOVA (2 groups, 2 hemispheres and 6 ROIs) revealed main effects of ROI ($F_{(5,\ 165)} = 36.856$, $p < .001$, partial eta$^2 = 0.528$) and group ($F_{(1,\ 33)} = 10.547$, $p = .003$, partial eta$^2 = 0.242$) as well as a significant group x ROI interaction ($F_{(5,\ 165)} = 9.832$, $p = .002$, partial eta$^2 = 0.230$). The main effect of group was associated with an overall decreased CSA in OA (mean = 1059.42 cm^2) compared to YA (mean = 1135.63 cm^2). Otherwise, all post-hoc *t*-tests (Bonferroni-corrected *p* value for 15 tests = .0033) for dependent samples used to disentangle the main effect of ROI reached significance (all *p* values < .001), indicating a complex pattern of results with the largest CSA in the bilateral STS (3760.82 cm^2), followed by the STG (1290.04 cm^2), PT (582.79 cm^2), PP (396.24 cm^2), HG (284.87 cm^2) and HS (251.85 cm^2). Finally, the group x ROI interaction was further inspected by *t*-tests for independent samples (Bonferroni-corrected *p* value for 6 tests = .0083), and this procedure revealed a reduced CSA in OA compared to YA in the HG ($t_{(35)} = 3.404$, $p = .002$).

The evaluation of CT by means of a 2 × 2 × 6 ANOVA (2 groups, 2 hemispheres and 6 ROIs) yielded a main effect of ROI ($F_{(5,\ 165)} = 4.329$, $p = .003$, partial eta$^2 = 0.116$) and group ($F_{(1,\ 33)} = 16.774$, $p < .001$, partial eta$^2 = 0.337$). The main effect of group was related to an overall reduced CT in OA (2.50 mm) compared to YA (2.88 mm). Additional *t*-tests for dependent samples computed to capture the origin of the main effect of ROI (Bonferroni-corrected *p* value for 15 tests = .0033) indicated again a complex pattern of results (all *p* values < .001), with an increased CT in the PT compared to the STS and HG, in the PP compared to the PT, STG, STS, HS and HG, and in the STG compared to the PT, STS, HS and HG. All results are summarized in Fig. 8.

3.4.2. Frontal brain areas: IFG, VLPF and DLPF cortex

The analysis of CSA by means of a 2 × 2 × 3 ANOVA (2 groups, 2 hemispheres and 3 ROIs) yielded main effects of group ($F_{(1,\ 33)} = 11.400$, $p = .002$, partial eta$^2 = 0.257$) and ROI ($F_{(2,\ 66)} = 22.565$, $p < .001$, partial eta$^2 = 0.406$) as well as a significant group x ROI interaction ($F_{(2,\ 66)} = 10.275$, $p = .001$, partial eta$^2 = 0.237$). The main effect of group was related to an overall decreased CSA in OA (mean = 3427.21 cm^2) compared to YA (mean = 3825.45 cm^2). Additional *t*-tests for dependent samples used to disentangle the main effect of ROI (Bonferroni-corrected *p* value for 3 tests = .0166) revealed an increased CSA in the DLPF cortex compared to the VLPF cortex ($t_{(36)} = -30.736$, $p < .001$) and the IFG ($t_{(36)} = -44.974$, $p < .001$) as well as in the VLPF cortex compared to the IFG ($t_{(36)} = -50.795$, $p < .001$). Finally, *t*-tests for independent samples used to capture the origin of the group x ROI interaction (Bonferroni-corrected *p* value for 3 tests = .0166) revealed an increased CSA in YA compared to OA in the VLPF ($t_{(35)} = 2.756$, $p = .009$) and DLPF cortex ($t_{(35)} = 3.033$, $p = .005$).

The 2 × 2 × 3 ANOVA (2 groups, 2 hemispheres and 3 ROIs) computed with CT data revealed main effects of group ($F_{(1,\ 33)} = 42.579$, $p < .001$, partial eta$^2 = 0.563$) and ROI ($F_{(2,\ 66)} = 7.864$, $p = .004$, partial eta$^2 = 0.192$). The main effect of group was driven by an increased CT in YA (mean = 2.69 mm) compared to OA (mean = 2.33 mm). Otherwise, post-hoc *t*-tests for dependent samples computed to uncover the origin of the main effect of ROI (Bonferroni-corrected *p* value for 3 tests = .0166) showed increased CT in the IFG compared to the VLPF ($t_{(36)} = 15.062$, $p < .001$) and DLPF ($t_{(36)} = 13.326$, $p < .001$) cortex as well as in the VLPF compared to the DLPF cortex ($t_{(36)} = 8.863$, $p < .001$). To conclude, the anatomical data corroborated the hypothesis that aging is generally associated with overall reduced gray matter parameters. All results are summarized in Fig. 9.

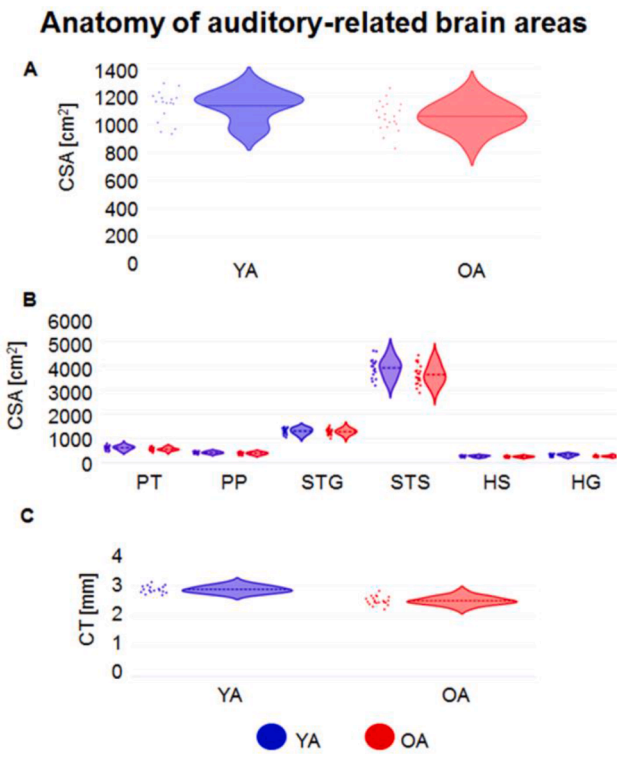

Fig. 8. Main anatomical results of the evaluation of cortical surface area (CSA, A and B) and cortical thickness (CT, C) in auditory-related brain areas, single-subject data and violin plots with density distribution and mean. A shows the main effect of group in CSA, whereas B depicts the main effect of ROI as well as the ROI x group interaction in CSA. C refers to main effect of group in CT. Blue violin plots = younger adults (YA), red violin plots = older adults (OA). PT = planum temporale, PP = planum polare, STG = superior temporal gyrus, STS = superior temporal sulcus, HS = Heschl's sulcus, HG = Heschl's gyrus.

3.5. Correlation analyses

3.5.1. Correlations between EEG data and behavior/brain anatomy

According to the results, we additionally performed six correlation analyses with N100 latencies, P200 latencies and P200 amplitudes. In particular, based on the group x CV syllable interaction effects we revealed in the latency of the N100 component as well as in the behavioral data of the phonetic categorization task, we inspected possible associations between the percentage of /da/ attributions in response to the CV syllable with a VOT of 30 ms and mean N100 latencies averaged across the three ROIs while processing the same stimulus. Furthermore, we correlated mean P200 amplitudes and latencies elicited by the stimulus with a VOT of 30 ms across the three ROIs with the percentage of /da/ classifications of the same CV syllable (group x CV syllable interaction effects). Given that the generators of the N100/P200 complex have mainly been attributed to the auditory-related cortex (Bosnyak et al., 2004; Liegeois-Chauvel et al., 1994; Picton et al., 1999; Scherg and von Cramon, 1986), we also correlated mean P200 amplitudes as well as N100/P200 latencies elicited by the stimulus characterized by a VOT of 30 ms across the three ROIs with mean CSA and CT of all bilateral auditory-related brain regions (main effect of group) as well as with the mean bilateral CSA of the HG (group x ROI interaction). Finally, as an addendum, we additionally correlated mean P200 amplitudes as well as N100/P200 latencies across the three ROIs in response to the stimulus with a VOT of 30 ms with mean CSA and CT of the left PT. These supplementary correlation analyses were motivated by the fact that the left PT has repeatedly been shown to be sensitive to rapidly changing temporal speech cues (Zaehle et al., 2008, 2004; Zatorre and Belin, 2001). Importantly, to avoid spurious relationships, we computed the correlation analyses separately for the two groups, and corrected for multiple comparisons using the Bonferroni procedure. In particular, the correlations computed with P200 amplitudes, N100 latencies and P200 latencies were separately adjusted for six tests, resulting in a Bonferroni corrected value of $p = .0083$. According to this procedure, within the YA cohort none of the correlations computed with P200 amplitudes (all p values $> .038$), N100 latencies (all p values $> .404$) and P200 latencies (all p values $> .354$) reached significance. Also within the OA group, none of the partial correlations computed with N100 (all p values $> .247$) and P200 (all p values $> .317$) latency data reached significance. However, mean P200 amplitudes across the three ROIs in response to the CV syllable with a VOT of 30 ms were positively related to the mean CSA of the bilateral HG (Fig. 10, $r = .603$, $p = .006$, all other p values $> .176$).

3.5.2. Correlations between behavior and brain anatomy

For assessing brain-behavior relationships, we specifically focused on those behavioral indices which differed between the two groups, namely mean percentage /da/ assignments for the CV syllables with a VOT of 10, 20 and 30 ms in the phonetic categorization task (CV syllable x group interaction). In particular, the mean percentage of /da/ categorizations for the three stimuli was correlated with the 6 anatomical ROIs which significantly differed between the two groups, namely mean CSA and CT of all bilateral auditory-related brain regions, mean CSA of the bilateral HG, mean CSA and CT of all bilateral frontal areas, and mean CSA of the bilateral VLPF and DLPF cortex. Furthermore, based on the same argument mentioned above, mean categorization performance was also correlated with CT and CSA of the left PT. All correlations were computed separately for the two groups, and adjusted for multiple comparisons using the Bonferroni procedure (corrected p value for 8 correlations = .00625). Correlation analyses within the group of YA revealed that the mean percentage /da/ assignments for the stimuli with a VOT of 10, 20 and 30 ms was positively related to the mean CSA of all bilateral auditory-related brain regions ($r = .651$, $p = .005$), mean CSA of all bilateral frontal areas ($r = .652$, $p = .005$), and mean CSA of the bilateral VLPF and DLPF cortex ($r = .653$, $p = .004$, all other correlations $p > .011$). In contrast, within the OA group we did not reveal significant relationships between mean phonetic categorization assignments and the inspected anatomical parameters (all p values $> .072$, Fig. 11). Taken together, the results of the correlation analyses are in line with the hypothesis that not only auditory-related brain areas but also prefrontal regions contribute to phonetic categorization processes, even though the significant effects were restricted to the sample of YA.

Finally, we also used explorative correlation analyses to assess relationships between mean d-prime metrics averaged across the 6 ΔVOT conditions and the same 8 anatomical indices described above. In particular, we computed separate correlations for the two groups to inspect associations between mean d-prime values and mean CSA and CT of all bilateral auditory-related brain regions, mean CSA of the bilateral HG, mean CSA and CT of all bilateral frontal areas, mean CSA of the bilateral VLPF and DLPF cortex and CT and CSA of the left PT (Bonferroni-corrected p value for 8 correlations = .00625). The aim of these additional correlations was to examine potentially different neuroanatomical implications to the phonetic discrimination task as a possible indicator of compensation for age-related changes while at the same time controlling for response biases. However, within the YA (all p values $> .023$) and OA (all p values $> .035$) groups none of the correlations reached significance.

4. Discussion

4.1. General discussion

The aim of this study was to determine the origins of temporal speech processing differences between OA and YA that cannot simply be explained by pure-tone hearing loss because PTA was treated as a

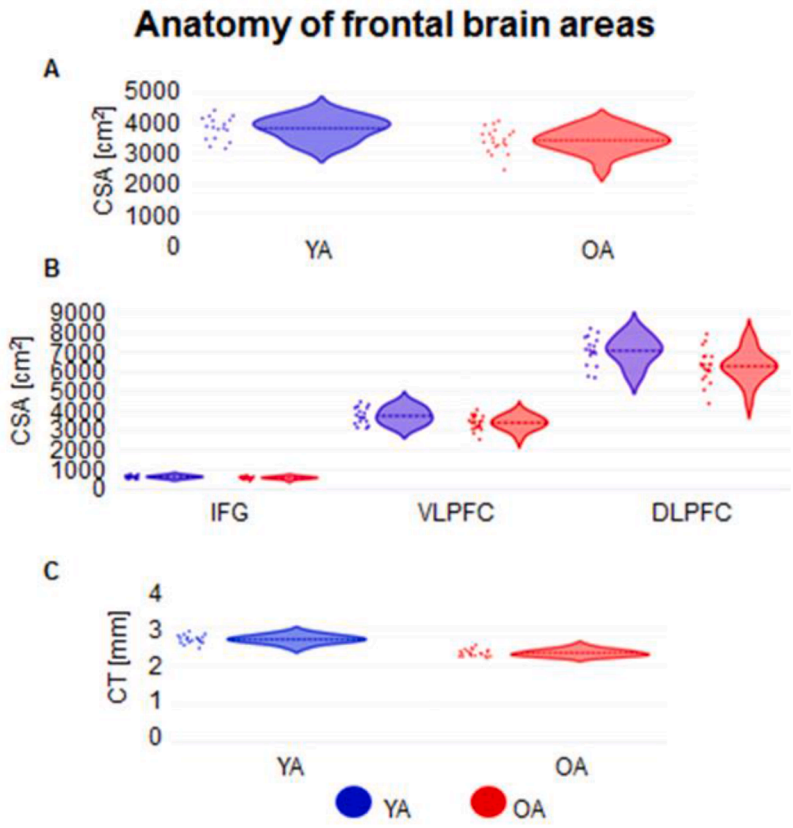

Fig. 9. Main anatomical results of the evaluation of cortical surface area (CSA, A and B) and cortical thickness (CT, C) in frontal brain areas, single-subject data and violin plots with density distribution and mean. A shows the main effect of group in CSA, whereas B depicts the main effect of ROI as well as the ROI x group interaction in CSA. C refers to main effect of group in CT. Blue violin plots = younger adults (YA), red violin plots = older adults (OA). IFG = inferior frontal gyrus, VLPFC = ventrolateral prefrontal cortex, DLPFC = dorsolateral prefrontal cortex.

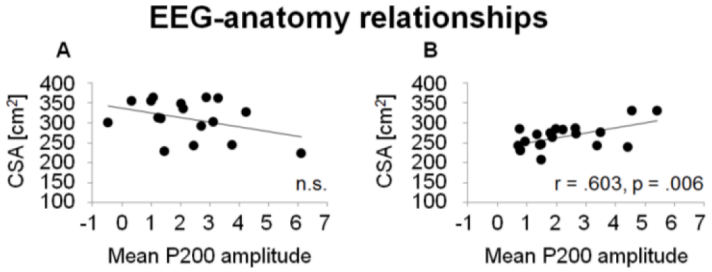

Fig. 10. Correlations between mean cortical surface area (CSA) of the bilateral HG and mean P200 amplitudes across the three regions of interest (ROIs) in response to the CV syllable with a VOT of 30 ms. n.s. = not significant. A = correlation within the sample of younger adults (YA), B = correlation within the sample of older adults (OA).

covariate of no interest in all group comparisons. Furthermore, we believe that the increased hearing threshold in OA in the high frequency range is not sufficient to satisfactorily explain group differences in the processing of the CV syllables /da/ and /ta/, especially because the same consonant and the vowel of the syllable /da/ were consistently used to form the CV syllables of the VOT continuum. With this background in mind, we combined structural MRI and EEG, and examined behavioral profiles of YA and OA while the participants performed a phonetic categorization and discrimination task with CV syllables varying in VOT. Although OA had PTAs clearly below a clinically relevant threshold of 25 dB (World Health Organization, WHO), they demonstrated specific singularities in the phonetic categorization task. These distinctive age-related temporal speech processing abilities were manifested in a shift of the boundary of the psychometric categorization functions with more /ta/ categorizations in OA, especially for the CV syllables with a short VOT. Furthermore, OA exhibited differential latencies and amplitudes of auditory-evoked ERPs while encoding the CV syllables varying in VOT. OA were also characterized by an overall reduced CSA and CT in auditory-related and frontal brain regions compared to YA, and in the latter group we found a close relationship between CSA in both bilateral auditory-related and frontal gross anatomical clusters and the categorization of CV syllables with a short VOT (explained variance ~ 40%). Overall, these results provide a framework for rationalizing the multi-faceted dimensions of age-related temporal speech processing.

4.2. Psychometric data

Based on previous work, we tested a small set of cognitive functions which have been shown to be affected by aging, and been proposed to have an influence on phonetic processing and discrimination (Albouy et al., 2017; Elmer et al., 2021, 2017; Shafto and Tyler, 2014), namely short-term memory and working memory. Based on a taxonomy of mnemonic functions (Albouy et al., 2017; Elmer et al., 2017), phonetic discrimination tasks are strongly rooted in these mnemonic functions. In fact, to make same-different judgements, the participants have to keep the two stimuli in short-term memory, and to compare the mnemonic traces of both items by engaging working memory functions. Nevertheless, according to the psychometric data, we did not reveal

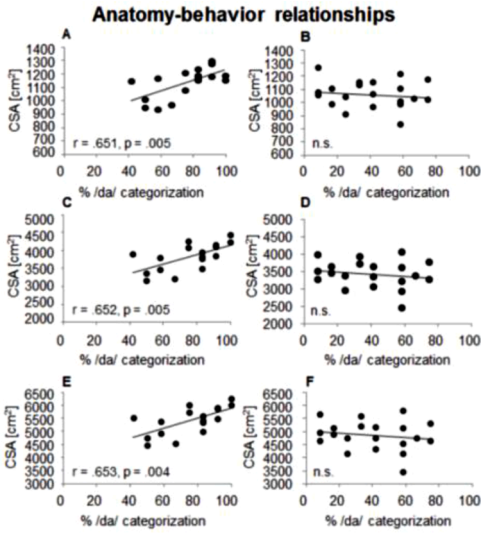

Fig. 11. Correlations between cortical surface area (CSA) and mean percentage /da/ assignments for the consonant-vowel (CV) syllables with a voice-onset time (VOT) of 10, 20 and 30 ms within the sample of younger (YA, A, C, E) and older adults (OA, B, D, F). A and B = correlations between mean percentage /da/ assignments and mean CSA of all bilateral auditory-related brain regions. C and D = correlations between mean percentage /da/ assignments and mean CSA of all bilateral frontal regions. E and F = correlations between mean percentage /da/ assignments and mean CSA of the bilateral VLPF and DLPF cortex.

between-group differences in these two cognitive functions, leading to suggest that the behavioral metrics of the phonetic categorization and discrimination tasks were not directly influenced by these variables.

4.3. Behavioral data of the phonetic categorization and discrimination tasks

To examine age-related temporal speech processing peculiarities, we selected two specific phonetic tasks consisting of categorizing and discriminating CV syllables varying in VOT. A combination of these two tasks is commonly used to determine the so-called categorical perception effect (Fry et al., 1962; Liberman et al., 1961). Categorical perception refers to the mapping of acoustically distinct elements onto a single phonetic category, and allows to deal with environmental variations in phonetic units due to different speakers, speech rates or contexts (Campbell et al., 2018; Fry et al., 1962; Kuhl, 2004; Liberman et al., 1961). Such a degree of perceptual constancy is normally accompanied by a reduced phonetic discrimination of speech elements situated nearby the prototypical items of a continuum compared to those spanning the phonetic boundary, even though the acoustic differences between the stimulus pairs are identical (Fry et al., 1962; Kuhl, 2004). It is believed that reduced discrimination abilities within a phonetic category are mediated by prototypical items which are stored in memory and act as a magnet for speech sound variations (Lively and Pisoni, 1997).

Although we are fully aware of the usefulness of combining phonetic categorization and discrimination tasks for linking categorical perception to discrimination abilities, here we applied these two tasks within a different framework. In particular, since the categorization of speech sounds plays an important role in understanding speech in everyday life situations (Smits et al., 2006), we wanted to test whether OA are prone to distinct assignments of CV syllables with a short VOT situated nearby the prototypical item /da/ due to temporal speech processing difficulties. On the other hand, the phonetic discrimination task was administered using a fast mapping procedure with the general aim of determining participants' minimal VOT separation width across a continuum without entitlement to track identical acoustic differences between pairs of CV syllables. In this context, it is noteworthy to mention that we avoided presenting ambiguous stimulus pairs situated in the middle of the continuum, and each of the four stimuli with a VOT of 10, 30, 50 and 70 ms was paired with items located across the midpoint of the continuum.

In line with what is usually found in phonetic categorization tasks (Fry et al., 1962; Liberman et al., 1961; Zaehle et al., 2008, 2004), the stimuli situated at the two extremes of the range were more often identified as prototypical items compared to those placed in the middle of the continuum (Fig. 4). However, a similar correspondence was not reflected in the RT data, indicating participants' preference for accuracy over speed. Most notably, the evaluation of the percentage of /da/ assignments in the phonetic categorization task also clearly showed an age-related shift of the boundary of the psychometric function with more /ta/ categorizations in OA for the stimuli with a short VOT. In fact, OA performed at chance level in response to the CV syllables with a VOT of 10 (prototypical /da/) and 20 ms, whereas in the YA the boundary was in the proximity of the stimulus with a VOT of 30 ms. This result is particularly interesting in that it provides concrete evidence that OA showed a less consistent categorization of the prototypical CV syllable /da/, with possible repercussions on everyday's communication behavior. This group-specific shift of the boundary also translated into an overall increased number of /da/ classifications in YA compared to OA (main effect of group) and was paralleled by a CV syllable x group interaction effect. Together with the shift of the boundary of the psychometric categorization function, the latter interaction underscored the existence of temporal speech processing differences between YA and OA, specifically in response to CV syllables with short VOTs of 10, 20 and 30 ms. One possible explanation for this effect is that due to spectral hearing loss in the normative range, OA used compensatory listening strategies and more likely relied on the temporal cue of the aspiration period to categorize the CV syllables instead of using the spectral information of the stimuli.

The analyses of d-prime and RT data of the phonetic discrimination task only yielded main effects of ΔVOT. As expected, the main effects of ΔVOT are fully in line with previous reports (Elmer et al., 2017; Hutchison et al., 2008; Zaehle et al., 2008), and were mainly driven by better and faster discrimination of CV syllables with large compared to small ΔVOT. Furthermore, same stimuli (ΔVOT = 0) were associated with faster RTs and more often correctly recognized than items with a short ΔVOT in the range of 20–40 ms. Although the origin of these effects was unclear, it is possible that two concordant stimuli elicited a perceptual priming effect which facilitated decision making compared to the more demanding perceptual distinction of small VOT differences (Schacter and Buckner, 1998; Schacter et al., 2004; Wiggs and Martin, 1998).

While the results of previous studies led to the assumption that aging has an influence on the distinction of brief temporal acoustic features (Hutka et al., 2013; Schneider and Hamstra, 1999), in the present work we did not reveal between-group differences in the discrimination of CV syllables varying in VOT. Nevertheless, OA demonstrated a shift of the boundary of the psychometric categorization function which was mainly mediated by a more frequent classification of CV syllables with a short VOT to the category of /ta/. Such a distortion of the psychometric categorization function as a function of age is not completely novel and has, for example, also been reported by Bidelman and colleagues using a vowel categorization task (Bidelman et al., 2014). Bidelman and co-workers (Bidelman et al., 2014) argued that a possible explanation for differences in categorical perception between OA and YA might be anchored in an altered neural representation of speech objects which may result in reduced consistency of phonetic categories that blurs the distinction between adjacent phonemes along a continuum. In this vein, the shift of the boundary of the psychometric categorization function we revealed in OA despite comparable performance of YA and OA in the phonetic discrimination task leads to suggest a discrete influence of aging on speech processing that goes beyond mere perceptual acuity

(Bidelman et al., 2014; Pisoni and Luce, 1987). Nevertheless, it should also be mentioned that our study was not conclusive in determining whether the increased consistency of phonetic categories we noticed in YA was determined by discrete between-group differences in the neural representation of the VOT or of the stimulus duration because the CV syllables varied on both dimensions. However, since both perspectives refer to changes in temporal speech patterns, we conclude that the temporal dimension was a critical variable.

4.4. EEG data

Meanwhile, there is common agreement that the N100 and P200 ERP components constitute sensitive measures of the timing and strength of endogenous processes in auditory-related cortical regions. In fact, multiple studies identified the main sources of these two ERPs in the primary and secondary auditory cortex (Bosnyak et al., 2004; Liegeois-Chauvel et al., 1994; Picton et al., 1999; Scherg and von Cramon, 1986). Drawing on this background, in the present work we made use of these two auditory-evoked responses to objectify the neural encoding of CV syllables with a VOT of 10 (prototypical /da/), 30, 50 and 70 ms (prototypical /ta/) at the processing level of the auditory-related cortex.

Until now, only a few studies examined differences in the categorization or discrimination of CV syllables varying in VOT as a function of age using behavioral indices or EEG metrics (Abada et al., 2008; Oron et al., 2019; Toscano and Lansing, 2019; Tremblay et al., 2003). For example, Oron and colleagues (Oron et al., 2019) adopted a passive listening paradigm in association with EEG to investigate the encoding of Polish CV syllables, and revealed an overall age-related decline in voicing perception that was reflected in increased N100/P200 ERP amplitudes. Also Tremblay and colleagues (Tremblay et al., 2003) examined the neural representation of CV syllables as well as the ability to discriminate speech tokens along a /ba/-/pa/ VOT continuum in two groups of YA and OA. As a main result, the authors reported that OA had more difficulties than YA in discriminating the 10 ms VOT contrast. Moreover, OA exhibited longer N100 and P200 latencies indicating altered temporal response properties in the auditory system (Tremblay et al., 2003).

The ERP results of our study provided further evidence for a distinct neural representation of CV syllables varying in VOT in the two groups. In fact, although we did not detect between-group differences in terms of N100 amplitudes, OA were characterized by larger P200 amplitudes in response to the stimulus with a VOT of 30 ms compared to the one with a VOT of 50 ms (CV syllable x group interaction). Interestingly, within the OA group such a differential neural processing between stimuli lying on the left and right side of the continuum was also manifested in the timing of the N100 component, with longer latencies for the CV syllable with a VOT of 30 ms compared to those with a VOT of 50 and 70 ms (CV syllable x group and CV syllable x group x ROI interactions). In addition, OA were generally characterized by longer P200 latencies compared to YA while encoding CV syllables with a VOT of 30, 50 and 70 ms (CV syllable x group interaction). The increased P200 amplitudes we revealed in OA are not only compatible with the previous findings of Oron and colleagues (Oron et al., 2019), but also fit the behavioral results of the phonetic categorization task showing that OA more consistently attributed the ambiguous CV syllable with a VOT of 30 ms to the category of /ta/ compared to YA who performed at chance level. Since within the OA group such a distinctive processing of the item with a VOT of 30 ms was also manifested in longer N100 latencies compared to the two stimuli with a VOT of 50 and 70 ms situated on the right side of the continuum, we may infer that increased P200 amplitudes in OA reflected neuro-functional compensation mechanisms (Anderson et al., 2020; Bartres-Faz and Arenaza-Urquijo, 2011) which were needed to cope with a non-prototypical speech element placed on the left side of the continuum, possibly due to reduced consistency of phonetic categories with a short VOT. It is also conceivable that compensatory mechanisms in response to the ambiguous item with a VOT of 30 ms were required to counteract slower age-related impulse propagation in the auditory system which was generally manifested in longer P200 latencies. Interestingly, this age-related P200 latency effect was also consistent with a study of Tremblay and colleagues (Tremblay et al., 2003), and possibly associated with a reduced myelin integrity in the ascending auditory pathways (Long et al., 2018; Lutz et al., 2007), or with a loss of myelin sheaths embedded in between neural microcolumns in the auditory cortex (Hutsler, 2003; Meyer et al., 2014). However, since morphological features of myelin determine the speed of impulse transmission (Zatorre et al., 2012), an unequivocal interpretation of this result can only be made using sophisticated diffusion tensor imaging protocols. Hence, for future studies it would be interesting to examine whether the longer N100/P200 latencies as well as the distinctive psychometric categorization function we revealed in the OA cohort were possibly related to the white matter architecture of the auditory system which is essential for an appropriate temporal resolution of the speech signal (Gordonsalant and Fitzgibbons, 1993; Strouse et al., 1998; Walton, 2010). Finally, it is noteworthy to mention that the compensatory mechanisms addressed above can potentially express at least three different processes, namely the general recruitment of additional neurons in the auditory cortex (Kuhnis et al., 2013; Meyer et al., 2012), a frontal top-down regulation of auditory functions (Giroud et al., 2018b; Lijffijt et al., 2009; Strait et al., 2010, 2015), or even a change in the interhemispheric balance (Shafto and Tyler, 2014). Although it results difficult to draw a clear conclusion on the specific compensatory mechanisms involved, the positive correlation we revealed in the OA group between mean CSA of the bilateral HG and mean P200 amplitudes in response to the CV syllable with a VOT of 30 ms leads us to speculate that the spectrum for functional compensation was dependent, at least partially, upon the gray matter integrity of the auditory cortex.

Influential models of auditory (Griffiths and Warren, 2002; Zatorre and Belin, 2001) and speech (Giraud et al., 2007; Hickok and Poeppel, 2007) processing converge to the notion that at least in young adults, the left auditory cortex in general and the PT in particular favor the extraction of information from short temporal integration windows (~20–40 ms), whereas the right counterpart primarily relies on long integration windows (~150–250 ms) (Poeppel, 2003). Therefore, it is not surprising that CV syllables are often preferentially processed in the left auditory-related cortex (Elmer et al., 2012; Jancke et al., 2002; Zaehle et al., 2004), and that vowels more strongly recruit the right hemisphere (Jancke et al., 2002; Kuhnis et al., 2013). Nevertheless, in our study we were not able to infer specific associations between the gray matter architecture of the left PT, EEG indices and phonetic categorization or discrimination performance. However, this does not preclude that the processing of CV syllables varying in VOT was mainly dependent on the left PT. In fact, the increased P200 magnitudes we revealed in OA could potentially mirror the functional recruitment of additional neural ensembles or even a top-down tuning of auditory-related cortical fields in the left PT (Elmer et al., 2013, 2012; Giroud et al., 2018b; Strait et al., 2010, 2015). Moreover, drawing on the perspective of a change in the interhemispheric balance introduced above (Giroud et al., 2019; Keller et al., 2019), it is also possible that the hemispheric specialization of the left and right PT for the extraction of information from short or long temporal integration windows is reduced as a function of aging, and that OA additionally engaged the right-sided PT to compensate for age-related temporal speech resolution deficits in the left hemisphere (Shafto and Tyler, 2014; Taylor and Burke, 2002). Although such a discussion about functional hemispheric specialization in association with temporal speech processing and aging can only be adequately addressed using MRI protocols, our EEG data complemented the behavioral results and provided additional evidence for distinctive effects of aging on the functional neural architecture underlying the processing of CV syllables varying in VOT.

4.5. Neuroanatomical data

Phonetic categorization and discrimination tasks have been associated with widely distributed neural circuitry in both perisylvian (Benson et al., 2006; Binder, 2000; Binder et al., 1997; Blumstein et al., 2005; Elmer et al., 2012; Fuhrmeister and Myers, 2021; Jancke et al., 2002; Zaehle et al., 2008, 2004) and frontal brain regions (Fuhrmeister and Myers, 2021; Zaehle et al., 2008; Zatorre et al., 1996). Using functional MRI (fMRI), Blumstein and colleagues investigated the neural systems underlying the perception of phonetic category structure using CV syllables varying along a /da/-/ta/ continuum (Blumstein et al., 2005). As a main result, the authors observed that the bilateral IFG was more strongly activated for items situated at the phonetic category boundary, whereas the bilateral STG was less sensitive to differences in phonetic category structure. Along this line, Zaehle et al. used a similar procedure to examine the neural substrate of phonetic categorization, and exclusively revealed left-sided activations in the HG and PT (Zaehle et al., 2004). Furthermore, in a second fMRI study with similar CV syllables varying in VOT along a /da/-/ta/ continuum, the same group evaluated brain responses in the context of a same-different task, and noticed phonetic discrimination-related activation patterns in the left IFG, bilateral middle frontal gyrus, bilateral frontal operculum as well as in the STS, HG and PT (Zaehle et al., 2008). In a further study, Fuhrmeister and Myers (Fuhrmeister and Myers, 2021) inspected the neuroanatomical correlates of individual variability in phonetic categorization by means of a fricative continuum, and showed that the CSA of the right middle frontal gyrus was positively related to categorical perception, whereas the gyrification of the bilateral HG was predictive of less consistent task responses.

Inspired by all these previous studies as well as by the vast literature showing an influence of age on gray matter parameters (Bethlehem et al., 2022; Sele et al., 2020, 2021; Shafto and Tyler, 2014), we focused our analyses on two specific cortical clusters of auditory-related and frontal brain regions. In particular, the evaluation of CSA and CT of auditory-related brain regions included the bilateral PT, PP, STG, STS, HG and HS. In contrast, the analysis of the frontal cluster relied on the bilateral IFG, VLPF and DLPF cortex. Importantly, all these auditory-related and frontal brain regions have previously been shown to contribute to the representation and control of speech and language in association with cognitive functions (Abutalebi and Green, 2007; Hagoort, 2014; Scott and Johnsrude, 2003; Specht, 2014). The HG and HS are mainly involved in processing basic acoustic features (Hall et al., 2003), whereas the PT and PP play an important role for more complex spectrotemporal analyses (Griffiths and Warren, 2002; Jancke et al., 2002; Zaehle et al., 2008, 2004). Furthermore, the bilateral STG and STS are essential structures for speech comprehension (Hickok and Poeppel, 2007; Specht, 2014) and some aspects of voice perception (Belin et al., 2000; Lattner et al., 2005). Regarding the frontal cluster, the IFG in general and Broca's area in particular have been shown to be implicated in processing phonetic, semantic and syntactic information (Friederici, 2002; Specht, 2014), but also to contribute to domain-general functions such as working memory, cognitive control or action processing (Fedorenko et al., 2012). Otherwise, the VLPF and DLPF cortex are part of the executive control system (Funahashi and Andreau, 2013; Rodriguez-Fornells et al., 2009; Weinberger et al., 1996) as well as important relay stations in the context of dual stream models of speech and language processing (Friederici, 2009; Hickok and Poeppel, 2007; Specht, 2014).

The analysis of CSA and CT in auditory-related brain regions revealed main effects of ROI and group, and the evaluation of CSA also brought to light a group x ROI interaction. The main effects of ROI are not discussed further because they just reflected the different sizes of the parcellated brain regions, cortical folding, gyrification, or even the number and width of cortical microcolumns (Rakic, 1995, 2000; van der Meer and Kaufmann, 2022; Zilles et al., 1988). More interestingly, the main effects of group are in line with several previous reports showing age-related gray matter differences in bilateral auditory-related brain regions (Bethlehem et al., 2022; Cardin, 2016; Giroud et al., 2018a, 2019; Isler et al., 2021; Profant et al., 2014), although such a characteristics seems to be more common for CT than CSA parameters (Giroud et al., 2019). Furthermore, the age-related reduction in CSA was particularly evident for the HG, as reflected by the group x ROI interaction. This specific result leads us to speculate that an influence of age on impulse transmission along the ascending auditory pathways was possibly the primary origin of the general between-group differences we revealed in the CSA of auditory-related brain areas (Long et al., 2018; Lutz et al., 2007).

Interestingly, the inspection of CSA and CT in frontal regions led to the same main and interactions effects as we found for the auditory-related brain regions. In particular, OA were generally characterized by reduced CSA and CT in all inspected bilateral areas, as manifested by the main effect of group. Furthermore, the evaluation of CSA also yielded a group x ROI interaction effect that was associated with an increased CSA in YA compared to OA in both the bilateral VLPF and DLPF cortex. Such neuroanatomical changes in the frontal cortex as a function of age are by no means novel, and have previously repeatedly been documented using longitudinal (Sele et al., 2020; Taki et al., 2013; Thambisetty et al., 2010) as well as cross-sectional approaches (Salat et al., 2004; Tisserand et al., 2002). Nevertheless, it is interesting to denote that the age-related changes in CSA were more pronounced in the VLPF and DLPF cortex compared to the IFG. Although this group x ROI interaction is not easy to explain, it might possibly reflect a relative use-dependent preservation of linguistically relevant operations in a core area of the language network subserving auditory-motor integration (Hagoort, 2014). Future studies combining functional and structural MRI in association with an extensive screening of cognitive and language functions might be helpful to better understand the meaning of the different gray matter peculiarities we observed in the frontal cortex.

Finally, and most importantly, within the group of YA but not in OA, we revealed a close relationship between CSA in auditory-related as well as frontal brain regions and the percentage of /da/ classifications for CV syllables with a short VOT. This result is particularly interesting, for two specific reasons. First, the correlations underscore the importance of frontal brain regions (Giroud et al., 2018a), which are not mandatory part of the classical language network (Hickok and Poeppel, 2007; Specht, 2014), for an appropriate processing and differentiation of CV syllables varying on the temporal dimension, even though the exact underlying cognitive and perceptual operations are not yet completely understood. Second, since the correlations only reached significance in the YA group, we speculate about the existence of a critical gray matter threshold which is crucial for an appropriate temporal resolution of speech sounds. This latter hypothesis could, for example, be tested by examining different populations suffering from dementia at different stages and accompanied by a variable degree of gray matter atrophy in auditory-related and frontal brain regions.

5. Limitations

Despite the elaborate multimodal approach used in our study, there are some limitations that are worth mentioning. A first limitation is that we adopted a fully automated parcellation procedure which relied on the Destrieux atlas implemented in the FreeSurfer software to subdivide the cortex into ROIs. A shortcoming of this procedure is that some ROIs were rather well-defined small areas, whereas other ones constituted larger brain regions hosting a variety of psychological and cognitive functions. A second limitation of our study is that in the phonetic discrimination task we used a fast mapping procedure to determine participants' minimal VOT separation width instead of testing all equidistant VOT differences within and across phonetic categories. Accordingly, we did not provide a full assessment of discrimination performance along the entire VOT continuum.

6. Conclusions

We used a multidimensional approach to characterize age-related differences in temporal speech processing irrespective of pure-tone hearing loss, and provided evidence for a multifactorial genesis of this specific phenomenon. In particular, we showed that OA were characterized by a distinctive psychometric categorization function which was reflected in more frequent /ta/ categorizations for the CV syllable with a short VOT in the absence of any between-group differences in phonetic discrimination abilities. Furthermore, such a discrete influence of aging on temporal speech processing was manifested in the timing and strength of auditory-evoked ERPs, and accompanied by differential gray matter integrity in gross anatomical clusters situated in auditory-related and frontal brain regions. These results contribute to a better understanding of how normal aging impacts basic temporal speech processing mechanisms, and of how they are anchored in the brain at both the functional and neuroanatomical levels.

Data and code availability statement

All data included in this study are available from NG upon request. Due to ethical considerations the data cannot be made openly available. However, the data will be shared upon request without any restrictions.

CRediT authorship contribution statement

Stefan Elmer: Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. **Ira Kurthen:** Data curation, Formal analysis, Investigation, Methodology. **Martin Meyer:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Nathalie Giroud:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing, Investigation, Methodology.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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