Effect of Healthy Aging and Gender on Syntactic Input Processing: a P600 Event-Related Potential Study

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Abstract

Purpose: The present study aimed to investigate the effect of healthy aging and gender, as well as the interaction thereof, on syntactic input processing during sentence comprehension. This was achieved through the recording of the P600 event-related potential.

Method: Sixty Flemish (native speakers of Dutch) participants (30 men and 30 women), equally distributed into three age groups (young, middle-aged, elderly), were subjected to a visually presented word order violation task under simultaneous electro-encephalography recording. The task contained sixty sentences, of which half were grammatical and half contained a word order violation. P600 responses were analyzed for amplitude, latency, topographical distribution and source localization.

Results: Regarding the effect of healthy aging, no age-related differences were found for the amplitude, onset latency and topographical distribution of the P600 effect (difference wave). Although aging effects on the P600 effect amplitude were absent, a reduced P600 amplitude in response to both the grammatical and ungrammatical sentences was found, next to a reduced overall degree of source activation in linguistic ROIs and a reduced behavioural accuracy in response to the word order violation was observed in the elderly group. . Regarding the effect of gender, females exhibited a larger P600 effect amplitude and a reduced behavioural accuracy compared to males. No gender-related differences were found for P600 effect onset latency, topographical distribution and source activation.

Conclusion: While the present study demonstrates no effect of aging on the P600 effect, the lower behavioural response and absence of any activation shift argues against functional compensation. Moreover, although increased neural activation in women combined with their reduced behavioural accuracy may indicate the use of different cognitive strategies in men and women, source localization analysis could not objectify this hypothesis.

Key Words: healthy aging, gender, P600, syntactics

1. Introduction

Healthy aging has been associated with structural cortical changes, characterized by gray matter loss across the cerebral cortex (Fjell et al., 2014; Ramanoël et al., 2018). This gray matter loss is heterogeneous in nature and does not affect all cortical structures to the same extent (Fjell et al., 2014). Both areas involved in domain-general cognitive functions, such as the medial frontal gyrus (MFG) and prefrontal cortex, and structures engaged in domain-specific linguistic functions, such as the inferior frontal gyrus (IFG), superior temporal gyrus (STG) and the (medial) temporal lobes, have been reported to undergo these normal age-related changes (Ramanoël et al., 2018; Tisserand, 2004). Moreover, Ramanoël et al. (2018) found the loss of gray matter to be associated with a decreased performance on both domain-general and domain-specific cognitive tasks. A frontotemporal network, which appears to be highly sensitive to these age-related structural changes, has frequently been reported to underly syntactic comprehension processing (Friederici and Kotz, 2003; Kaan and Swaab, 2003; Grodzinsky et al., 2021). This network predominantly involves Broca's area (BA 44/45), the frontal operculum, the superior and middle temporal gyrus and the anterior temporal lobe. Based on these findings, one would expect the structural breakdown of both the frontotemporal syntactic comprehension network and supporting domain-general cognitive networks to result in inefficient syntactic processing strategies and a corresponding behavioural decline in the elderly. However, literature on the effect of aging on syntactic comprehension displays varying results.

Indeed, a few studies have reported a decline in syntactic comprehension in older adults based on behavioural experiments using a wide variety of tasks (e.g. sentence picture matching task, syntactical judgement task, pseudoverb tasks) (Antonenko et al., 2013; Peelle et al., 2010; Poulisse et al., 2019; Waters and Caplan, 2001), which provide evidence for a reduced accuracy and slower reaction times in the elderly. In contrast, several studies which measured behavioural performance have reported preserved syntactic comprehension processing in older adults (Campbell et al., 2016; Davis et al., 2014; Samu et al., 2017; Shafto and Tyler, 2014; Tyler et al., 2010). The resilience of syntactic comprehension on these behavioural tasks against the effect of aging can be explained by two dominant neurocognitive theories concerning neuroplasticity: the compensation hypothesis (Cabeza et al., 2002; Grossman et al., 2002; Reuter-Lorenz, 2002; Samu et al., 2017; Tyler et al., 2010) and the functional maintenance hypothesis (Campbell et al., 2016; Samu et al., 2017). Evidence for these hypotheses largely originates from functional magnetic resonance imaging (fMRI) research but is also supported by behavioural and structural neuroimaging research. The functional compensation hypothesis, describes a gradual loss in the neural structure associated with normal aging resulting in neural reorganization (Samu et al., 2017). Compensation refers to the positive association between cognitive performance and the increase in neural activity in older adults (Samu et al., 2017). To maintain adequate cognitive performance, older adults may utilize such compensatory processing strategies (Cabeza et al., 2002; Reuter-Lorenz, 2002; Samu et al., 2017). In the absence of a significant difference in behavioural performance between younger and older adults, Tyler et al. (2010) found an age-related activity increase in right frontal hemisphere regions in older adults during syntactic comprehension. Interestingly, this activity increase was associated with age-related atrophy in the left frontotemporal syntax network. The shift from a left frontotemporal network to a more bilateral network for syntactic processing in older adults may reflect a functional compensation for the age-related gray matter loss in the left-lateralized frontotemporal syntax system, which allows preserved performance (Tyler et al., 2010). According to the second theory, the functional maintenance hypothesis, older adults show preserved performance due to the conservation of the neural system without reduced specialization or compensation (Campbell et al., 2016; Samu et al., 2017). Contrary to the study Tyler et al. (2010) that described an increase in right-frontal activation in syntactic comprehension tasks with age, Campbell et al. (2016) did not find evidence for a compensatory response during natural language comprehension. Campbell et al. (2016) demonstrated a preserved functionality and within-network connectivity of the frontotemporal neural syntax network in older adults, even though these adults showed a structural decline in gray matter integrity and reduced between-network connectivity to more domain-general task-related networks. The dissociation between the results of the prior studies discussed might partly be explained by methodological differences since tasks with various types of stimuli and syntactic violations have been used. Therefore, a summary of the modality tested, task used, syntactic manipulation studied, as well as stimuli details of the prior studies, can be found in Appendix 1.

In addition to gray matter changes associated with aging, structural gender-related differences have been reported in cerebral areas important for language processing (Harasty et al., 1997; Sowell et al., 2003). Moreover, men and women appear to engage different brain areas during general language processing (Baxter et al., 2003). Studies on gender-related differences in syntactic sentence comprehension, however, are scarce. In relation to age, different evolutions in anatomical changes have been found in men and women with increasing age (Coffey et al., 1998; Cowell et al., 1994; Sowell et al., 2003). Whereas Costa et al. (2013) established that both functional and structural neural differences between women and men result in different aging patterns, few studies investigated the interaction between age and gender in language abilities. In a behavioural analysis of a corpus of dyadic conversations, Moscoso del Prado Martín (2017) found a significantly greater decline in the syntactic structure diversity in men. The peak in the usage of the most syntactic diverse utterances could be observed around the age of 45 years in men, followed by a clear decrease in the richness of the grammatical structures they use. In contrast, women performed at a higher level of syntactic diversity with increasing age, until their late fifties. However, it remains unclear if the same pattern can be observed for language comprehension.

In summary, it is not clear whether healthy aging is accompanied by a functional loss or preservation of syntactic comprehension processing abilities. Moreover, on the one hand, preserved syntactic comprehension abilities may reflect a preserved neural system in older adults (functional maintenance) (Campbell et al., 2016; Samu et al., 2017; Shafto and Tyler, 2014), but on the other hand, older adults may utilize compensatory processing to preserve their performance (functional compensation) (Peelle et al., 2010; Tyler et al., 2010). With regard to gender, the question arises as to whether men and women show different patterns in syntactic comprehension processing and to what extent there is an interaction between gender and age.

The existing literature on syntactic comprehension mostly relies on behavioural and functional neuroimaging investigations. Although behavioural experiments are widely used in aging studies, these only reflect the final result of several underlying cognitive processes (Luck, 2014). Neuroimaging methods such as fMRI and PET do provide information about functional neural brain activity but have limited temporal resolution. Furthermore, syntactic comprehension requires an integration of domain-specific language functions and domain-general cognitive functions. Based on behavioural and neuroimaging methods, it remains difficult to differentiate between these two. The event-related potential (ERP) technique provides information about neural processing between stimulus onset and response during syntactic comprehension processing. ERPs are time-locked voltage fluctuations, reflecting the summation of post-synaptic activity of firing neurons (Friederici and Kotz, 2003; Luck, 2014). They measure the moment-by-moment activity following a stimulus or even the brain state before stimulus onset (Luck, 2014) in the order of milliseconds. ERPs reflect several cognitive processes separated in time, which may be accumulated in neuroimaging methods, and therefore provide a great temporal resolution (Friederici and Kotz, 2003).

Following the temporospatial processing model of Dominey & Inui (2009), the temporal aspect of sentence comprehension consists of three phases, each associated with specific language-related ERP components (Friederici, 2002). Phase 1 involves lexical categorization in the superior and middle temporal gyrus (STG and MTG) and the transfer of this information to the left inferior frontal gyrus (left IFG). This process is associated with an early left anterior negativity (ELAN) ERP in the 150–200 ms timeframe. In phase 2, semantic and morphosyntactic integration takes place in BA 45/47 and BA 44/45, respectively. This process is reflected in the N400 and left anterior negativity (LAN) in the 300–500 ms time frame. In phase 3, late syntactic integration takes place in the inferior frontal gyrus, BA 44, the left frontal operculum and the basal ganglia (Friederici and Kotz, 2003), which is associated with the P600. ERP research into syntactic input processing has largely focused on the ELAN (Herrmann et al., 2011) and P600 component (Hagoort, et al., 1993; Osterhout and Holcomb, 1992), reflecting early automatic and late controlled syntactic processes respectively (Hahne and Friederici, 1999). Since the exact meaning of the ELAN and its involvement in syntactic processing was questioned (Steinhauer and Drury, 2012), the present study focusses on the P600 component. This language-related brain response is a positive-going deflection that starts around 500 ms after the onset of a keyword, that is, the word that causes the sentence to be ungrammatical, and lasts several hundred milliseconds (Hagoort et al., 1993; Osterhout and Holcomb, 1992). Sentences with syntactic violations, difficulties in syntactic integration, and violations of structural preferences have been shown to evoke this ERP component (Friederici, 2004; Hagoort et al., 1993). Maximal P600 amplitudes have been typically observed at bilateral posterior electrode sites, but a frontal distribution has also been reported (Brothers et al., 2021; Friederici et al., 2002; Kaan and Swaab, 2003; Kuperberg et al., 2020). The functional significance of the P600 is still a topic of debate. The P600 effect is not only associated with the processing of syntactic violations but also with syntactic reanalysis and repair processes and complexity in grammatical sentences (Friederici, 2002; Kaan et al., 2000). Furthermore, the strict syntactic view of the P600 is challenged by studies reporting a P600 in response to semantic anomalies (Kuperberg, 2007). Neural generators of the P600 component have been localized in the bilateral posterior superior temporal gyrus (Friederici and Kotz, 2003; Grodzinsky and Friederici, 2006; Service et al., 2007) and a predominantly left-lateralized or bilateral fronto-temporo-parietal network (Gonda et al., 2020; Kielar et al., 2015; Leminen et al., 2016).

The P600 in the aging brain has been examined in a few studies. Based on a semantic and syntactic violation experiment, Zhu, Hou and Yang (2018) found an increased P600 peak latency in older compared to young adults. Since these findings were accompanied by a decrease in the behavioural accuracy in older adults, the authors argued for lower age-related efficiency of syntactic processing. Interestingly, the amplitude of the P600 was similar across the two age groups. However, correlation analysis showed that a larger amplitude of the P600 was associated with lower syntactic performance, but only in older adults. Similarly, Kemmer et al. (2004) reported no age-related differences in overall P600 amplitude in a number violating comprehension task. However, in contrast to Zhu et al. (2018), both Kemmer et al., (2004) and Leckey and Federmeier (2017) found no difference in the P600 latency between the younger and older age group. With regards to the topographical distribution of the P600 component, age-related changes have also been reported. Kemmer et al. (2004) established a qualitative change in topography such that, compared to younger adults, older adults showed a P600 effect that was larger at frontal electrodes and more bilaterally distributed. Similarly, in a two-word phrase grammaticality judgement task, Leckey and Federmeier (2017) found P600 topography in the elderly to comprise anterior electrode sites and to change from a strongly lateralized to a more bilateral activation pattern with increasing age. These results are in line with those from neuroimaging studies that indicate a shift from the left frontotemporal network to a more bilateral network for syntactic processing in older adults (Tyler et al., 2010). However, whether or not this finding can be associated with the functional compensation hypothesis is unclear.

For conclusion, study design heterogeneity often leads to contrasting results, highlighting the need for a carefully considered methodology in research concerning language processing. Additionally, there is a need for neurophysiological research, which provides on-line temporal information about the syntactic comprehension process. Finally, as current P600 research on healthy aging is limited to an investigation of amplitude, latency and topographic distribution, it is not possible to draw conclusions on the involved neural structures. The implementation of P600 source localization may provide insight into the generators of the P600 component and possible shifts in lateralization patterns associated with aging and gender. Therefore, the current study aimed to examine the effects of healthy aging and gender on syntactic processing during sentence comprehension. For this purpose, the P600 component was measured in a syntactic word order violation paradigm. To assess the effect of aging and gender, participants were systematically allocated to specific age and gender groups. The obtained age and gender-dependent reference values allow for the comparison of patient populations (people with aphasia, developmental stuttering, dyslexia, …) with age and gender-matched controls. Regarding the effect of healthy aging, we expected P600 amplitude and latency not to be subject to aging based on previous research (Kemmer et al., 2004; Lekey and Federmeier, 2017). Following the functional compensation hypothesis, we expected a shift from a left-lateralized network for syntactic processing in young adults (Tyler et al., 2010), to a more bilateral frontotemporal network in older adults. Regarding the effect of gender, no electrophysiological studies investigating differences in the P600 between men and women have previously been carried out to the best of our knowledge. However, based on evidence from the P300 (Aerts et al., 2015) and N400 (Cocquyt et al., 2021; Daltrozzo et al., 2007), we expected syntactic word order violations to elicit a more positive P600 amplitude in women compared to men. No differences in onset latency between men and women were expected.

2. Method

2.1. Participants

Sixty Dutch-speaking healthy participants, thirty men and thirty women, were included in this study. Participants were right-handed, as assessed by the Dutch Handedness Inventory (scores ranged from +8 to +10) (Van Strien, 2003), reported no subjective complaints of hearing loss, and had normal to corrected vision. Participants did not have a history of developmental speech, language, or learning disorders or neurological/neuropsychiatric disorders. To examine aging effects, the participants were allocated to three age groups (20-39 years, 40-59 years, and 60-79 years). Each age group consisted of ten men and ten women. All participants completed the Dutch version of the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). Based on the cut-off score of 26, none of the participants met the exclusion criterion of the presence of mild cognitive impairments. Table 1 describes the age, education level, and MoCA scores of the three different age groups. This study was approved by the Ethical Committee of the Ghent University Hospital and all participants confirmed informed consent.

2.2. Behavioural assessment

Syntactic comprehension processing abilities were measured using the syntactical judgement subtest of the Verbs and Sentences Test (Werkwoorden- en Zinnentest, WEZT; Bastiaanse et al., 2000).

Participants were asked to judge 50 auditorily presented sentences on grammaticality. This grammaticality referred to the thematic roles, with an agent-subject reversal in incorrect sentences (e.g. "The cigarette had smoked the women.").

2.3. Experimental procedure

2.3.1. Procedure

For all participants, the EEG recording took place at the Ghent University Hospital. During this EEG recording, a visually presented syntactic word order violation paradigm was used, consisting of a total of sixty sentences of which thirty were grammatical sentences and thirty sentences contained a word order violation. Sentences were distributed over four experimental blocks of fifteen sentences each. The experimental paradigm was proceeded by a training block of six sentences. The sentences of each block were randomly presented on a Dell laptop screen, one word at a time.

The participants were seated approximately 75 cm from the laptop screen and were instructed to move as little as possible. After each experimental block, participants were able to take a break if wanted. The generation and the presentation of the stimuli were accomplished by E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA). Also, the accuracies and button press reaction times (ms) were registered in E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA).

At the start of each trial, participants focused on a 1.5 s lasting white fixation cross, centred on a black screen, in order to reduce vertical and horizontal eye movements. Next, the words of the sentences appeared at the centre of the screen. Each word lasted 500 ms and was followed by a blank screen for 500 ms. Following the last word, a blank screen of 1.5 s was presented, which was followed by the word "press". When the sentence was grammatical, the participants were instructed to press the green button on the Chronos response box (Psychology Software Tools, Pittsburgh, PA) with their right index finger. When the sentence was ungrammatical, the participants were instructed to press the red button. The participants received no feedback on the type of errors. The total duration of the experiment was seventeen minutes and thirty seconds. A schematic overview of the task procedure can be found in Figure 1.

2.3.2. Stimulus material

The word order violation task consisted of sixty Dutch sentences, which were selected from the experimental stimuli in the study of Hagoort, Wassenaar and Brown (2003). An adaptation of the sentences of Hagoort et al. (2003), which contained a Dutch word that is not frequently used in Flemish, was made. To rule out any prosodic or rhythmic effects on the critical violation regions, the present study used visually presented sentences, whereas the sentences in the study of Hagoort et al. (2003) were presented auditorily. Thirty of the sentences were grammatical (e.g. “The doctor tells the woman about her extremely *small* chance of recovery.”[1]). The other half were ungrammatical, containing a word-order violation (e.g. “The hunter shoots the running *fast* deer in the woods.” [1]), and these were not the counterparts of the grammatical sentences. The grammatical and ungrammatical sentences contained an adverb-adjective-noun and an adjective-adverb-noun construction respectively and were matched for sentence length (mean number of words: 10.7), number of words preceding the critical word (mean number of words: 6) and frequency. The critical word in the sentences of this word-violation task was the adjective in the grammatical condition and the adverb in the ungrammatical condition. In addition to the sixty selected sentences of Hagoort et al. (2003), six similar sentences were created for the training block.

2.3.3. EEG recording

Continuous EEG was recorded from 32 Ag/AgCl electrodes, using an EasyCap electrode cap (Brain Products, Munich, Germany), at the following scalp sites (International 10-20 system, American Electroencephalographic Society, 1991): Fp1/2, Fpz, F3/4, Fz, FC1/2, FC5/6, C3/4, T7/8, Cz, CP1/2, CP5/6, P3/4, P7/8, Pz, TP9/10, POz, O1/2, and Oz. AFz and FCz were used as the ground electrode and the online reference electrode respectively. By using an abrasive electrolyte gel (Abralyt 2000,

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[1] The (violation of) the word order preference is underlined. The critical word is in italics.

EasyCap), the electrode impedances were kept below 20 kΩ. The preparation of the EEG registration was done by an experienced researcher. The EEG signals were collected with a BrainVision BrainAmp amplifier (Brain Products, Munich, Germany) and were digitized with a sampling rate of 500 Hz. As recording software, BrainVision Recorder was used (Brain Products, Munich, Germany).

2.3.4. ERP data analysis

The offline EEG analysis was performed using BrainVision Analyzer 2 software (Brain Products, Munich, Germany). Button press accuracies were measured and both trials with accurate, and inaccurate button press responses were included in the analysis. First, bad electrode channels caused by damaged electrodes were eliminated and the training block was removed. None of the disabled electrodes were the online reference electrodes or the electrodes of interest for further amplitude, latency or topography analyses. Next, the continuous EEG data were band-pass filtered with half-amplitude cut-off frequencies of 0.3 and 30 Hz (12 dB/octave roll-off), using an infinite impulse response filter. EEG registrations were also notch filtered at 50 Hz. Thereafter, artefacts induced by horizontal eye movements and eye blinks were removed through Independent Component Analysis (ICA). Artefact-related components were identified and removed based on visual inspection of the waveform and scalp topography. The disabled channels were interpolated following the ICA and the data were then re-referenced to the algebraic average of the left and right mastoid electrodes (TP9, TP10).

Next, continuous EEG recordings were segmented for grammatical and ungrammatical sentences into 1800-ms epochs of 300-ms before the onset of the critical word to 1500-ms after the onset of the critical word. Subsequently, a baseline correction was carried out using a window of 300 ms to 0 ms prior to the stimulus onset and automatic artefact rejection was applied using the following criteria: maximum gradient criterion of 75 µV, minimal-maximal amplitude criterion of 100 µV, maximum difference criterion of 150 µV, and low activity criterion of 0.5 µV during 100 ms. All participants met the following inclusion criterion: less than 25% of their trials were rejected. The artefact rejection was equal across all age groups, gender groups and age x gender groups. Artefact-free segments were averaged for the responses on the grammatical and ungrammatical sentences. Finally, the difference waves of the P600 were computed by subtracting the averaged ERPs elicited in response to the grammatical sentences from those elicited in response to the ungrammatical sentences.

Mean amplitude values, measured as the mean voltage in a 500 – 1000 ms time window were extracted for individual waveforms in response to grammatical and ungrammatical sentences as well as the difference waveform (termed P600 effect). Moreover, to evaluate the time course of the P600 effects, mean amplitudes were extracted across five time windows of 100 ms each (500 – 600 ms, 600 – 700 ms, 700 – 800 ms, 800 – 900 ms and 900 – 1000 ms). All amplitude measures were extracted from frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4) electrodes. The onset latency of the P600 was estimated by calculating the positive area under the ERP waveform over the time window 500 – 1000 ms for both the individual and difference waveforms. The 25% signed fractional area latency was defined by the time point that divided the first 25% of the area from the last 75% of the area (Luck, 2014). Onset latency values were extracted and averaged across three parietal electrode sides (P3, P4, Pz), as the P600 is typically associated with a posterior distribution (Kaan and Swaab, 2003).

2.3.5. Source localization

For each subject, the evoked responses to the grammatical and ungrammatical sentences were source localized using dynamic Statistical Parametric Mapping (dSPM; Dale et al., 2000) as implemented in the MNE-Python package (Gramfort et al., 2014). For the calculation of the forward solution with fixed dipole orientations, Freesurfer’s average brain model was used with a source space of 5124 dipoles distributed on the cortical surface. After source localizing both the averaged ERPs elicited by grammatical and ungrammatical sentences, the difference wave was calculated. Five different regions of interest (ROIs) within the linguistic cortex were selected based on the literature on previously established neural generators of the P600 event-related component, namely the auditory association cortex (AAC), the inferior parietal cortex (IPC), the lateral temporal cortex (LTC), the medial temporal cortex (MTC), and the insular and frontal opercular cortex combined with the posterior opercular cortex (IFCop + insula). The different anatomical ROIs were defined using the Human Connectome Project's multi-modal cortical parcellation (Glasser et al., 2016) and are shown in Appendix 2. Further, the area surfaces and MNI centre coordinates are shown in Appendix 3. To obtain a single time-series for each ROI, the time-series of the dipoles within the ROI were averaged across dipoles at each time point. Similar to the ERP analysis, the mean activation was calculated for each of the selected ROIs in both hemispheres between 500 – 1000 ms to evaluate the time course of the P600 effects.

2.4. Statistical analysis

For the statistical analyses IBM SPSS Statistics 27 (SPSS Corporation, Chicago, IL, USA) was used. The 0.05 alpha level was used to determine statistical significance. First, a univariate ANOVA with age group (young, middle-aged, elderly) and gender (female, male) as independent variables was performed to investigate the behavioural and electrophysiological accuracy data. Further, for the analysis of the P600 (500 – 1000 ms) amplitude values, mean amplitudes were analysed using a repeated-measures ANOVA with age group and gender as between-subject factors and gramaticality (grammatical or ungrammatical sentences) as a within-subject factor. A univariate ANOVA was used to determine the effect of aging and gender on the P600 effect (difference waves: ungrammatical minus grammatical sentences). To investigate timing-related differences between age groups and/or gender, a repeated-measures ANOVA was performed with time window as within-subject factor. For the analyses of the P600 and the P600 effect, the amplitudes were averaged across the nine electrode positions (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Moreover, for the effect of aging and gender on the onset latency of the P600 amplitudes, a repeated-measures ANOVA was performed with grammaticality as within-subject factor. A univariate ANOVA was used to determine the effect of age group and/or gender on the onset latency of the P600 effect. Considering the topographical distribution of the P600 effect, a repeated-measures ANOVA was used with age group and gender as between-subject factors and A-P distribution (frontal, central, parietal) and laterality (left, middle, right) as within-subject factor. To investigate the effect of age group and gender on the P600 source localization, a repeated-measures ANOVA was performed with ROI (auditory association cortex, inferior parietal cortex, lateral temporal cortex, medial temporal cortex and inferior frontal cortex pars opercularis + insula) and hemisphere (right or left) as within-subject factors. In the case of inhomogeneous covariances (Levene's test), when more than two levels of a within-subject factor were applied, the Greenhouse-Geisser correction was administered for adjusted degrees of freedom, F-values and p-values. The post hoc pairwise comparisons were run using the Bonferroni correction procedure.

3. Results

3.1. Demographic data

Table 1 describes the demographic data (age, education level and MoCA scores) of the three different age groups, for men and women separately. A Kruskal-Wallis test comparing the MoCA scores and education level between the three age groups for men and women separately showed a statistically significant difference between the education level of the female young, middle-aged and elderly adults ($H(2) = 14.289$; $p < .001$). Younger females had a higher education level than middle-aged females (mean difference: 0.7; $p = .032$) and the elderly females (mean difference: 1.6; $p < .001$). There was no significant education level difference between the three male age groups. Further, a significant difference between men and women in the education level was only found in the elderly age group ($H(2) = -2.678$; $p = .007$). The elderly women displayed a lower education level than the elderly men (mean difference: 1.2). Finally, MoCA scores did not show significant differences between the different age and gender groups.

3.2. Behavioural assessment

The standardized evaluation of grammatical versus ungrammatical sentences, as measured with the WEZT, showed a high behavioural accuracy in the three age groups. Mean behavioural scores can be found in Table 2. No significant main effects of age group or gender or an interaction between age and gender were found.

3.3. Electrophysiological evaluation

3.3.1. Behavioural accuracy

Behavioural accuracy scores are provided in Table 2. A significant main effect of age group was found on the behavioural accuracy for the grammatical tasks during EEG recording (main effect of age group: *F*(5.689, 54) = 2, *p* = .006) using a univariate ANOVA. Post hoc pairwise comparisons using a Bonferroni test revealed that the behavioural accuracy was 2.4 points (95% CI [0.6 – 4.1], *p* = .006) higher in the young group compared to the elderly (mean difference: 2.4, 95% CI [0.6 – 4.1], *p* = .006). Furthermore, males showed a significantly higher accuracy than females (main effect of gender: *F*(5.088, 54) = 1, *p* = .028) with a mean difference of 1.3 (95% CI [0.1 – 2.5]). Finally, no two-way interaction was found between gender and age group.

3.3.2. The P600 (effect)

Amplitude of the P600 (effect). A two-way ANOVA analysis was performed to investigate the effect of gender and age on the P600 effect in a broad time window (500 – 1000 ms), as measured by the differences wave (ungrammatical minus grammatical sentences). A significant gender effect was found (main effect of gender: *F*(1, 54) = 6.146, *p* = .016). Post hoc pairwise comparisons showed that the females had significantly more positive activity than the males (mean difference: 2.7 µV, 95% CI [0.5 – 4.9]) (Figure 3). The main effect of age group and the interaction between gender and age group on the P600 effect was not significant. P600 mean amplitude values over the broad time window are reported in Appendix 4. The results of the analyses on the amplitudes of the difference waves measured in five temporally more refined time windows (500 – 600 ms, 600 – 700 ms, 700 – 800 ms, 800 – 900 ms, and 900 – 1000 ms) to investigate age and gender effects, can be found in Appendix 5. Mean amplitude values of the P600 effect for the five 100 ms time windows are reported in Appendix 6.

Across the nine electrode positions and across grammatical and ungrammatical sentences, a comparison of the P600 amplitude in a broad time window (500 – 1000 ms) revealed significantly less positive activity with increasing age (main effect of age group: *F*(2, 54) = 5.431, *p* = .007). Post hoc pairwise comparisons showed significantly less positive activity in the elderly compared to the young (mean difference: 1.4 µV, 95% CI [0.4 – 2.5], *p* = .005), whereas no significant difference was found between the young and middle-aged and between the middle-aged and the elderly. Importantly, the P600 amplitude was significantly less positive in grammatical compared to ungrammatical sentences (main effect of grammaticality: *F*(1, 54) = 110.45, *p* < .001, mean difference: 2.8 µV, 95 % CI [2.3 – 3.4]), indicative of the P600 effect. Moreover, a significant grammaticality by gender effect was found (grammaticality by gender interaction: *F*(2, 54) = 6.135, *p* = .016). Post hoc pairwise comparisons showed that for grammatical sentences, females had significantly less positive activity compared to males (mean difference: 0.6 µV, 95% CI [0.04 – 1.3], *p* = .035), whereas the P600 amplitude in response to ungrammatical sentences was higher in females compared to males, although this difference did not reach statistical significance (mean difference: 0.7 µV, 95% CI [0.4 – 1.8], *p* = .216). A summary of the statistical results is provided in Table 3. The ERPs are visualized in Figure 2. There was no significant main effect of gender and no interaction effects between age group and gender, between grammaticality and age group, and between grammaticality, age group and gender. Appendix 6 additionally depicts the P600 in response to the grammatical and ungrammatical condition for all 9 electrode positions for each participant subgroup.

Onset latency of the P600 (effect). Focusing on the P600 latencies of the individual waveforms, no significant main effect or interaction effects of grammaticality, age, or gender was found across the parietal electrode positions. In accordance, there were no significant main effects of age group and gender on the onset latency of the P600 effect, as measured on the difference waves. Onset latencies are reported in Appendix 7.

Topographical distribution of the P600 effect. The repeated-measures ANOVA showed that there was a significant main effect of A-P distribution on the P600 effect (main effect of A-P distribution: *F*(1.253, 67.684) = 24.094, *p* < .001). Descriptively, the P600 effect increased from anterior to posterior electrode positions. Post hoc pairwise comparisons revealed that, compared to frontal electrode positions, the P600 effect was significantly higher at central electrode positions (mean difference: 2.2 µV, 95% CI [1.3 – 3.1], *p* < .001) and parietal electrode positions (mean difference: 3.1 µV, 95% CI [1.6 – 4.6], *p* < .001). However, there was no significant difference regarding the mean amplitude between central and parietal electrode positions. Additionally, a significant interaction was found between A-P distribution and age group (A-P distribution by age group interaction: *F*(2.507, 67.684) = 4.932, *p* = .006). This interaction revealed that, although a similar A-P distribution of the P600 effect was found in all three age groups, post hoc pairwise comparisons between electrode positions did not reach statistical significance in some of the groups. However, no significant main effect of age group was found and no significant interaction effects between A-P distribution, age and gender, and between age group and gender were found. Mean amplitude values for frontal, central, parietal, left, midline and right electrode positions are displayed in Appendix 8 for each age and gender group separately. Topographic distribution in the 500 – 1000 ms time window for each age category and gender is visualized in Appendix 9. With regards to the effect of laterality, a significant main effect of laterality was found on the P600 effect (main effect of lateralization: *F*(2, 108) = 47.843, *p* < .001). Post hoc pairwise comparisons showed that the P600 effect was significantly higher at the midline electrode positions compared to the right (mean difference: 1.3 µV, 95% CI [0.7 – 1.9], *p* < .001) and the left electrode positions (mean difference: 2.6 µV, 95% CI [1.9 – 3.2], *p* < .001). The P600 effect was also significantly larger at the right compared to the left electrode positions (mean difference: 1.3 µV, 95% CI [0.6 – 2.0], *p* < .001). Moreover, a significant interaction between A-P distribution, lateralization, and gender was found (A-P distribution by lateralization and gender interaction: *F*(4, 216) = 4.176, *p* = .032). This interaction revealed that, although the effect of A-P distribution on P600 effect was similar at all right, midline and left electrode positions and in both genders, not all post hoc pairwise comparisons reached statistical significance in males and females.

Source activation of the P600 effect. A significant main effect of ROI on the P600 effect source activation (*F*(4, 216) = 78.947; *p* < .001) was revealed by the repeated-measures ANOVA. Post-hoc comparison between the ROIs indicated higher activation in the MTC as compared to the IPC (mean difference: 2.008, 95% CI [1.395 – 2.621], *p* < .001), the IFCOp/insula (mean difference: 2.006, 95% CI [1.423 – 2.589], *p* < .001), the AAC (mean difference: 1.184, 95% CI [0.881 – 1.488], *p* < .001) and the LTC (mean difference: 1.079, 95% CI [0.794 – 1.364], *p* < .001). Furthermore, a significantly higher degree of activation was detected in the LTC as compared to the IPC (mean difference: 0.929, 95% CI [0.556 – 1.302], *p* < .001) and the IFCOp/ insula (mean difference: 0.927, 95% CI [0.581 – 1.273], *p* < .001). Similarly, the AAC was shown to exhibit greater activation as compared to the IPC (mean difference: 0.823, 95% CI [0.449 – 1.198], *p* < 001) and the IFCOp/insula (mean difference: 0.822, 95% CI [0.459 – 1.184], *p* < .001). In addition, a significant interaction was found between ROI and age group (ROI by age group interaction: *F*(8, 216) = 4.491; *p* < .001). Young participants were found to show significantly higher activation as compared to the middle-aged in both the MTC (mean difference: 1.756, 95% CI [0.262 – 3.250], *p* = .016), the LTC (mean difference: 1.233, 95% CI [0.273 – 2.193], *p* = .007) and the AAC (mean difference: 1.092, 95% CI [0.105 – 2.079], *p* = .025). Comparison of the activation in the left and right hemisphere revealed no interaction between ROI and hemisphere. Finally, a significant main effect of age on source activation of the P600 effect (main effect of age: *F*(2, 54) = 3.872; *p* = .027) was revealed by the repeated-measures ANOVA. Post-hoc pairwise comparison showed that in comparison to the middle-aged, less overall activation was found in the elderly (mean difference = 0.908, 95% CI [0.099 – 1.717], *p* = .023). In contrast, main effect of gender and hemisphere was found and none of the other two-, three- or four way interactions were significant. Source activation is visualized in Figure 4.

4. Discussion

The present study aimed to investigate the effects of healthy aging and gender on syntactic processing in sentence comprehension. To this end, sixty healthy participants (30 women and 30 men), equally divided among three age groups (young, middle-aged and elderly) completed a visually presented syntactic word order violation paradigm during EEG registration. In the following sections, the results on the effects of aging and gender on the P600 component are discussed separately.

4.1. The effects of healthy aging on syntactic sentence processing

The P600 was elicited using a syntactic word order violation paradigm, which was associated with a behavioural task. At the end of each sentence, participants were asked to make a judgment on the grammaticality by means of a button press response. Compared to the young and middle-aged, the elderly showed significantly reduced behavioural accuracy. In all three age groups, the syntactic word order paradigm elicited a significant P600 effect (P600 amplitudes elicited by the ungrammatical condition > P600 amplitudes elicited by the grammatical condition) in a broad time window (500 – 1000 ms). Time window analysis revealed a similar progression of the P600 effect within each age category, characterized by a gradual increase of the effect from 500 – 900 ms post stimulus onset, followed by a decrease of the effect from the 900 – 1000 ms time window onwards. Accordingly, previous inquiries mainly provide evidence for the absence of any age-related alterations in the amplitude of the P600 effect (Kemmer et al., 2004; Leckey and Federmeier, 2017; Zhu et al., 2018). Similarly, in the present study, no differences in amplitude of the P600 effect (difference wave) could be observed between the three age groups. Based upon the P600 effect (difference wave), healthy aging seems to have little effect on the amplitude of the brain’s response to syntactical word order violations, despite the associated age-related decrements in behavioural accuracy of syntactical judgements in sentences. In contrast to the absence of any aging effects on the amplitudes of the P600 difference waves, the behavioral data show that the elderly were significantly less accurate than the younger adults in their syntactical judgement at the end of each sentence. This discrepancy is consistent with other studies suggesting that age increase may affect response-related processes more than late, preresponse cognitive processes (Bashore & Smulders, 1995; Hartley, 2001).

Regarding the onset latency of the P600 effect, no significant difference was found between the three age groups. This finding is in line with some earlier reports of similar P600 latency in young and elderly

(Kemmer et al., 2004; Leckey and Federmeier, 2017). In contrast, however, Zhu et al. (2018) reported delayed peak latency for the P600 effect in the elderly. Furthermore, our findings do not correspond to the robust age-related delays that were found in the P300 (Fjell and Walhovd, 2001). In addition, the results of the present study are not in agreement with the cognitive slowing hypothesis, which states that deficits in cognitive performance arise when central information processing is slow and less efficient (Salthouse, 1996). Indeed, the age-related reduction in behavioural accuracy may provide evidence for a decline in cognitive performance. However, the amplitude and onset latency results do not provide evidence for delayed syntactic input processing. The conflicting results obtained in inquiries into the P600 effect reveal the issue of methodological difference regarding the used paradigm. First, the participant selection criteria used in the present study might provide an alternative explanation for the absence of aging effects on the onset latency. Zhu et al. (2018), who observed delayed peak latency of the P600 effect in the elderly reported a relatively lower score on the MoCA (mean 27.4 (SD 1.7)) in the elderly as compared to the MoCA scores obtained by the elderly participants in the present study (male: mean 28.7 (SD 0.95); female: mean 28.4 (SD 0.84)). Based on the adoption of the same cut-off scores, in both studies, participants were considered to be cognitively healthy adults. However, our participant group showed a higher degree of general cognitive status, which may explain the absence of delayed syntactic processing. In addition, with respect to education level, the same general tendency was observed in the current study and Zhu et al. (2018) with young participants having a higher education level than the elderly. Since different measures were used for defining education level in the current study (obtained educational degree) and Zhu et al. (2018) (years of education), comparison requires some caution and educational level cannot be ruled out as an influencing factor. Further, the discrepancy in results between previous P600 research and the current results might be explained by methodological differences concerning the paradigms used. Paradigms with various types of syntactic violations (syntactic word order violation, syntactic agreement violation, combination of semantic and syntactic violation) and a varying degree of difficulty have been reported to elicit a P600 response and have been used in these studies (Kemmer et al., 2004; Leckey and

Federmeier, 2017; Zhu et al., 2018). Syntactic processing requires a dynamic interaction between domain-general cognitive (e.g. working memory load) and linguistic skills. This dynamic interaction varies depending on the syntactic task. In this respect, Zhu et al. (2018) described semantic processing load and working memory load as factors that affect the P600. As reported by Zhu et al. (2018), Waters and Caplan (2005) described the interference of high working memory load, which proved to be sensitive to age-related changes (Kemtes and Kemper, 1997; Park and Reuter-Lorenz, 2009) on syntactic processing. In the elderly, Alatorre-Cruz et al. (2018) reported a reduction in P600 amplitude in syntactic tasks placing high demand on working memory compared to tasks with minimal working memory load. This distinction was not observed in the young group. In the syntactic word order violation paradigm used in the present study, sentences were visually presented word by word, with the critical word (word on which the violation occurred) being presented near the end of the sentence (word 9 out of 12). The design of this paradigm may impose large demands on the working memory in the elderly, hence affecting P600 amplitude in response to both the ungrammatical and grammatical sentences separately. The reduced behavioural accuracy found in the elderly compared to the young and the finding that this age-related difference does not extend to the other behavioural tasks (WEZT), which may be designed in such a way as to create less pressure on the working memory, provides additional evidence for the effect of a high working memory load. Given the absence of aging effects on the amplitude of the P600 difference waves in the current study, the extent to which the reduced P600 amplitude in response to both the grammatical and ungrammatical sentences in the elderly is attributable to the influence of confounding factors such as working memory remains unclear.

The topographical distribution of the P600 effect increased from anterior to posterior electrode positions in all three age groups, similar to prior studies describing the P600 as a positive component that is maximal over centroparietal electrodes (Faustmann et al., 2007; Hagoort et al., 2003). Laterality results of the present study showed that the P600 is maximal over midline and right hemispheric electrodes, consistent with previous results on lateralization of the topographical distribution of the P600 effect indicating midline and/or right lateralized effects (Osterhout and Holcomb, 1992; Gouvea et al., 2010; Hagoort et al., 2003; Kemmer et al., 2004). In contrast to Kemmer et al. (2004) and Leckey and Federmeier (2017), who observed the P600 effect in elderly to be more pronounced over frontal sites and to be more bilaterally distributed compared to the young group, our results did not support an age-related topographical shift. Again, methodological differences such as the used language paradigm or participant selection criteria might offer an explanation for the dissociation between the results of Kemmer et al. (2004) and Leckey and Federmeier (2017) on the one hand, and the present results on the other hand. Whereas a syntactic violation paradigm was used in each study, the nature of the syntactic violation (e.g. verb-subject agreement violation in Kemmer et al. (2004) versus word order violation in the present study) and the difficulty of the paradigm (e.g. two-word sentences in Leckey and Federmeier (2017) versus twelve-word sentences in the present study) differed between these studies. Regarding participant selection, age and gender distribution of the elderly group is comparable across the three studies. However, Kemmer et al. (2004) do not provide information on educational level of the participants. In Leckey and Federmeier (2017), the elderly group exhibited a considerably lower mean MoCA score (mean = 26) compared to the elderly group in the present study. Thus, general cognitive status differences between the participants in the prior and present studies might provide an explanation for the different results. Nevertheless, the present results are somewhat remarkable given that the results of Kemmer et al. (2004) and Leckey and Federmeier (2017) are in accordance with the evidence of a posterior to anterior shift in aging (PASA; Davis et al., 2008) and a hemispheric asymmetry reduction in older adults (HAROLD-theory; Cabeza, 2002). The PASA and HAROLD model describe an increased recruitment of frontal regions and regions contralateral to the language-dominant hemisphere, respectively, for language processing with increasing age. This recruitment is described as a compensatory mechanism in order to maintain function. Furthermore, as previously reported by Kemmer et al. (2004) and Faustmann et al. (2007), comparable age-related shifts to a more frontally distributed topographical distribution in elderly were reported in relation to the P300 (Fabiani et al., 1998; Friedman et al., 1997). Considering the P600 has been described as a member of the P300 family, a similar effect would be expected in our data.

While the results of the topographical distribution provide insight into the P600 effect at cortical level, little information is provided on the neural structures involved in the generation of the response. Additional source localization analysis was performed in order to obtain insight into overall source activation and age-related changes in activation patterns. Overall source analyses in the 500-1000ms time window revealed maximal activation in the bilateral MTC, followed by the AAC and LTC, indicating a dominant involvement of the temporal cortex in syntactic input processing. In comparison to these regions, although still actively involved, less activation was observed in the IFGOp/insula and IPC. Our findings indicate the involvement of a bilateral fronto-temporal network in syntactic input processing at sentence level. The current results are consistent with the majority of previous inquiries into sources of the P600 effect, that demonstrated involvement of the bilateral superior temporal cortex (Grodzinsky and Friederici, 2006; Service et al., 2007), a bilateral fronto-temporal network (Leminen et al., 2016) or a widespread bilateral fronto-temporo-parietal network (Kielar et al., 2015). However, the IPC, in which we established the lowest degree of activation, has also been implicated in models of syntactic processing (Matchin and Hickock, 2020; Meltzer-Asscher and Thompson, 2014).

As for the effect of age on source activation, comparison of the degree of activation in the selected ROIs revealed an overall higher degree of activation in middle-aged compared to the elderly. In addition, higher activation was found in all temporal cortex ROIs (ACC, MTC and LTC) in the young group compared to the middle-aged. This decreased activation in language-related ROIs with increasing age does not correspond with the absence of significant amplitude differences of the P600 effect between the three age groups. However, P600 amplitude reductions in response to both the grammatical and ungrammatical sentences were found in the elderly. Finally, no age-related intra-hemispheric shift in source activation or an interhemispheric shift in lateralization could be observed within the language-related ROIs. To date, no studies have systematically examined the effect of age on source activation of the P600 effect. However, functional neuroimaging studies investigating age-related changes in syntactic comprehension processing revealed reduced recruitment of language-related regions due to a loss of gray matter density and a shift from a lateralized to a bilateral network

(Tyler et al., 2010). Tyler et al. (2010) interpreted these results as evidence for a compensatory mechanism, as also pointed to by Cabeza (2002) and Wingfield and Grossman (2006). However, in the current study, neither the results of the topographical analysis, nor the source localization results indicate any age-related activation or lateralization shift. Moreover, the additional observations of a decreased behavioural accuracy in the elderly and reduced recruitment of language-related ROIs found with increasing age precludes the current results from being situated within the functional compensation hypothesis (Campbell et al., 2016; Samu et al., 2017) or the functional maintenance hypothesis (Cabeza et al., 2002; Grossman et al., 2002; Reuter-Lorenz, 2002; Samu et al., 2017; Reuter-Lorenz, 2002; Tyler et al., 2010), both of which presuppose functional preservation. In the case of compensation, a preserved behavioural accuracy would be expected to be accompanied by increased neural activity (increased P600 amplitude) and an activation shift (Samu et al., 2017). By contrast, a similar P600 amplitude and behavioural accuracy in the elderly compared to the young and middle-aged, indicating preservation of the neural system, would provide evidence for the functional maintenance hypothesis (Campbell et al., 2016; Samu et al., 2017). In contrast, given the decreased behavioural accuracy and reduced source activation, the current results might add to the hypothesis of inefficient syntactic processing in elderly (Zhu et al., 2018). Possibly, a reduced recruitment of language-specific regions due to age-related structural neural changes, in the absence of compensational recruitment of other neural structures, underlies the inefficient syntactic processing, as reflected in a reduced behavioural accuracy. Nevertheless, while our findings do not provide evidence for an age-related activation shift within the language network, compensational mechanisms through the recruitment of regions outside the language network cannot be ruled out based on the current results. Finally, it should be emphasized that, although lateralization indices revealed bilateral recruitment in most ROIs, a large standard deviation was obtained. This may indicate that our results, which do not capture any age-related shift in lateralization, are attributable to a large inter-individual variability.

4.2. The effects of gender on syntactic sentence processing

Women showed higher activation compared to men, as reflected by a larger amplitude of the P600 effect in the broad time window (500-1000 ms). This difference is mainly attributable to an increased P600 amplitude in reaction to the grammatical sentences, as no significant gender-related differences were found in P600 amplitude in the ungrammatical condition. These findings are in line with previous research on linguistic ERPs, showing an increased P300 (Aerts et al., 2015; for review see Melynyte et al., 2018) and N400 (Cocquyt et al., 2021; Daltrozzo et al., 2007) amplitude in women for phonological and semantic input processing, respectively. The increased amplitude in women was suggested to reflect the use of different cognitive strategies for (verbal) information processing in both genders (Cocquyt et al., 2021) and might indicate the recruitment of a larger neuronal network. Indeed, structural and functional neuroimaging studies have provided evidence supporting the engagement of different brain areas in language processing in men and women (Baxter et al., 2003; Harrington and Farias, 2008). Regarding the structural differences, in a recent review, Sato (2020) summarized evidence on structural gender differences in gray matter volume, density and symmetry, both in general and in language-related areas (Gennatas et al., 2017; Nunez et al., 2018; Ruigrock et al., 2014). Moreover, Harasty et al. (1997) found women to show a proportionally larger Broca’s area and superior temporal cortex, structures that have been described as important neural generators of the P600 (Grodzinsky and Friederici, 2006; Kielar et al., 2015; Leminen et al., 2016; Service et al., 2007). Regarding the functional differences, functional neuroimaging studies often point to lateralization differences in language-related areas (Baxter et al., 2003; Kaiser et al., 2007; Rossel et al., 2002) between men and women, with language being represented more bilaterally in women. Accordingly, in relation to verb generation and orthographic sentence comprehension, Harrington and Farias (2008) showed a more bilaterally distributed activation in the insular region in women compared to men. Possibly these structural and functional differences might be associated with the P600 amplitude contrasts between men and women.

However, in the present research, neither the results of the topographical distribution nor source localization results indicated any gender-related activation differences. Moreover, no lateralization differences were found between men and women. In addition, based on previous research which states that women generally perform stronger on behavioural language tasks, it would be expected that the recruitment of a larger neural network would lead to a higher behavioural accuracy. Interestingly, however, the current results showed that men exhibited higher behavioural accuracy on the syntactic judgment task associated with our syntactic word order violation paradigm. Whereas both the current amplitude results and the majority of the available structural and functional neuroimaging literature on gender-related differences in language processing argue for the use of different cognitive strategies in men and women, current results of topographic distribution and source activation do not support this hypothesis. A number of factors should be considered when interpreting this. Firstly, Sommer (2004) pointed to task-related differences as a possible explanation for varying findings in literature. Accordingly, the applied paradigm in the current study might explain the lack of gender-related differences in topographic distribution and source activation in our results. Secondly, only a limited amount of evidence is available for the absence of gender-related structural and functional activation differences (Sato et al., 2020; Sommer, 2004; Watkins, 2001; Weiss et al., 2003). As suggested by Kaiser et al. (2009), the underreporting of findings indicating the absence of gender-related differences might explain the discrepancy between our results and the existing literature. Finally, source activation analysis was applied on only a number of ROIs, limited to the linguistic cortex. This methodological decision might provide an explanation for the lack of gender differences in this research, as the recruitment of additional, domain-general areas outside the selected ROIs in women cannot be ruled out.

Lastly, with respect to the onset latency of the P600 effect, no gender-related differences were found, indicating similar syntactic processing speed in both males and females. Furthermore, processing in both genders remained comparable in all three age categories. To our knowledge, no previous inquiries into the P600 included the investigation of gender-related effects. However, our findings are in line with investigations of Aerts et al. (2015) and Cocquyt et al. (2021) who observed no gender-related differences in the P300 and N400 language-related component, respectively. In contrast, Daltrozzo et al. (2007) reported an earlier N400 effect in women as compared to men in an auditory semantic priming paradigm. Whilst the amplitude results give rise to the hypothesis of different neural networks in men and women, our findings indicate that this does not lead to alterations in processing speed.

In conclusion, while the findings on an increased P600 amplitude in women would suggest that men and women use different cognitive strategies for syntactic processing, neither the results of the P600 latency, nor the topographical distribution or source localization results indicate any gender-related differences in processing speed, source activation or lateralization in syntactic processing.

4.3. Directions for future research

To our knowledge, the present study is the first to systematically investigate the effect of age, gender and the interaction thereof on syntactic input processing by means of an event-related potential. In comparison to behavioural studies, linguistic ERPs have proven to be more objective and sensitive to evaluate neurolinguistic processes (Cocquyt et al., 2020). Alternatively, in comparison to functional neuroimaging studies, ERPs have a high temporal resolution, allowing them to provide detailed information on the time course of certain neurolinguistic processes (Luck, 2014).

Whereas the effect of aging on the P600 effect has previously been investigated (Kemmer et al., 2004; Leckey and Federmeier, 2017; Zhu et al., 2018), the present study offers added value. First, in contrast to the aforementioned studies who compared the P600 effect in young and elderly, we aimed to identify gradual age-related changes in syntactic processing by including a middle-aged group. Secondly, age and gender dependent reference values are obtained for the P600 amplitude and latency characteristics, allowing for the comparison of patient populations (people with aphasia, people with developmental disorders…) with age and gender matched controls. However, considering the limited size of our experimental group, these values should be interpreted with some caution. Thirdly, in addition to the comparison of the standard ERP characteristics, including amplitude, latency and topographical distribution, the current study provides added value through the implementation of source localization analysis. While topographical distribution can in fact offer some information on activation differences between age and gender groups, little information is provided on the underlying neural generators, cortical activation patterns and source lateralization. The applied source localization method enables understanding of the activation of linguistic ROIs in both hemispheres during syntactic sentence processing. A downside of the applied methodology is that the selection of ROIs limited to the linguistic cortex (except for the IPC), results in a lack of information on possible activation in areas outside these areas. Moreover, as argued by Sommer (2004), source activation might be highly dependent on the selected task. Following this hypothesis, the age and gender-related differences we observed in P600 amplitude and latency values may also be task-specific. Future research assessing the effects of age and gender in other syntactic paradigms may provide insight into the extent to which our results are task-specific or generalizable to overall syntactic processing. Lastly, the current study applied source localization based on EEG registration with a low-density 32-electrode system. Future studies investigating the activation of linguistic ROIs during syntactic input processing by means of higher-density EEG (64 or 128-electrode system) are recommended to further improve localization precision.

Disclosure of conflict of interest

None of the authors reported any conflict of interest.

Data availability statement

The datasets generated and analyzed during this study are not publicly available due to an ongoing patent application.

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Figures

Figure 1. Schematic overview of the task procedure. Two examples of the target stimuli are presented for the syntactically correct condition with an adverb-adjective-noun construction ("The doctor tells the woman about her extremely small chance of recovery.") and syntactically incorrect condition with an adjective-adverb-noun construction ("The hunter shoots the running fast deer in the woods.") (ms = milliseconds).

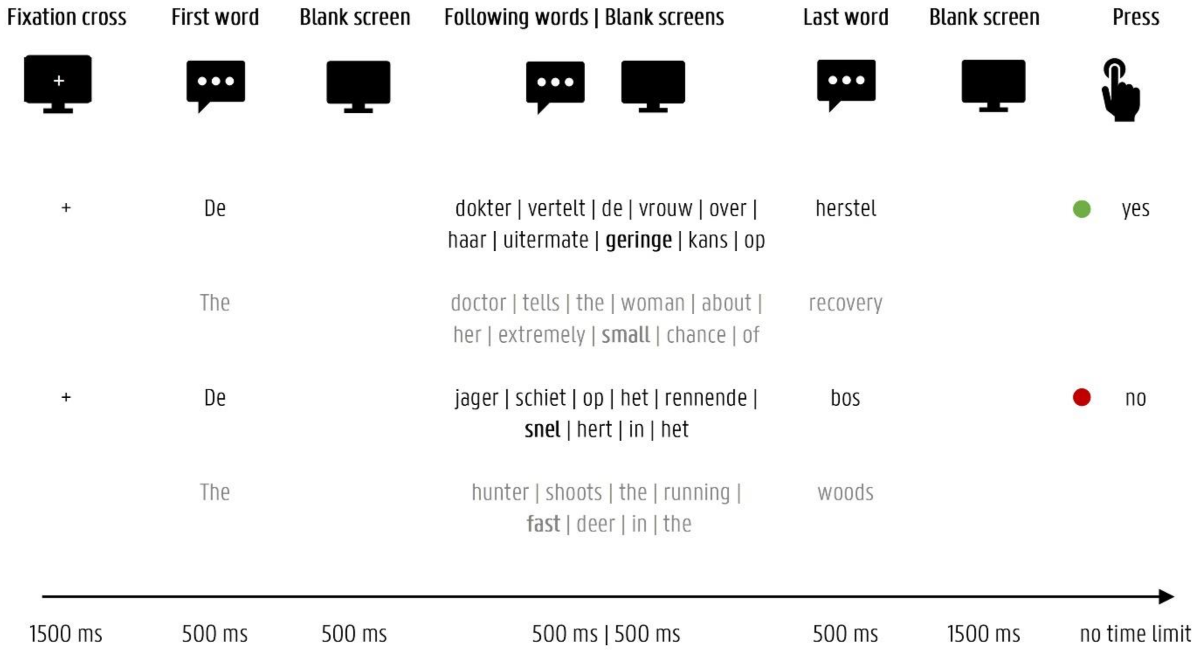


Figure 2. Grand average waveforms of the male and female subjects in the young, middle-aged, and elderly age groups elicited in response to correct and incorrect sentences at Pz.

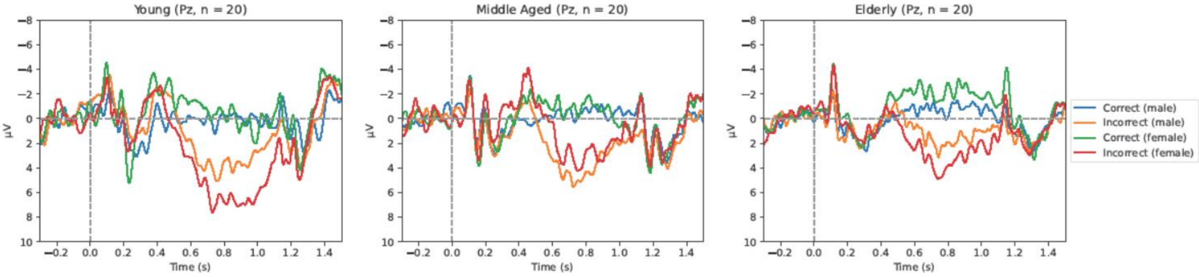


Figure 3. Grand average difference waveforms of the male and female subjects in the young , middle-aged, and elderly age groups at Pz.

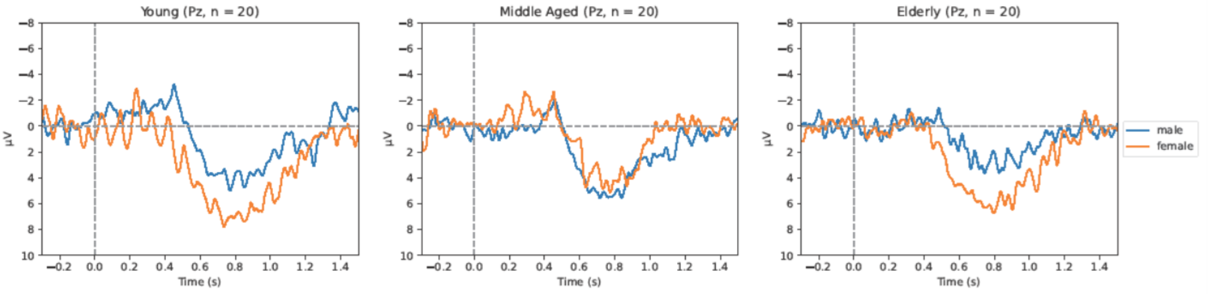


Figure 4. Source activation of the ROIs investigated, in the young, middle-aged and elderly age group for the female and male subjects separately.

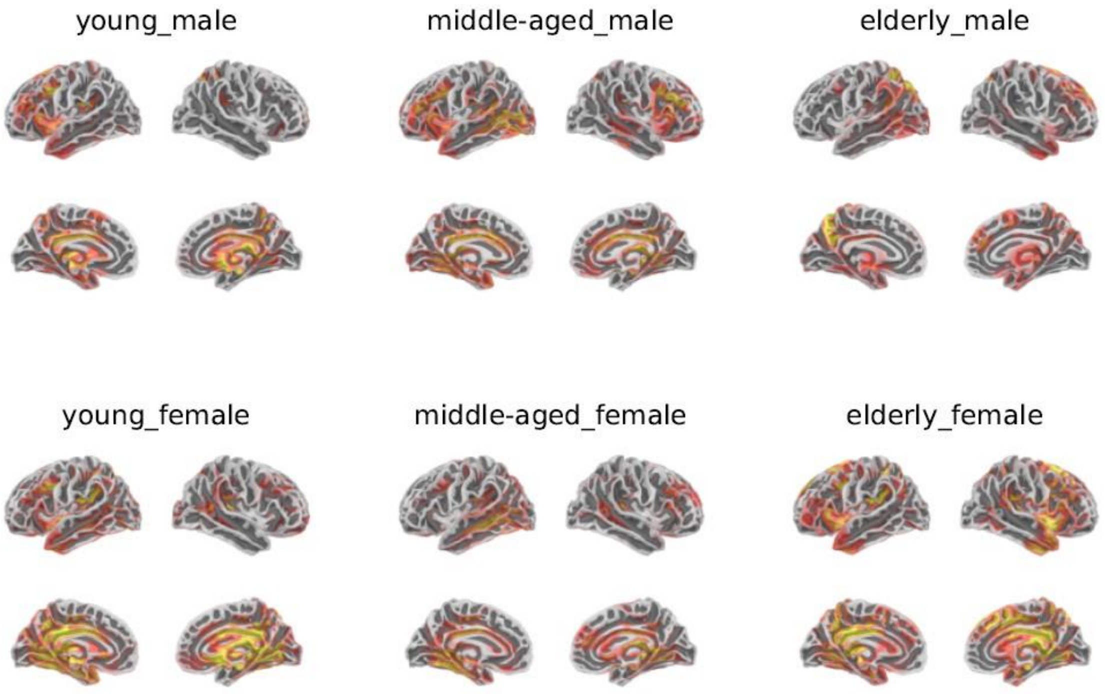


Table 1. Demographic details of the 30 male and 30 female participants presented for the young, middle-aged, and elderly age group.

	Young (20-39 years)		**Middle-aged (40-59 years)**		**Elderly (60-79 years)**	
	Male	Female	Male	Female	Male	Female
Age (years)	29.5 (5.08)	30.1 (4.53)	49.2 (5.57)	49.0 (7.36)	68.3 (6.34)	69.1 (4.58)
Education level[a]	1.3 (0.48)	1.4 (0.52)	1.7 (0.68)	2.1 (0.74)	1.8 (0.79)	3.0 (0.82)
MoCA score (/30)	28.9 (0.74)	29.4 (0.70)	28.2 (1.40)	28.5 (1.18)	28.7 (0.95)	28.4 (0.84)

Note: MoCa = Montréal Cognitive Assessment (Nasreddine et al., 2005); reported values are mean (standard deviation)

[a] Education level was rated on a four-point scale: 1, higher education-academic; 2, higher education-nonacademic; 3, higher secondary school; 4, lower educational school.

Table 2. Overview of the behavioural accuracy measures for male and female subjects in each age group (young, middle-aged, elderly).

	Young (20-39 years)		**Middle-aged (40-59 years)**		**Elderly (60-79 years)**	
	Male	Female	Male	Female	Male	Female
WEZT total score (/50)	50.0 (0.00)	49.9 (0.32)	49.8 (0.42)	49.4 (0.84)	49.7 (0.68)	49.9 (0.32)
P600 behavioural response (/60)	59.3 (1.25)	59.4 (0.52)	59.6 (0.97)	57.9 (2.81)	59.2 (1.32)	55.8 (4.37)

Note. Reported values are mean (standard deviation).

Table 3. Overview of the statistical results of the amplitudes and the onset latencies of the P600 and of the amplitudes, the onset latencies, the topography and source localization of the P600 effect.

ERP	Factor	df	F-value	*p*-value
1. Amplitude (µV)				
P600 (500 – 1000 ms)	Age group (Age)	2, 54	5.43	.007**
	Gender (Gen)	1, 54	0.01	.950
	Age x Gen	2, 54	2.76	.072
	Grammaticality (Gram)	1, 54	110.45	< .001***
	Gram x Age	2, 54	0.71	.496
	Gram x Gen	1, 54	6.14	.016*
	Gram x Age x Gen	2, 54	2.05	.139
P600 effect (500 – 1000 ms)	Age group (Age)	2, 54	0.71	.497
	Gender (Gen)	1, 54	6.15	.016*
	Age x Gen	2, 54	2.04	.140
P600 effect (5 time windows)	Age group (Age)	2, 54	0.72	.493
	Gender (Gen)	1, 54	6.13	.016*
	Age x Gen	2, 54	2.04	.139
	Time window[1] (Time)	2.38, 128.40	13.16	< .001***
	Time x Age[1]	4.76, 128.40	1.62	.162
	Time x Gen[1]	2.38, 128.40	0.05	.972
	Time x Age x Gen[1]	4.75, 128.40	0.36	.866
2. Onset latency				
P600 (500 – 1000 ms)	Age group (Age)	2, 54	0.12	.488
	Gender (Gen)	1, 54	0.72	.293
	Age x Gen	2, 54	0.39	.569
	Grammaticality (Gram)	1, 54	0.85	.513
	Gram x Age	2, 54	0.15	.921
	Gram x Gen	1, 54	0.84	.157
	Gram x Age x Gen	2, 54	0.02	.945
P600 effect (500 – 1000 ms)	Age group (Age	2, 54	0.65	.853
	Gender (Gen)	1, 54	2.30	.154
	Age x Gen	2, 54	1.29	.653
3. Topography				
P600 effect (500 – 1000 ms)	Age group (Age)	2, 54	0.71	.497
	Gender (Gen)	1, 54	6.17	.016
	Age x Gen	2, 54	2.04	.140
	A-P distribution (AP dis)[1]	1.25, 67.68	24.09	< .001***
	AP dis x Age[1]	2.51, 67.68	4.93	.006**
	AP dis x Gen[1]	1.25, 67.68	1.93	.167
	AP dis x Gen x Age[1]	2.51, 67.68	2.89	.051
	Lateralisation (Lat)	2, 108	47.84	< .001***
	Lat x Age	4, 108	0.18	.942
	Lat x Gen	2, 108	0.68	.499

	Lat x Age x Gen	4, 108	1.13	.344
	AP dis x Lat	4, 216	1.83	.133
	AP dis x Lat x Age	8, 216	1.15	.331
	AP dis x Lat x Gen	4, 216	4.177	.004**
	AP dis x Lat x Age x Gen	8, 216	1.16	.330
	4. Source localization			
	Age group (Age)	2, 54	3.87	.027*
	Gender (Gen)	1, 54	0.450	.485
	Age x Gen	2, 54	1.16	.323
	ROI	4, 216	78.95	< .001***
	ROI x Age	8, 216	4.49	< .001***
	ROI x Gen	4, 216	0.74	.435
	ROI x Gen x Age	8, 216	0.45	.705
	Hemisphere	1, 54	1.32	.256
	Hemisphere x Age	2, 54	0.75	.478
	Hemisphere x Gen	1, 54	1.42	.238
	Hemisphere x Gen x Age	2, 54	1.00	.375
	ROI x Hemisphere	4, 216	2.49	.065
	ROI x Hemisphere x Age	8, 216	0.40	.871
	ROI x Hemisphere x Gen	4, 216	1.22	.305
	ROI x Hemisphere x Age x Gen	8, 216	0.64	.689

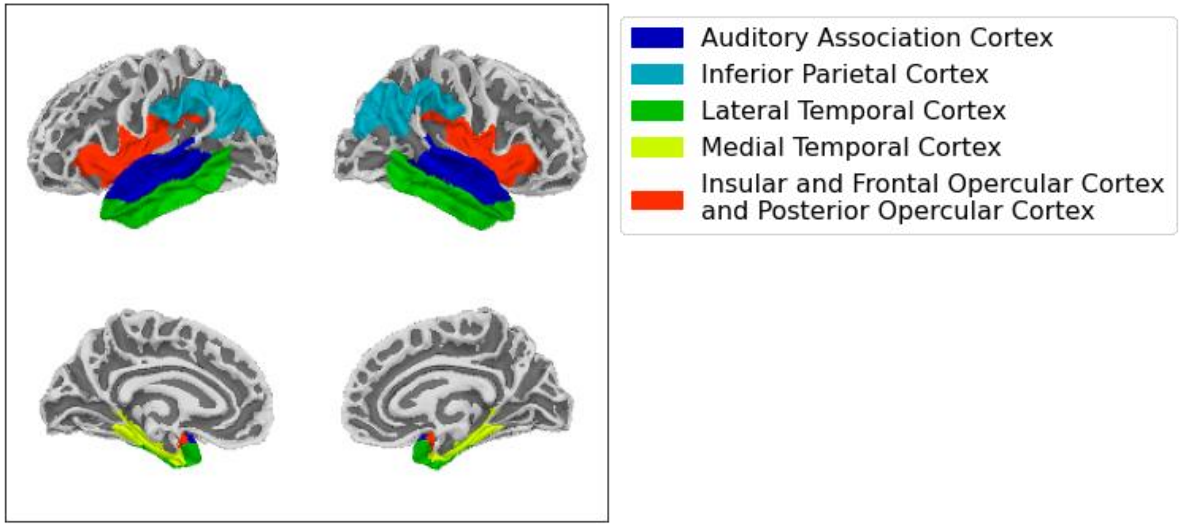
Note: ERP = event-related potential; µV = microvolt; ms = milliseconds; df = degrees of freedom; s = significant; ns = not significant; ^{1}: the Greenhouse-Geisser corrected F-values, degrees of freedom and p-values; * *p* < .05, ** *p* < .01, *** *p* < .001.

Appendix 1. Methodological information (modality tested, task used, syntactic manipulation and stimuli details) of the behavioral and electrophysiological studies discussed.

Study	**Experiment**	**Modality**	**Task**	**Stimuli details**	**Syntactic manipulation**	**Outcome**
Antonenko et al., 2013	Behavioural MRI	Auditory	Sentence-picture matching task	Sentences with increasing complexity (syntactic levels: no hierarchical embeddings versus embeddings)	Syntactic complexity manipulation	**Decline** in syntactic comprehension in older adults
Peelle et al., 2010	Behavioural fMRI	Auditory	Character gender determination	Meaningful six-word sentences (center-embedded subject-relative clause)	Syntactic complexity manipulation	**Decline** in syntactic comprehension in older adults
Poulisse et al., 2019	Behavioural	Auditory	Grammaticality judgement	Real and pseudoverb sentences: pseudoverbs and common English words paired with a correct/incorrect pronoun	Syntactic agreement violation	**Decline** in syntactic comprehension in older adults
Campbell et al., 2016	Behavioural fMRI	Auditory	Natural listening (task-free) Grammaticality judgement	Syntactically ambiguous (two possible syntactic interpretations) or unambiguous (one possible syntactic interpretation) sentences	Syntactic ambiguity	**Preserved** syntactic comprehension in older adults
Davis et al., 2014	Behavioural fMRI	Auditory	Natural listening (task-free) Grammaticality judgement	Syntactically ambiguous sentences (difference between dominant and subordinate interpretations)	Syntactic ambiguity	**Preserved** syntactic comprehension in older adults
Samu et al., 2017	Behavioural MRI	Auditory	Grammaticality judgement	Sentences with increasing syntactic processing required: unambiguous sentences (one meaning), dominant sentences (ambiguous phrases in their more frequent meaning), subordinate sentences (ambiguous	Syntactic ambiguity	**Preserved** syntactic comprehension in older adults

				phrases with their less frequent meaning) and disambiguating continuation word (‘is’ or ‘are’)		
Tyler et al., 2010	Behavioural fMRI	Auditory	Word-monitoring task	Normal sentences (normal grammatical structure and sentence meaning), anomalous sentences (grammatically correct but had no overall sentential meaning), unstructured strings of words (same type of syntactic structure and length, but with no discernible meaning)	Syntactic ambiguity	**Preserved** syntactic comprehension in older adults
Zhu et al., 2018	EEG	Visual	Grammaticality judgement	Congruent sentences, semantic violation sentences (mismatched verb), combined semantic and syntactic violation sentences (semantically and syntactically mismatched verb instead of noun)	Semantic and syntactic violation	**Lower** efficiency in syntactic ability in older adults
Kemmer et al., 2004	EEG	Visual	Grammaticality judgement	Sentences with correct and incorrect grammatically: number agreement errors (subject/verb agreement error or antecedent/reflexive pronoun number agreement error)	Syntactic subject-number agreement violation	**Preserved** syntactic comprehension in older adults More **bilateral** and **frontal** involvement in older adults
Leckey and Federmeier, 2017	EEG	Visual	Syntactic determiner violation in verbs and nouns	Two-word sentences manipulated in visual field and correct or incorrect determiner-noun or determiner-verb agreement	Syntactic determiner-nouns/verbs violation	**Preserved** syntactic comprehension in older adults More **bilateral** involvement in older adults

Appendix 2. Selected Regions of Interest (ROIs) for source localization analysis.



Appendix 3. MNI-coordinates and area surfaces of the five different regions of interest (ROIs) within the linguistic cortex (AAC, IPC, LTC, MTC, IFCop + insula).

ROI	**Hemisphere**	**Area (cm²)**	**MNI-coordinates cluster center**		
			x	y	z
Auditory Association Cortex (AAC)	left	21.56	-51.34	-20.4	-6.24
	right	25.19	50.09	-17.8,	6.78
Inferior Parietal Cortex (IPC)	left	38.30	-49.14	-55.01	38.12
	right	35.85	53.4,	-51.64	39.77
Lateral Temporal Cortex (LTC)	left	39.76	-53.87	-22.57	-28.36
	right	40.94	56.3	-20.03	-28.99
Medial Temporal Cortex (MTC)	left	22.62	-22.05	-25.01	-23.80
	right	18.87	22.95	-25.38	-21.14
Insular and frontal opercular cortex + posterior opercular cortex (IFCop + insula)	left	44.87	-34.49	-3.5	12.61
	right	43.15	35.42	-3.31	12.51

Appendix 4. Mean amplitude values over the 500-1000ms time window for the correct grammaticality, incorrect grammaticality and P600-effect over frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4) electrode sites reported per age category and gender group.

		Correct grammaticality	Incorrect grammaticality	P600-effect
Young (20-39 years)		0.45 (1.230) -0.12 – 1.03	3.42 (2.170) 2.41 – 4.44	5.94 (4.124) 4.01 – 7.87
	male	0.51 (1.280) -0.41 – 1.42	2.23 (1.500) 1.16 – 3.30	3.43 (3.203) 1.14 – 5.73
	female	0.39 (1.242) -0.50 – 1.28	4.62 (2.125) 3.10 – 6.14	8.45 (3.418) 6.00 – 10.89
Middle-aged (40-59 years)		-3.20 (1.144) -0.86 – 0.21	2.84 (2.273) 1.78 – 3.91	6.33 (4.451) 4.24 - 8.41
	male	0.08 (0.828) -0;52 – 0.67	3.30 (2.585) 1.45 – 5.15	6.45 (4.627) 3.14 – 9.76
	female	-0.71 (1.315) -1.66 – 0.22	2.38 (1.937) 1.00 – 3.77	6.20 (4.516) 2.97 – 9.43
Elderly (60-79 years)		-0.69 (1.215) -1.26 - -0.12	1.71 (2.233) 0.67 – 2.76	4.81 (4.766) 2.58 – 7.04
	male	-0.17 (1.105) -0.96 – 0.62	1.41 (1.497) 0.34 – 2.49	3.16 (3.235) 0.85 – 5.47
	female	-1.21 (1.140) -2.02 - -0.39	2.02 (2.843) -0.02 – 4.05	6.45 (5.609) 2.43 – 10.46

Note. Reported values are mean (standard deviation) and 95% confidence interval.

Appendix 5. Summary of statistical analysis result comparing the amplitude of the P600 effect across five time windows of 100 ms each (500 – 600 ms, 600 – 700 ms, 700 – 800 ms, 800 – 900 ms and 900 – 1000 ms), as well as the interaction with aging and gender.

Analysis of main effect					**Post-hoc pairwise comparison**			
Factor	**df**	**F**	**p**	**η^2**	**Factors showing significant difference**	**mean difference (μV)**	**p**	**95% CI**
P600 effect								
Time window	2.378	13.163	< .001*	0.196	600-700 ms amplitude > 500-600 ms amplitude	1.278	< .001	.649 – 1.908
					700-800 ms amplitude > 500-600 ms amplitude	1.592	< .001	0.653 – 2.532
					800-900 ms amplitude > 500-600 ms amplitude	1.674	< .001	0.704 – 2.645
					900-1000 ms amplitude > 500-600 ms amplitude	1.230	.05	0.244 – 2.217
Time window x age	4.756	1.623	0.162	0.057	-	-	-	-
Time window x gender	2.378	0.046	0.972	0.001	-	-	-	-
Time window x age x gender	4.756	0.361	0.866	0.013	-	-	-	-

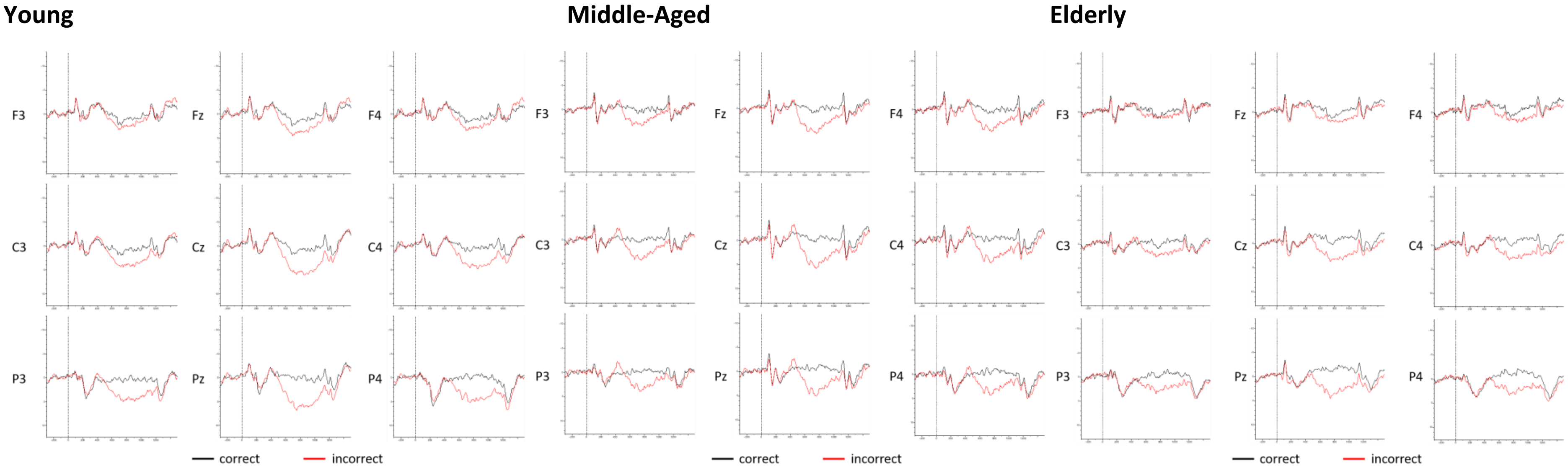
Note. Only statistically significant results from post-hoc pairwise comparison are specified; η^2 = partial eta squared.

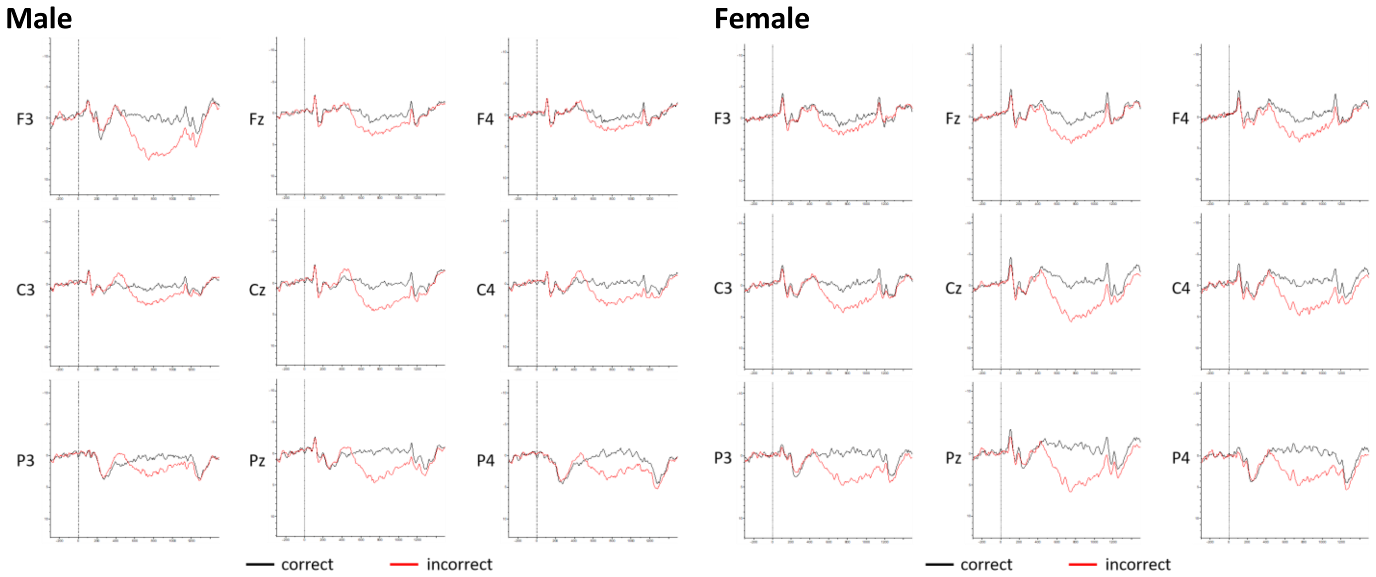
Appendix 6. Mean amplitude values of the P600 effect over the 500-600ms, 600-700ms, 700-800ms, 800-900ms and 900-1000ms time window over frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4) electrode sites reported per age category and gender group.

		500-600 ms	**600-700ms**	**700-800ms**	**800-900ms**	**900-1000ms**
Young (20-39 years)		1.62 (2.659) 0.38 – 2.87	2.94 (2.461) 1.79 – 4.10	3.38 (2.381) 2.26 – 4.49	3.65 (2.354) 2.55 – 4.75	3.26 (2.489) 2.09 – 4.42
	male	0.50 (2.307) -1.15 – 2.15	1.90 (2.421) 0.17 – 3.63	1.94 (1.694) 0.73 – 3.15	2.46 (1.944) 1.07 – 3.85	1.78 (1.899) 0.43 – 3.14
	female	2.74 (2.610) 0.88 – 4.61	3.99 (2.123) 2.47 – 5.51	4.81 (2.124) 3.29 – 6.33	4.84 (2.184) 3.28 – 6.41	4.73 (2.157) 3.19 – 6.27
Middle-aged (40-59 years)		1.87 (2.788) 0.57 – 3.18	3.59 (2.898) 2.24 – 4.95	4.05 (2.524) 2.87 – 5.23	3.69 (2.417) 2.56 – 4.82	2.61 (2.089) 1.64 – 3.59
	male	1.86 (2.883) -0.20 – 3.93	3.49 (2.751) 1.52 – 5.46	4.23 (2.475) 2.45 – 6.00	3.90 (2.623) 2.02 – 5.78	2.66 (2.335) 0.99 – 4.33
	female	1.88 (2.845) -0.15 – 3.92	3.70 (3.184) 1.42 – 5.98	3.87 (2.693) 1.95 – 5.80	3.48 (2.314) 1.83 – 5.14	2.56 (1.938) 1.18 – 3.95
Elderly (60-79 years)		1.57 (2.208) 0.54 – 2.61	2.37 (2.655) 1.12 – 3.61	2.42 (2.597) 1.21 – 3.64	3.65 (2.354) 2.55 – 4.75	3.26 (2.489) 2.09 – 4.42
	male	0.68 (2.228) -0.91 – 2.27	1.34 (2.181) -0.22 – 2.90	1.74 (1.576) 0.62 – 2.87	1.87 (1.837) 0.56 – 3.19	2.25 (1.180) 1.41 – 3.10
	female	2.47 (1.886) 1.12 – 3.81	3.39 (2.791) 1.40 – 5.39	3.10 (3.275) 0.76 – 5.44	3.63 (4.008) 0.76 – 6.49	3.53 (3.326) 1.15 – 5.91

Note. Reported values are mean (standard deviation) and 95% confidence interval.

Appendix 7. Grand average waveforms of the young (10 male, 10 female), middle-aged (10 male, 10 female), elderly (10 male, 10 female), male (10 young, 10 middle-aged, 10 elderly) and female (10 young, 10 middle-aged, 10 elderly) groups elicited in response to correct and incorrect sentences at nine electrode sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4).




Male
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
correct
incorrect
Female
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
correct
incorrect

Appendix 8. Onset latency values (25% signed fractional area latency over the 500-1000ms time window) for the correct condition, incorrect condition and P600-effect over parietal (P3, P4 and Pz) electrode sites reported per age category and gender group.

		correct condition	incorrect condition	P600-effect
Young (20-39 years)		668 (109.1) 663 – 641	688 (58.2) 661 – 715	692 (58.3) 665 – 720
	male	645 (96.2) 577 – 714	682 (61.4) 638 – 726	710,1 (66,31) 663 – 758
	female	690 (121.5) 603 – 777	694 (57.5) 653 – 735	674 (45.5) 642 – 707
Middle-aged (40-59 years)		676 (115.4) 622 – 730	678 (66.0) 647 – 709	677 (46.6) 655 – 699
	male	654 (105.6) 651 – 633	668 (28.6) 579 – 702	672 (43.8) 641 – 703
	female	698 (126.2) 608 – 788	688 (81.3) 630 – 746	682 (51.0) 645 – 718
Elderly (60-79 years)		658 (133.7) 648 – 613	676 (58.1) 649 – 703	675 (52.0) 651 – 700
	male	657 (119.5) 571 – 742	685 (71.3) 634 – 736	693 (50.2) 657 – 729
	female	660 (153.1) 550 – 769	666 (42.9) 636 – 697	658 (50.0) 622 – 694

Note. Reported values are mean (standard deviation) and 95% confidence interval.

Appendix 9. Mean amplitude values of the P600 effect in the 500 – 1000ms time window over frontal (F3, Fz, F4), central (C3, Cz, C4), parietal (P3, Pz, P4), left (F3, C3, P3), midline (Fz, Cz, Pz) and right (F4, C4, P4) electrode positions reported per age category and gender group.

		Frontal	Central	Parietal	Left	Midline	Right
Young (20-39 years)		3.32 (4.472) 1.23 – 5.42	6.30 (4.743) 4.08 – 8.52	8.20 (4.308) 6.18 – 10.21	4.65 (3.965) 2.80 – 6.51	5.79 (4.188) 3.83 – 7.75	7.37 (4.659) 5.19 – 9.55
	male	1.10 (2.868) -0.95 – 3.15	3.47 (3.743) 0.79 – 6.15	5.73 (3.843) 2.98 – 8.48	2.32 (3.381) -0.10 – 4.73	3.34 (3.002) 1.19 – 5.49	4.65 (3.822) 1.91 – 7.38
	female	5.55 (4.794) 2.12 – 8.98	9.12 (3.966) 6.28 – 11.96	10.66(3.303) 8.30 – 13.03	6.99 (3.098) 4.78 – 9.21	8.25 (3.825) 5.51 – 10.98	10.10(3.834) 7.35 – 12.84
Middle-aged (40-59 years)		5.94 (4.672) 3.75 – 8.13	6.86 (4.725) 4.65 - 9.07	6.18 (5.584) 3.57 – 8.79	5.08 (4.761) 2.80 – 7.26	6.36 (4.004) 4.49 – 8.24	7.59 (5.045) 5.22 – 9.95
	male	5.83 (5.104) 2.18 – 9.48	6.89 (4.809) 3.45 – 10.33	6.63 (5.767) 2.50 – 10.75	5.00 (4.926) 1.48 – 8.53	6.33 (4.567) 3.06 – 9.59	8.02 (4.840) 4.56 – 11.48
	female	6.05 (4.472) 2.85 – 9.25	6.83 (4.899) 3.32 – 10.33	5.73 (5.668) 1.68 – 9.79	5.05 (4.857) 1.58 – 8.53	6.40 (3.605) 3.82 – 8.98	7.16 (5.468) 3.25 – 11.07
Elderly (60-79 years)		2.51 (4.799) 0.27 – 4.76	5.33 (5.319) 2.84 – 7.81	6.58 (5.603) 3.96 – 9.20	3.50 (4.160) 1.55 – 5.44	4.94 (4.847) 2.67 – 7.21	5.98 (5.591) 3.37 – 8.60
	male	2.27 (3.477) -0.22 – 4.75	3.85 (3.548) 1.31 – 6.39	3.36 (3.783) 0.65 – 6.07	2.36 (3.362) -0.04 – 4.77	3.09 (3.108) 0.87 – 5.31	4.03 (3.707) 1.38 – 6.68
	female	2.76 (6.032) -1.55 – 7.08	6.80 (6.505) 2.15 – 11.45	9.80 (5.380) 5.94 - 13.65	4.63 (4.731) 1.25 – 8.02	6.79 (5.686) 2.72 – 10.86	7.94 (6.615) 3.21 – 12.67

Note. Reported values are mean (standard deviation) and 95% confidence interval.

Appendix 10. Topographical distribution of the (A) P600 effect in the 500-1000ms time window for young (20-39 years), middle-aged (40-59 years) and elderly (60-79 years), and. (B) P600 effect in the 500-1000ms time window for males and females.