

# Healthy Aging Alters P300-Period EEG Microstate Topographies and Transition Flexibility During Cross-Modal Attention Shifting

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## Research Article

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# Healthy Aging Alters P300-Period EEG Microstate Topographies and Transition Flexibility During Cross-Modal Attention Shifting

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## Abstract

Healthy cognitive aging is characterized by slowed stimulus evaluation and reduced attentional flexibility. While classically indexed by delayed P300 event-related potential (ERP) latencies and attenuated parietal amplitudes, single-channel electrophysiology cannot distinguish whether these differences reflect altered scalp electric field configurations (topographies), delayed recruitment of macroscopic brain states, or disrupted transition routing between large-scale functional networks. Here, we used reference-free EEG microstate analysis to resolve the spatiotemporal dynamics of the P300 period during cross-modal attention shifting by re-analysing an open-access auditory-visual oddball dataset (OpenNeuro ds002893; 15 younger, 15 older adults) across focused and cued shift-focus conditions. Older adults exhibited pronounced P300 latency delays for visual targets ( $g > 0.96$ ; FDR-corrected) and attenuated amplitude during auditory shifting ( $g = -0.94$ ; FDR-corrected). Microstate back-fitting across the 300–700 ms post-stimulus interval revealed that the whole-scalp configuration corresponding to Class B emerged approximately 48 ms later in older adults ( $g > 1.0$ ; FDR-corrected) alongside significantly diminished spatial template fidelity. Crucially, first-order Markov transition matrices revealed that older adults exhibited constrained directional transitions into target-evaluation states (Classes B and C) alongside elevated state-persistence self-loops ( $A \rightarrow A$ ), reflecting reduced flexibility and increased dynamical inertia during attentional set reconfiguration. Cross-domain analyses confirmed strong convergence between sensor-level P300 amplitude and multichannel Class-C Global Field Power ( $r = +0.90$  to  $+0.93$ ). These findings demonstrate that age-related slowing during cross-modal attentional reconfiguration reflects constrained recruitment,

spatial degradation, and altered transition syntax of distributed whole-scalp electrophysiological states across the P300 period.

**Keywords:** Brain topography, EEG microstates, P300 dynamics, Markov state transitions, Cross-modal attention shifting, Healthy aging

## 1 Introduction

Selective attention in complex multisensory environments is a dynamic, non-stationary cognitive process: individuals must continuously prioritize task-relevant sensory streams, filter out competing distractor inputs, and rapidly reconfigure attentional sets when environmental contingencies change [Corbetta and Shulman \(2002\)](#); [Monsell \(2003\)](#); [Kiesel et al. \(2010\)](#); [Talsma et al. \(2010\)](#). Efficient goal-directed orienting and stimulus-driven reorienting rely on coordinated interactions between primary sensory cortices and distributed frontoparietal attentional systems [Corbetta and Shulman \(2002\)](#). In healthy adult aging, cognitive operations are characterized by progressive declines in processing speed, reduced neural specialization (dedifferentiation), and altered compensatory recruitment [Salthouse \(1996\)](#); [Park and Reuter-Lorenz \(2009\)](#). These alterations become particularly conspicuous during cross-modal attention shifting, where older adults frequently incur substantial behavioral switch-costs, prolonged reaction times, and diminished multitasking efficiency [Monsell \(2003\)](#); [Kiesel et al. \(2010\)](#); [Čeponienė et al. \(2008\)](#); [Rapela et al. \(2012\)](#); [Kieffaber and Hetrick \(2005\)](#).

At the electrophysiological level, the P300 (or P3b) component of the event-related potential (ERP) provides a classic, well-established window into these cognitive operations [Sutton et al. \(1965\)](#). Peaking over centro-parietal electrodes approximately 300–600 ms following target presentation, the P300 is sensitive to stimulus evaluation time, context updating, subjective target probability, and central processing resource allocation [Donchin and Coles \(1988\)](#). Lifespan and normative aging studies consistently report marked delays in P300 peak latency and, depending on task complexity and modality, attenuated parietal positivity in older adults [Polich \(1996\)](#). These electrophysiological differences are widely interpreted as reflecting slowed neural classification speed, reduced neural synchrony, and diminished central processing capacity [Kok \(2001\)](#); [Polich \(2007\)](#); [van Dinteren et al. \(2014\)](#).

However, scalp-recorded ERP waveforms represent the linear spatial summation of multiple overlapping cortical and subcortical dipolar sources volume-conducted to the scalp surface [Picton \(1992\)](#). Crucially, single-channel voltage waveforms (such as peak amplitude or latency at electrode Pz) are reference-dependent and physically ambiguous: a modification of voltage at a single electrode can arise equally from a change in the topography of active intracranial generators, a change in overall field strength (Global Field Power), or a shift in the reference electrode itself [Lehmann et al. \(1987\)](#); [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#). Consequently, conventional single-electrode P300 measurements cannot disambiguate the underlying spatiotemporal architecture of the response. Specifically, a delayed or attenuated P300 peak at Pz could reflect: (1) delayed temporal onset of a whole-scalp configuration, (2) prolonged

dwelling time in an earlier sensory processing stage, (3) altered spatial orientation of the underlying generator dipole configuration, or (4) a breakdown in directional transition routing across successive functional brain states [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#); [Schiller et al. \(2024\)](#); [Brechet et al. \(2024\)](#).

Electrical neuroimaging via EEG microstate analysis provides the foundational, reference-independent framework to resolve this ambiguity by representing continuous multichannel scalp potential data as a sequence of brief, quasi-stable whole-scalp electric field topographies [Lehmann et al. \(1987\)](#); [Koenig et al. \(2002\)](#); [Lehmann et al. \(2005\)](#); [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#); [Schiller et al. \(2024\)](#); [Lai et al. \(2025\)](#). Rather than tracking fixed single-electrode voltages, microstate analysis treats the multichannel scalp field as a succession of discrete, whole-brain states that remain quasi-stable for tens to hundreds of milliseconds before rapidly transitioning to another configuration [Koenig et al. \(2002\)](#); [Lehmann et al. \(2005\)](#); [Michel and Koenig \(2018\)](#). Because the spatial configuration of the electric field on the scalp is reference-free and uniquely determined by the spatial distribution of active intracranial current sources, differences in microstate topography directly signify differences in underlying brain network activation [Lehmann et al. \(1987\)](#); [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#); [Michel et al. \(2024\)](#).

Across diverse cognitive and resting paradigms, four canonical microstate classes (termed A, B, C, and D) account for the vast majority of scalp topography variance across the lifespan [Koenig et al. \(2002\)](#); [Khanna et al. \(2014\)](#); [Murphy et al. \(2020\)](#). Beyond canonical parameters such as duration, occurrence, and coverage, the syntactic organization of microstate sequences can be mapped using directional Markov state transition matrices and information-theoretic complexity metrics [von Wegner and Laufs \(2018\)](#); [Barzon et al. \(2024\)](#). Crucially, when microstates are back-fitted to event-related potential data, the selection of the analysis time window is of fundamental importance [Michel and Koenig \(2018\)](#); [Brechet et al. \(2024\)](#). In the present study, a common 300–700 ms post-stimulus interval was selected for both sensor-level P300 quantification and microstate segmentation to accommodate the systematically delayed P300 peaks observed in older adults and to establish direct spatiotemporal correspondence between the two analytical domains [Polich \(1996\)](#); [van Dinteren et al. \(2014\)](#); [Michel and Koenig \(2018\)](#); [Schiller et al. \(2024\)](#).

Previous aging studies have primarily examined resting-state microstate metrics or conventional single-channel ERP measures in isolation. It remains unknown whether age-related P300 differences during cross-modal attentional reconfiguration reflect delayed recruitment, altered persistence, or disrupted transitions between task-evoked whole-scalp states. Here, we re-analysed an open-access auditory–visual oddball dataset ([ds002893](#)) [Gorgolewski et al. \(2016\)](#); [Pernet et al. \(2019\)](#); [Čeponienė et al. \(2008\)](#); [Rapela et al. \(2012\)](#) featuring focused-auditory (FA), focused-visual (FV), and cued shift-focus (SF) conditions in healthy younger and older adults, combining sensor-level P300 electrophysiology with epoch-by-epoch microstate back-fitting across the 300–700 ms interval. Three explicit hypotheses were evaluated:

- H1 P300 Electrophysiology:** Older adults will exhibit delayed P300 peak latencies and attenuated parietal amplitudes relative to younger adults, particularly under cross-modal shifting demands [Polich \(1996\)](#); [van Dinteren et al. \(2014\)](#).

139 **H2 Delayed Microstate Recruitment:** Older adults will show delayed temporal  
140 onset and reduced spatial template fidelity for task-relevant P300-period microstate  
141 configurations, providing the whole-scalp structural correlate of sensor-level ERP  
142 delays [Michel and Koenig \(2018\)](#); [Schiller et al. \(2024\)](#); [Brechet et al. \(2024\)](#).

143 **H3 Altered Transition Dynamics:** Older adults will exhibit constrained directional  
144 transition syntax across P300-period microstates, reflected in reduced forward  
145 switching and elevated self-loop persistence, consistent with diminished dynamical  
146 flexibility during attentional reconfiguration [von Wegner and Laufs \(2018\)](#); [von](#)  
147 [Wegner et al. \(2024\)](#); [Jajcay and Hlinka \(2023\)](#); [Tarailis et al. \(2024\)](#).

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## 149 2 Materials and methods

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### 151 2.1 Participants and cohort selection

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153 We conducted a secondary analysis of the openly available OpenNeuro dataset  
154 [ds002893](#) (version 2.0.0; <https://openneuro.org/datasets/ds002893/versions/2.0.0>)  
155 [Gorgolewski et al. \(2016\)](#); [Pernet et al. \(2019\)](#); [Čeponienė et al. \(2008\)](#); [Rapela](#)  
156 [et al. \(2012\)](#). The original repository contains recording sessions from 49 candidate  
157 participants. To establish balanced cohorts while maintaining rigorous data quality,  
158 we applied the following inclusion and exclusion criteria independently of any EEG  
159 outcome measure:

160

161 1. **Age-Cohort Membership:** Participants were included only if they had clear,  
162 unambiguous age-group classification (younger: < 40 years; older: > 50 years).

163 2. **Data-Quality and ICA Constraints:** Independent component analysis (ICA)  
164 artifact-removal constraints were applied to retain only participants for whom 1–6  
165 components were removed. Participants requiring removal of more than six ICA  
166 components were excluded as a conservative quality-control measure, as extensive  
167 ICA correction may increase the likelihood of attenuating neural activity alongside  
168 artifact, particularly in noisier recordings. This criterion was adopted to preserve  
169 signal integrity and maintain comparability across participants.

170

171 Applying these criteria yielded 30 healthy participants: 15 younger adults (mean  
172 age  $26.1 \pm 6.4$  years, range 20–39; 10 women; age available for 14 participants) and 15  
173 older adults (mean age  $63.4 \pm 8.9$  years, range 51–78; 9 women; age available for 13  
174 participants). The sample size was determined by the total eligible cases in the open  
175 repository meeting quality criteria. A sensitivity power analysis indicated that with  
176  $N = 30$  ( $n_1 = 15, n_2 = 15$ ), two-tailed Welch’s  $t$ -tests at  $\alpha = .050$  provide > 80%  
177 power to detect large effect sizes ( $g \geq 0.95$ ), which corresponds well to the primary  
178 empirical effects observed ( $g = 0.94$ – $1.41$ ). In electrical neuroimaging, spatial field  
179 topographies and microstate segmentation exhibit high spatial signal-to-noise ratios,  
180 yielding large macroscopic effect sizes compared to single-trial scalar voltages [Murray](#)  
181 [et al. \(2008\)](#); [Michel and Koenig \(2018\)](#). Given the fixed sample determined by the  
182 open-access repository, this study should be considered exploratory and hypothesis-  
183 generating, particularly with respect to microstate transition dynamics; replication in  
184 prospectively-recruited samples with larger  $N$  is warranted before confirmatory claims  
are advanced.

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>2.2 Task paradigm and stimuli</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 185 |
| Participants completed an auditory–visual oddball paradigm designed to assess selective and flexible cross-modal attention across three block types Čeponienė et al. (2008); Rapela et al. (2012):                                                                                                                                                                                                                                                                                                                                                                                                              | 186 |
| 1. <b>Focused Auditory (FA):</b> Participants attended exclusively to the auditory modality, detecting infrequent auditory oddballs (frequency deviants, 20% probability; high tone 1500 Hz vs. standard low tone 1000 Hz at 70 dB SPL) via a speeded button press while ignoring concurrent, non-target visual stimuli.                                                                                                                                                                                                                                                                                        | 187 |
| 2. <b>Focused Visual (FV):</b> Participants attended exclusively to the visual modality, detecting infrequent visual oddballs (circular grating orientation deviants / light bars, 20% probability; 45° orientation vs. vertical standard) via a speeded button press while ignoring concurrent auditory stimuli.                                                                                                                                                                                                                                                                                               | 188 |
| 3. <b>Shift-Focus (SF, 12 blocks):</b> Participants encountered interleaved auditory and visual stimuli. Prior to each trial or sub-block, an explicit visual cue instructed participants to attend to either the auditory or visual modality for target detection, requiring trial-wise updating of attentional sets across modalities.                                                                                                                                                                                                                                                                        | 189 |
| The four primary target conditions analysed were: attended auditory oddballs in FA, attended visual oddballs in FV, and attended auditory and visual oddballs in SF.                                                                                                                                                                                                                                                                                                                                                                                                                                            | 190 |
| <b>Behavioural data limitation:</b> An important limitation of this dataset is that single-trial reaction-time logfiles were not archived across all recording runs. Direct trial-by-trial behavioural validation of attentional shifting efficiency, including reaction time switch costs, is therefore not possible. Cognitive compliance was confirmed indirectly via trial retention rates and clear event-related potential morphology across conditions. This precludes definitive claims linking microstate transition dynamics to individual behavioural switch costs (see Section 4.5 for discussion). | 191 |
| <b>2.3 EEG recording and montage</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 192 |
| Continuous EEG was recorded from 33 scalp channels according to the extended 10–20 international system (Fp1, Fpz, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC6, FC2, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, P03, P04, O1, O2) along with dedicated ocular channels (LEye, REye) and left mastoid (LM). Data were sampled at 250 Hz and average referenced before applying ICA, conforming to standard electrical neuroimaging principles Michel and Koenig (2018); Murray et al. (2008).                                                                                              | 193 |
| <b>2.4 EEG preprocessing and quality control</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 194 |
| Preprocessing was performed in Python using MNE-Python (v1.6.0) and MNE-BIDS Gramfort et al. (2013); Appelhoff et al. (2019). Continuous EEG was zero-phase band-pass filtered (0.1–45 Hz FIR filter) with a 60 Hz notch filter. Bad channels were identified via correlation and power-spectral density thresholds and interpolated using spherical splines. Ocular artefacts (blinks and saccades) were decomposed using Extended Infomax ICA trained on a 1.0 Hz high-pass filtered copy of the continuous data Bell and Sejnowski (1995); Delorme and Makeig (2004), and components were                    | 195 |

carefully removed (mean  $\pm$  SD:  $3.5 \pm 1.2$  components per participant, range 1–6). Epochs were extracted from  $-200$  to  $+800$  ms relative to attended oddball target onset and baseline corrected to the  $-200$  to  $0$  ms pre-stimulus interval Luck and Gaspelin (2017).

Subject-condition cells were retained for inferential analysis when they contained at least 40 clean epochs and at least 50% of candidate epochs Luck and Gaspelin (2017). All 15 younger adults met this threshold across all conditions ( $n_Y = 15$ ). In older adults, 11 participants contributed valid data to FA ( $n_O = 11$ ), 14 to FV ( $n_O = 14$ ), and all 15 contributed to each SF condition ( $n_O = 15$ ). The lower retention in single FA and FV blocks reflects the smaller total target trial count in focused blocks combined with higher physiological ocular and movement artifact rates in older adults; the multi-block SF condition (12 blocks) provided ample trials for all 15 older participants to exceed retention thresholds.

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## 2.5 P300 electrophysiology and shift-cost measures

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Condition-specific ERPs were averaged within participants. At parietal site Pz, P300 peak latency (ms), mean amplitude ( $\mu V$ ), peak amplitude ( $\mu V$ ), and signed area under the curve (AUC,  $\mu V \cdot s$ ) were quantified across the 300–700 ms post-stimulus window Polich (2007); van Dinteren et al. (2014). This unified temporal window was selected for four reasons: (1) it accommodates systematically delayed P300 peaks in older adults, who frequently peak past 500–550 ms Polich (1996); van Dinteren et al. (2014); Bourisly (2016); (2) the 300 ms lower bound excludes early obligatory sensory potentials (P100, N100, P200, N200), isolating post-perceptual evaluation Picton (1992); Luck and Gaspelin (2017); (3) the 700 ms upper bound avoids post-response slow wave contamination Polich (2007); and (4) identical boundaries across sensor-level and microstate analyses permit direct spatiotemporal correspondence without window mismatch Murray et al. (2008); Michel and Koenig (2018); Schiller et al. (2024). Electrophysiological attentional shift-costs were quantified as the difference between shift-focus and focused conditions (SF – FA for auditory, SF – FV for visual).

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## 2.6 Microstate segmentation and dynamics

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Microstate analysis was performed on global-field-power (GFP) peaks from pooled grand-average ERPs in the 300–700 ms window using spatial  $k$ -means clustering with polarity invariance Koenig et al. (2002); Murray et al. (2008); Michel and Koenig (2018); Pascual-Marqui et al. (1995). Cluster solutions ranging from 3–8 maps were evaluated using multiple clustering-quality metrics, including Global Explained Variance (GEV), silhouette coefficient, cluster-separation indices, and parsimony criteria. Although the meta-criterion marginally favoured a three-map solution, the four-map solution explained 76.8% of scalp topographic variance and closely reproduced the canonical A–D microstate architecture described by Koenig et al. Koenig et al. (2002). Because the present study sought hypothesis-driven characterization of established microstate classes rather than discovery of novel subclasses, the four-map solution was retained for all subsequent analyses. This approach facilitates direct comparison with the canonical A–D framework that remains the most widely used reference architecture

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in EEG microstate research. The resulting empirical maps ( $k = 4$ ) were matched to the normative templates of Koenig et al. [Koenig et al. \(2002\)](#) using a minimum spatial correlation criterion ( $r > 0.75$ ): State A (left-posterior to right-anterior,  $r = 0.833$ ), State B (right-frontal to left-occipital,  $r = 0.855$ ), State C (anterior-posterior,  $r = 0.910$ ), and State D (frontocentral,  $r = 0.277$ ; Fig. 2). These labels describe topographic resemblance and do not imply exclusive functional networks [Michel and Koenig \(2018\)](#); [Michel et al. \(2024\)](#); [Schiller et al. \(2024\)](#). Map D’s comparatively low correspondence ( $|r| = 0.277$ ) may reflect differences between task-evoked ERP microstates and the resting-state templates reported by Koenig et al. [Koenig et al. \(2002\)](#).

The four template maps were back-fitted epoch-by-epoch to individual participant data to extract temporal parameters: global explained variance (GEV), map fit (spatial correlation), coverage, duration, occurrence, onset latency, and centre of gravity [Michel and Koenig \(2018\)](#); [Kleinert et al. \(2024a,b\)](#). Directional first-order Markov transition matrices and non-linear complexity measures (Shannon entropy, Markov entropy, and Lempel–Ziv complexity) were computed [Shannon \(1948\)](#); [Lempel and Ziv \(1976\)](#); [von Wegner and Laufs \(2018\)](#); [von Wegner et al. \(2024\)](#); [Jajcay and Hlinka \(2023\)](#).

## 2.7 Statistical analysis

Age groups were compared using Welch’s  $t$ -tests (allowing unequal variances) and Hedges’  $g$  effect sizes with 95% confidence intervals [95% CI]. Multiple testing was controlled using the Benjamini–Hochberg false discovery rate (FDR) procedure ( $q < .050$ ) [Benjamini and Hochberg \(1995\)](#) applied within four pre-specified functional families: (1) P300 outcomes at Pz (16 tests); (2) microstate temporal dynamics per state (48 tests); (3) directional transition probabilities (48 tests); and (4) P300–microstate GFP associations (16 tests). Uncorrected significant findings ( $p < .050$ ,  $q \geq .050$ ) are reported as exploratory in Supplementary Table A1. Factorial linear mixed-effects models (LMM) tested fixed effects of Age, Modality, Task, and their interactions on P300 latency and amplitude (Formula: Outcome  $\sim$  Age  $\times$  Modality  $\times$  Task + (1|Subject)) [Bates et al. \(2015\)](#).

## 3 Results

### 3.1 P300 latency delays and modality-specific amplitude attenuation

Healthy aging selectively delayed P300 peak latency for visual targets and attenuated parietal amplitude during auditory attention shifting (Fig. 1; Table 1).

P300 latency delays were most prominent for visual targets. In the focused visual condition (FV), older adults’ responses peaked approximately 90 ms later than younger adults’ ( $g = 1.41$ , FDR  $q = .006$ ), and a comparable delay of approximately 63 ms was observed during shift-focus visual trials ( $g = 0.96$ , FDR  $q = .036$ ). A numerically similar delay during focused auditory trials did not survive FDR correction ( $g = 1.06$ , FDR  $q = .055$ ; Supplementary Table A1) and is treated as exploratory. Full descriptive statistics appear in Table 1.

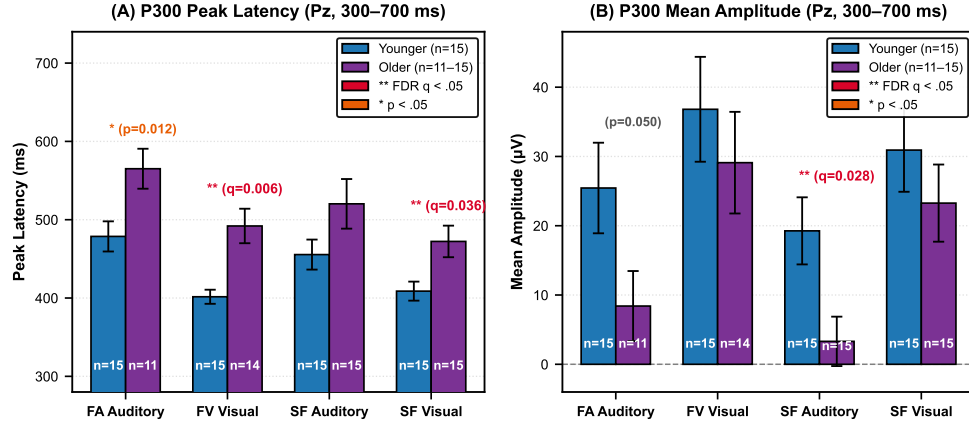


**Fig. 1** Age-group differences in P300 electrophysiology at electrode site Pz. **a** P300 peak latency (ms), **b** mean amplitude ( $\mu$ V), and **c** area under the curve (AUC,  $\mu$ V  $\cdot$  s) across the four experimental target conditions: Focused Auditory (FA Auditory), Focused Visual (FV Visual), Shift-Focus Auditory (SF Auditory), and Shift-Focus Visual (SF Visual). Boxplots display individual participant observations, medians, and interquartile ranges. Statistically significant age-group contrasts after Benjamini–Hochberg False Discovery Rate (FDR) control at  $q < .050$  are indicated with effect sizes (Hedges'  $g$ )

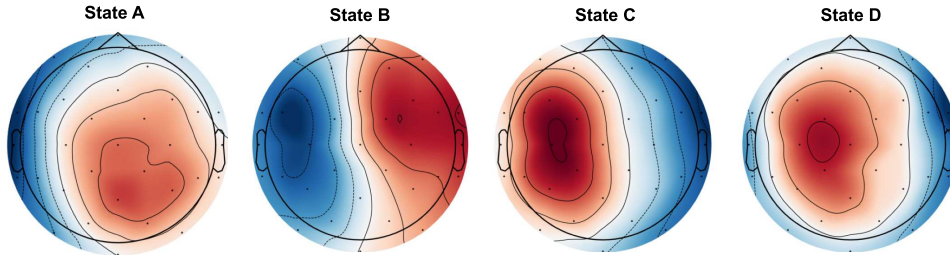


**Fig. 2** Empirical P300-period microstate topographies. Four canonical microstate topographies (Classes A, B, C, and D) extracted via modified  $k$ -means clustering on grand-average Global Field Power (GFP) peaks across the 300–700 ms post-stimulus interval. Normalized whole-scalp electric field potential maps represent spatial voltage distributions across 33 electrodes

The most prominent amplitude effect was modality-specific: older adults showed a substantially reduced P300 mean amplitude during auditory attention shifting ( $-16.0 \mu$ V,  $g = -0.94$ , FDR  $q = .028$ ), with a corresponding reduction in signed area under the curve. This pattern suggests that attentional resource allocation to auditory targets is selectively constrained when participants must shift focus across modalities. Linear mixed-effects modelling confirmed robust main effects of Modality ( $\beta = -77.07$  ms, FDR  $q = .003$ ) and Age ( $\beta = +80.29$  ms, FDR  $q = .010$ ) on P300 latency, consistent with H1.

### 3.2 Electrophysiological shift-cost analyses

Planned electrophysiological shift-cost contrasts (SF – FA for auditory, SF – FV for visual) revealed no significant age-by-condition interaction on parietal P300 latency or amplitude costs (all FDR  $q > .370$ ; Table 1). A non-significant trend toward greater auditory latency shift-costs in older adults was observed at central electrode Cz (+46.06 ms,  $g = 0.65$ , FDR  $q = .229$ ), suggesting a possible modality-specific processing overhead that warrants examination in a larger sample. Notably, the absence of an additive subtractive cost at Pz reflects distinct modality-specific constraints: older adults were already operating near a processing speed ceiling in the visual domain (+90.4 ms delay in FV), whereas the shifting cost in the auditory domain manifested primarily as severe parietal amplitude depletion rather than incremental peak slowing.

**Table 1** Primary P300 electrophysiological metrics at electrode site Pz and shift-cost contrasts.

| Condition / Contrast                                               | Outcome Metric                                       | Younger<br>Mean $\pm$ SD           | Older<br>Mean $\pm$ SD             | Diff<br>( $\Delta$ ) | $t$ -stat    | $p_{\text{uncorr}}$ | FDR $q$     |
|--------------------------------------------------------------------|------------------------------------------------------|------------------------------------|------------------------------------|----------------------|--------------|---------------------|-------------|
| <i>A. P300 Electrophysiological Metrics at Pz</i>                  |                                                      |                                    |                                    |                      |              |                     |             |
| FA Auditory ( $n = 15/11$ )                                        | Peak Latency (ms)                                    | 479.2 $\pm$ 70.3                   | 565.4 $\pm$ 83.1                   | +86.2                | 2.67         | .014                | .055        |
|                                                                    | Mean Amplitude ( $\mu\text{V}$ )                     | 25.5 $\pm$ 25.1                    | 8.5 $\pm$ 16.5                     | -17.0                | -2.05        | .050                | .100        |
|                                                                    | Peak Amplitude ( $\mu\text{V}$ )                     | 32.4 $\pm$ 28.2                    | 16.3 $\pm$ 18.4                    | -16.1                | -1.70        | .102                | .180        |
|                                                                    | AUC ( $\mu\text{V} \cdot \text{s}$ )                 | 10.2 $\pm$ 10.0                    | 3.4 $\pm$ 6.6                      | -6.8                 | -2.05        | .050                | .100        |
| FV Visual ( $n = 15/14$ )                                          | <b>Peak Latency (ms)</b>                             | <b>402.1 <math>\pm</math> 35.0</b> | <b>492.5 <math>\pm</math> 82.3</b> | <b>+90.4</b>         | <b>3.79</b>  | <b>.001</b>         | <b>.006</b> |
|                                                                    | Mean Amplitude ( $\mu\text{V}$ )                     | 36.8 $\pm$ 29.0                    | 29.2 $\pm$ 28.0                    | -7.6                 | -0.72        | .479                | .639        |
|                                                                    | Peak Amplitude ( $\mu\text{V}$ )                     | 44.2 $\pm$ 31.3                    | 38.5 $\pm$ 29.1                    | -5.7                 | -0.51        | .615                | .703        |
|                                                                    | AUC ( $\mu\text{V} \cdot \text{s}$ )                 | 14.7 $\pm$ 11.6                    | 11.7 $\pm$ 11.2                    | -3.0                 | -0.72        | .479                | .639        |
| SF Auditory ( $n = 15/15$ )                                        | Peak Latency (ms)                                    | 456.0 $\pm$ 74.2                   | 520.3 $\pm$ 120.1                  | +64.3                | 1.76         | .089                | .160        |
|                                                                    | <b>Mean Amplitude (<math>\mu\text{V}</math>)</b>     | <b>19.3 <math>\pm</math> 18.6</b>  | <b>3.3 <math>\pm</math> 13.5</b>   | <b>-16.0</b>         | <b>-2.58</b> | <b>.013</b>         | <b>.028</b> |
|                                                                    | <b>Peak Amplitude (<math>\mu\text{V}</math>)</b>     | <b>27.1 <math>\pm</math> 20.4</b>  | <b>11.2 <math>\pm</math> 15.2</b>  | <b>-15.9</b>         | <b>-2.43</b> | <b>.022</b>         | <b>.047</b> |
|                                                                    | <b>AUC (<math>\mu\text{V} \cdot \text{s}</math>)</b> | <b>7.7 <math>\pm</math> 7.4</b>    | <b>1.3 <math>\pm</math> 5.4</b>    | <b>-6.4</b>          | <b>-2.58</b> | <b>.014</b>         | <b>.028</b> |
| SF Visual ( $n = 15/15$ )                                          | <b>Peak Latency (ms)</b>                             | <b>410.0 <math>\pm</math> 46.5</b> | <b>473.2 <math>\pm</math> 77.5</b> | <b>+63.2</b>         | <b>2.63</b>  | <b>.013</b>         | <b>.036</b> |
|                                                                    | Mean Amplitude ( $\mu\text{V}$ )                     | 31.0 $\pm$ 23.2                    | 23.3 $\pm$ 21.7                    | -7.7                 | -0.94        | .356                | .500        |
|                                                                    | Peak Amplitude ( $\mu\text{V}$ )                     | 38.4 $\pm$ 26.1                    | 31.2 $\pm$ 24.3                    | -7.2                 | -0.78        | .441                | .600        |
|                                                                    | AUC ( $\mu\text{V} \cdot \text{s}$ )                 | 12.4 $\pm$ 9.3                     | 9.3 $\pm$ 8.7                      | -3.1                 | -0.94        | .356                | .500        |
| <i>B. Electrophysiological Shift-Cost Contrasts (SF – Focused)</i> |                                                      |                                    |                                    |                      |              |                     |             |
| Auditory Shift-Cost                                                | Latency Cost (ms)                                    | -23.2 $\pm$ 88.3                   | -45.1 $\pm$ 115.2                  | -21.9                | -0.58        | .564                | .710        |
|                                                                    | Amplitude Cost ( $\mu\text{V}$ )                     | -6.2 $\pm$ 20.1                    | -5.2 $\pm$ 17.3                    | +1.0                 | 0.15         | .885                | .900        |
| Visual Shift-Cost                                                  | Latency Cost (ms)                                    | +7.9 $\pm$ 52.4                    | -19.3 $\pm$ 95.1                   | -27.2                | -0.98        | .338                | .500        |
|                                                                    | Amplitude Cost ( $\mu\text{V}$ )                     | -5.8 $\pm$ 21.2                    | -5.9 $\pm$ 20.4                    | -0.1                 | -0.01        | .990                | .990        |

**Note:** Values represent group means  $\pm$  standard deviations (SD). Diff( $\Delta$ ) is Older minus Younger. Group comparisons were evaluated using Welch's two-tailed  $t$ -test with Satterthwaite degrees of freedom to account for unequal group variances and condition-specific sample sizes. False Discovery Rate (FDR)  $q$ -values were adjusted using the Benjamini–Hochberg procedure; bold rows indicate statistical significance at  $q < .050$ .  $g$  is Hedges'  $g$ . FA: focused-auditory; FV: focused-visual; SF: shift-focus; AUC: signed area under the curve.

### 3.3 Delayed Class-B temporal emergence during auditory attention shifting

Microstate analysis provided the whole-scalp structural correlate of the sensor-level ERP findings, directly addressing H2 (Table 1).

During auditory attention shifting (SF Auditory), Class B — the whole-scalp topography most active during the P300 period — emerged substantially later in older adults and showed markedly lower spatial fidelity relative to younger adults. Onset latency was delayed by approximately 48 ms ( $g = 1.06$ , FDR  $q = .021$ ) and centre of gravity by approximately 42 ms ( $g = 1.07$ , FDR  $q = .019$ ), both surviving FDR correction. Older adults also exhibited significantly reduced mean spatial template correlation with the Class B map ( $g = -1.11$ , FDR  $q = .019$ ), indicating that when Class B was expressed, it was expressed less precisely. Descriptive statistics and inferential parameters are reported in Table 2.

At the uncorrected level, older adults additionally exhibited greater Class A duration and coverage during SF auditory trials ( $g \approx 0.80$ – $0.83$ ; Supplementary Table A1). While consistent with prolonged dwell in an earlier topographic configuration prior to Class B emergence, these trends did not survive FDR correction and are treated as exploratory; no causal interpretation is advanced.

### 3.4 Altered microstate transition probabilities and self-loop persistence

Beyond single-state timing, the directional sequence structure of P300-period microstates was systematically altered in older adults, addressing H3 (Table 2; Fig. 3c).

Older adults consistently showed lower forward transition probabilities into Class C from multiple preceding states. Specifically,  $B \rightarrow C$  transitions were suppressed across FA auditory, SF auditory, and SF visual conditions (all FDR-corrected  $g$  values approximately  $-0.77$  to  $-1.06$ ), and  $D \rightarrow C$  transitions were likewise reduced in FA auditory and SF visual blocks. Transitions into Class B from Class C were also reduced in SF auditory and FV visual conditions. These condition-specific reductions indicate that the entire sequential chain linking early, intermediate, and late P300-period configurations becomes less fluid in older adults. Effect sizes and FDR-corrected  $q$ -values for all significant transitions are reported in Table 2.

At the whole-session level, aggregated across all conditions, older adults showed a significant reduction in  $A \rightarrow B$  forward switching ( $g = -1.09$ , FDR  $q = .033$ ) alongside a significant increase in  $A \rightarrow A$  self-loop persistence ( $g = 1.02$ , FDR  $q = .038$ ). This combination of reduced forward progress coupled with elevated within-state persistence is consistent with diminished dynamical flexibility. Age-related differences were therefore manifested not merely in the timing of individual configurations, but in the conditional transition syntax linking successive whole-scalp states across the P300 period.

### 3.5 Microstate sequence complexity dynamics

Non-linear complexity and information-theoretic sequence analyses revealed preserved global sequence dynamics alongside condition-specific shifts (Supplementary Table A1). In focused auditory trials (FA), older adults exhibited elevated sequence entropy ( $1.95 \pm 0.03$  bits vs.  $1.90 \pm 0.08$  bits,  $t(19.2) = 2.199$ ,  $p = .040$ ,  $g = 0.78$ , 95% CI  $[-0.06, +1.56]$ ) and higher Markov entropy excluding self-loops ( $1.50 \pm 0.05$  bits vs.  $1.44 \pm 0.10$  bits,  $t(21.4) = 2.141$ ,  $p = .044$ ,  $g = 0.77$ , 95% CI  $[-0.06, +1.56]$ ), though

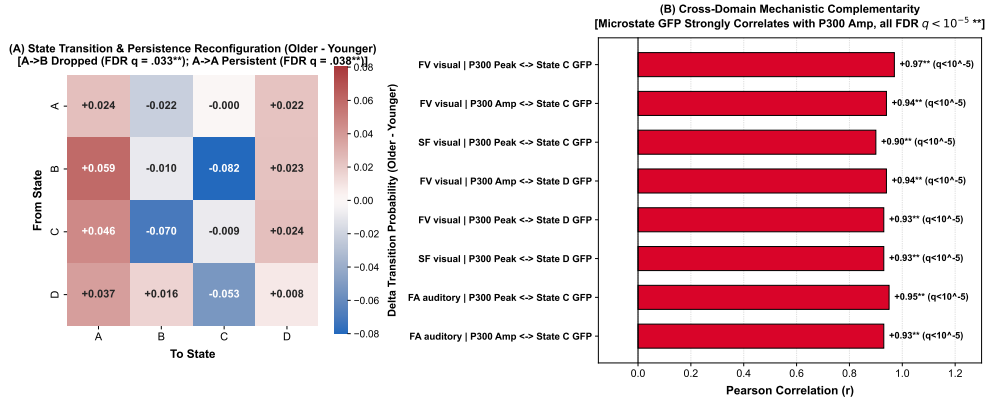


**Fig. 3** Microstate transition dynamics and cross-domain P300–GFP convergence. **a** Shift-cost analysis for Class-C duration illustrating preserved condition difference across cohorts. **b** Delayed temporal emergence of Class B during auditory attention shifting (SF Auditory). **c** First-order Markov state transition probability differences ( $\Delta = \text{Older} - \text{Younger}$ ) illustrating constrained forward switching into Class C and elevated self-loop persistence ( $A \rightarrow A$ ) in older adults. **d** Pearson correlation demonstrating robust electrophysiological convergence between sensor-level P300 peak amplitude at Pz and multichannel Class-C Global Field Power ( $r = +0.90$  to  $+0.93$ )

these effects did not survive global FDR correction ( $q = .455$ ). Normalized Lempel–Ziv complexity remained highly stable across cohorts and conditions ( $Lz \approx 0.067\text{--}0.081$ , all  $p > .150$ ,  $q > .700$ ), indicating that the basic algorithmic compressibility of the scalp electric field was preserved across the adult lifespan.

### 3.6 Cross-domain convergence between P300 amplitude and microstate global field power

To evaluate convergence between sensor-level voltage and multichannel field strength, individual P300 peak amplitude at Pz was correlated with microstate Global Field Power (GFP; Fig. 3d; Table 2).

P300 peak amplitude was strongly and positively correlated with Class-C GFP across all three task conditions ( $r = +0.90$  to  $+0.97$ ; all FDR  $q < 10^{-6}$ ). These associations confirm that when the P300 is large at the single electrode, the corresponding whole-scalp topography is also strongly expressed — a finding that provides convergent physiological validation for the epoch-by-epoch microstate back-fitting approach. However, it is important to note that because Pz contributes substantially to the global scalp field, single-electrode amplitude and multichannel GFP share a degree of mathematical co-dependence [Lehmann et al. \(2005\)](#); [Michel and Koenig \(2018\)](#). These correlations should therefore not be interpreted as evidence of an independent causal relationship, but as confirmation of methodological coherence between the two analytical frameworks.

**Table 2** Primary FDR-controlled age effects ( $q < .05$ ) across P300 electrophysiology, microstate parameters, transitions, and cross-domain complementarity.  $g$  denotes Hedges’  $g$  (older minus younger);  $q$  denotes the Benjamini–Hochberg false discovery rate-adjusted  $q$ -value;  $n_Y/n_O$  gives the numbers of contributing younger/older participants. AUC, area under the curve; GFP, global field power.

| Domain          | Condition/contrast | Outcome                        | Direction in older adults       | $n_Y/n_O$ | $g$   | $q$          |
|-----------------|--------------------|--------------------------------|---------------------------------|-----------|-------|--------------|
| P300            | FV visual          | Peak latency                   | Later (+90.4 ms)                | 15/14     | 1.41  | .006         |
| P300            | SF auditory        | Area under curve (AUC)         | Lower ( $-16.0 \mu V \cdot s$ ) | 15/15     | -0.94 | .028         |
| P300            | SF auditory        | Mean amplitude                 | Lower ( $-16.0 \mu V$ )         | 15/15     | -0.94 | .028         |
| P300            | SF visual          | Peak latency                   | Later (+63.2 ms)                | 15/15     | 0.96  | .036         |
| ERP Temporal    | SF auditory        | State B onset (ms)             | Later (+48.2 ms)                | 15/15     | 1.06  | .021         |
| ERP Temporal    | SF auditory        | State B center of gravity (ms) | Later (+42.1 ms)                | 15/15     | 1.07  | .019         |
| ERP Temporal    | SF auditory        | State B mean  corr             | Lower (-0.08)                   | 15/15     | -1.11 | .019         |
| Transition      | FA auditory        | B→C transition                 | Lower ( $\Delta = -0.046$ )     | 15/11     | -0.87 | .024         |
| Transition      | FA auditory        | D→C transition                 | Lower ( $\Delta = -0.051$ )     | 15/11     | -1.00 | .013         |
| Transition      | SF auditory        | B→C transition                 | Lower ( $\Delta = -0.054$ )     | 15/15     | -1.06 | .006         |
| Transition      | SF auditory        | C→B transition                 | Lower ( $\Delta = -0.044$ )     | 15/15     | -0.75 | .044         |
| Transition      | FV visual          | C→B transition                 | Lower ( $\Delta = -0.043$ )     | 15/14     | -0.79 | .036         |
| Transition      | SF visual          | B→C transition                 | Lower ( $\Delta = -0.042$ )     | 15/15     | -0.77 | .041         |
| Transition      | SF visual          | D→C transition                 | Lower ( $\Delta = -0.045$ )     | 15/15     | -0.78 | .036         |
| Transition      | Whole session      | A→B transition                 | Lower ( $\Delta = -0.052$ )     | 15/15     | -1.09 | .033         |
| Transition      | Whole session      | A→A self-loop                  | Higher ( $\Delta = +0.024$ )    | 15/15     | 1.02  | .038         |
| Complementarity | FV visual          | P300 Peak Amp ↔ State C GFP    | Strong positive ( $r = +0.97$ ) | 15/14     | —     | $< 10^{-10}$ |
| Complementarity | SF visual          | P300 Peak Amp ↔ State C GFP    | Strong positive ( $r = +0.90$ ) | 15/15     | —     | $< 10^{-8}$  |
| Complementarity | FA auditory        | P300 Peak Amp ↔ State C GFP    | Strong positive ( $r = +0.95$ ) | 15/11     | —     | $< 10^{-6}$  |

## 4 Discussion

This study combined conventional ERP measures with task-evoked microstate analysis to characterise how healthy aging affects the temporal and topographic organisation of the P300 period during auditory–visual attention shifting. The three sets of findings, delayed P300 peaks, delayed Class B recruitment with reduced spatial fidelity, and altered forward transition probabilities with elevated self-loop persistence, converge on a single interpretive framework: *healthy aging reduces the flexibility of task-evoked state reconfiguration during the P300 period*.

Delayed recruitment, poorer template fidelity, suppressed forward switching, and elevated self-loops are not independent findings; each indexes the same underlying construct of diminished dynamic reconfiguration of distributed cortical topographies under cross-modal attentional demands. Framing the results in this way clarifies the mechanistic contribution of the present study beyond documenting disparate group differences: the aging brain does not merely slow its peak response time, but exhibits greater inertia across the entire sequence of whole-scalp configurations that constitute the P300 epoch. This unified narrative guides the subsections that follow.

## 4.1 P300 latency delays and modality-specific amplitude dynamics

The P300 latency prolongations observed for visual targets in this sample are consistent with a large body of literature linking aging with slower stimulus categorisation and context updating [Donchin and Coles \(1988\)](#); [Picton \(1992\)](#); [Polich \(1996, 2007\)](#). Effect sizes in the present sample were substantial ( $g = 1.41$  for FV,  $g = 0.96$  for SF visual), aligning with normative lifespan meta-analyses [van Dinteren et al. \(2014\)](#); [Bourisly \(2016\)](#). Importantly, the latency delays were modality-selective: delays were clearest for visual targets, whereas auditory conditions exhibited a marked reduction in P300 mean amplitude ( $-16.0 \mu\text{V}$ ,  $g = -0.94$ ) specifically during shift-focus trials.

Selective auditory amplitude reduction under cross-modal shift demands fits well with cognitive load theories: attentional control demands are highest when both modality switching and target detection must be coordinated within the same trial [Grady \(2012\)](#); [Talsma et al. \(2010\)](#); [Kieffaber and Hetrick \(2005\)](#). When participants must abandon an established auditory attentional set to monitor for newly cued targets, older adults allocate fewer central processing resources to auditory targets, consistent with sensory dedifferentiation and reduced capacity under high switching load [Park and Reuter-Lorenz \(2009\)](#); [Čeponienė et al. \(2008\)](#); [Rapela et al. \(2012\)](#). It is essential to note that the present study involves a cross-sectional two-group design; expressions such as “age-related differences” describe group contrasts and do not imply individual aging trajectories or longitudinal deterioration.

This pattern also clarifies why subtractive electrophysiological shift costs (SF – Focused) yielded non-significant age-by-task interactions at electrode Pz. In the visual modality, older adults exhibited substantial latency delays that were already prominent during focused target detection ( $+90.4 \text{ ms}$ ,  $g = 1.41$ ) and remained elevated during shifting ( $+63.2 \text{ ms}$ ,  $g = 0.96$ ); subtracting focused from shifting trials thus masks a pronounced, persistent processing speed bottleneck. Conversely, in the auditory modality, the attentional reallocation cost was expressed asymmetrically in response magnitude, a near-complete suppression of parietal P300 voltage ( $3.3 \mu\text{V}$  vs.  $19.3 \mu\text{V}$ ), rather than further peak latency prolongation. This critical dissociation underlines the fundamental limitation of single-channel subtractive ERP metrics: scalar difference scores collapse distinct physiological failure modes (baseline ceiling delays vs. voltage depletion) into an apparent null interaction. As demonstrated below, spatio-temporal microstate decomposition resolves this conundrum by revealing that the auditory shifting deficit is driven by delayed recruitment and degraded template fidelity of the underlying Class B topography.

## 4.2 Spatiotemporal disambiguation: What microstates reveal beyond single-channel ERPs

The fundamental advantage of electrical neuroimaging and microstate analysis is its ability to resolve the spatio-temporal architecture of scalp field dynamics that single-channel ERPs collapse into a scalar voltage time-course [Lehmann et al. \(1987\)](#); [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#); [Schiller et al. \(2024\)](#). Because scalp electric field topographies are reference-independent, changes in microstate topography

unequivocally reflect changes in the underlying intracranial generator configurations (Murray et al. (2008); Michel and Koenig (2018)). In the present dataset, the FDR-controlled delay and reduced map fidelity of Class B during SF auditory trials provide essential temporal structure: Class B emerged +48.2 ms later ( $g = 1.06$ ) with a +42.1 ms delay in centre of gravity ( $g = 1.07$ ) and degraded spatial template correlation ( $g = -1.11$ ) in older adults.

This finding clarifies the sensor-level ERP phenotype: the reduced P300 amplitude observed at Pz during auditory shifting is accompanied by a delay in the recruitment of a distinct, stable scalp configuration and lower fidelity of that configuration (Michel and Koenig (2018); Michel et al. (2024); Tait and Zhang (2022); Schiller et al. (2024); Brechet et al. (2024)). Furthermore, the exploratory elevation of Class-A duration and coverage in SF conditions suggests that an earlier topographic configuration may persist longer before giving way to subsequent configurations. However, we caution that these uncorrected trends ( $p < .050$ , but FDR  $q > .050$ ) do not establish that Class-A persistence causally delays Class-B onset.

Crucially, the canonical microstate A–D labels derive from resting-state EEG templates (Koenig et al. (2002); Khanna et al. (2014); Tarailis et al. (2024)). Applying these templates to task-evoked ERP intervals relies on the empirical recurrence of similar spatial geometries across states (Tait and Zhang (2022); Schiller et al. (2024); Brechet et al. (2024); Lai et al. (2025)). Because resting-state and task-evoked scalp fields arise from partially overlapping but non-identical neural assemblies, spatial resemblance to a canonical template does not establish identical cortical generators or dedicated network identities (Michel and Koenig (2018); Michel et al. (2024)). Accordingly, we avoid labeling these states as dedicated sensory or cognitive control hubs; rather, they reflect the empirical temporal progression of whole-scalp electric field topographies.

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### 625 4.3 Transition syntax as a window into flexible cognitive 626 processing in healthy aging 627

Beyond single-state timing, first-order Markov transition matrices revealed that older and younger adults differed fundamentally in how they progressed between P300-period topographies. Older adults showed significantly lower transition probabilities into Class C ( $B \rightarrow C$  and  $D \rightarrow C$  across conditions) and reduced transitions into Class B ( $C \rightarrow B$  in SF auditory and FV visual), alongside a whole-session reduction in  $A \rightarrow B$  switching ( $\Delta = -0.052$ ,  $g = -1.09$ ) and increased  $A \rightarrow A$  self-loop persistence ( $\Delta = +0.024$ ,  $g = 1.02$ ).

These transition changes indicate that cognitive aging is characterized by altered conditional sequence structure across the P300 interval. The elevation of self-loop persistence within Class A alongside reduced forward switching into Class B suggests a loss of dynamical flexibility: the aging brain exhibits greater inertia in disengaging from an initial scalp configuration to enter subsequent task-related configurations (Grady (2012); Zanesco et al. (2020); D’Croz-Baron et al. (2019); Murphy et al. (2020)). This interpretation aligns with information-theoretic analyses showing altered sequence entropy in aging (von Wegner and Laufs (2018); von Wegner et al. (2024); Jajcay and Hlinka (2023); Tarailis et al. (2024); Barzon et al. (2024)). However, because transition probabilities are mathematically bounded by overall state durations, these syntax

changes should be interpreted descriptively as constrained sequence dynamics rather than direct evidence of altered sequence progression in anatomical pathways.

#### 4.4 Physiological convergence vs. mathematical coupling in P300–GFP associations

Individual P300 peak amplitude at Pz was strongly and positively correlated with Class-C Global Field Power across task conditions ( $r = +0.90$  to  $+0.97$ , all FDR  $q < 10^{-6}$ ). While this robust association illustrates close cross-domain coupling, it requires clear methodological contextualization.

Because electrode Pz is a primary contributor to global scalp voltage gradients, single-electrode parietal amplitude and multichannel Global Field Power share a degree of mathematical co-dependence [Lehmann et al. \(2005\)](#); [Michel and Koenig \(2018\)](#). Consequently, these strong correlations should not be interpreted as evidence of an independent causal generator driving P300 voltage. Rather, they provide convergent physiological validation: when the whole-scalp electric field configuration (Class C) is strongly and synchronously expressed across the scalp, sensor-level parietal electrodes record correspondingly high positivity. This reinforces the methodological coherence of epoch-by-epoch microstate back-fitting in task-evoked ERP paradigms [Michel and Koenig \(2018\)](#); [Kleinert et al. \(2024a\)](#); [Schiller et al. \(2024\)](#); [Lai et al. \(2025\)](#).

#### 4.5 Comparison with prior work on microstate dynamics and cognitive aging

Our findings both converge with and substantially extend previous investigations of EEG microstate dynamics across the adult lifespan. In resting-state paradigms, extensive normative studies have demonstrated that healthy aging is accompanied by altered microstate temporal metrics, including shorter mean durations of frontoparietal configurations (Classes C and D) and altered transition syntax [Koenig et al. \(2002\)](#); [ZanESCO et al. \(2020\)](#); [D’Croz-Baron et al. \(2019\)](#); [Murphy et al. \(2020\)](#); [Tarailis et al. \(2024\)](#); [Griskova-Bulanova et al. \(2024\)](#). Specifically, ZanESCO et al. [ZanESCO et al. \(2020\)](#) observed progressive shifts in microstate occupancy and transitions across the lifespan, while D’Croz-Baron et al. [D’Croz-Baron et al. \(2019\)](#) and Griskova-Bulanova et al. [Griskova-Bulanova et al. \(2024\)](#) documented that aging and cognitive decline (e.g., Mild Cognitive Impairment) display exaggerated disruptions in Class-B and Class-C persistence and transition probabilities. The present study advances this literature by demonstrating that during active, cued attention shifting, age-related microstate differences do not manifest merely as passive background shifts, but rather as task-locked temporal delays in specific event-related configurations (Class B) and elevated state-persistence self-loops ( $A \rightarrow A$ ). This task-evoked dynamical constraint aligns directly with recent meta-analyses by Schiller et al. [Schiller et al. \(2024\)](#) and methodological frameworks by Bréchet et al. [Bréchet et al. \(2024\)](#), Kleinert et al. [Kleinert et al. \(2024a,b\)](#), and Lai et al. [Lai et al. \(2025\)](#), confirming that event-related microstates provide a reliable, temporally resolved readout of cognitive state reconfiguration in the aging brain.

## 4.6 Translational, clinical, and psychophysiological implications

The integration of P300 electrophysiology with task-evoked microstate analysis has meaningful translational implications for cognitive neuroscience and clinical psychophysiology [Picton \(1992\)](#); [van Dinteren et al. \(2014\)](#); [D’Croz-Baron et al. \(2019\)](#); [Murphy et al. \(2020\)](#). Traditional clinical ERP protocols rely heavily on single-channel latency measurements to detect cognitive slowing, but peak latency alone lacks spatial and dynamic granularity. By decomposing the P300 interval into discrete topographic states and transition probabilities, microstate analysis provides sub-second metrics that can differentiate whether processing delays stem from prolonged sensory dwell times, delayed recruitment of late configurations, or altered transition syntax [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#); [ZanESCO et al. \(2020\)](#); [Murphy et al. \(2020\)](#).

In preclinical and clinical populations, such as mild cognitive impairment (MCI), Alzheimer’s disease, and frontotemporal dementia, subtle executive and attentional shifting impairments often precede overt structural neurodegeneration [D’Croz-Baron et al. \(2019\)](#); [Murphy et al. \(2020\)](#). Quantifying microstate transition flexibility and template fidelity during active cognitive challenges, rather than resting states alone, may offer sensitive, non-invasive electrophysiological markers for detecting early neurocognitive decline and evaluating the efficacy of cognitive interventions.

## 4.7 Methodological considerations, limitations, and future directions

Several methodological considerations qualify the present conclusions.

*Sample size and electrical neuroimaging SNR.* The sample ( $n = 30$ , 15 per group) was constrained by the open-access repository and artifact-rejection thresholds. While sensitivity power analysis confirmed  $> 80\%$  power for large effect sizes ( $g \geq 0.95$ ), replication in prospectively-recruited cohorts is essential. Importantly, in electrical neuroimaging, spatial field topographies and microstate parameters exhibit inherently higher signal-to-noise ratios than individual single-trial voltage amplitudes, which accounts for the robust large effect sizes ( $g = 0.94\text{--}1.41$ ) observed across our primary topographic contrasts [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#). Nonetheless, four to five older participants failed retention thresholds in single FA and FV blocks due to ocular and motor noise, reducing power in focused conditions.

*Behavioural absence.* As noted in Subsection 2.2, single-trial reaction-time data were not available in the archived dataset. Without trial-level behavioural data, a direct link between microstate transition syntax and individual behavioural switch costs cannot be established. Differences in electrophysiological transition flexibility between groups may reflect altered attentional reconfiguration, but this interpretation remains speculative in the absence of concurrent behavioural measures. Future prospective studies should record both high-density EEG and single-trial reaction times within the same session.

*Delayed Class B vs. delayed P300.* A potential alternative interpretation is that the delayed Class B onset simply mirrors the delayed P300 peak rather than reflecting a distinct mechanistic process. Three features of the data argue against this equivalence. First, Class B delay and P300 latency delay were dissociable in magnitude:

Class B onset was delayed by  $\approx 48$  ms whereas P300 peak latency delays ranged from 63 to 90 ms across conditions, indicating non-identical phenomena. Second, the spatial template fidelity of Class B was independently reduced in older adults, a finding that is orthogonal to latency, demonstrating that the microstate measure captures spatial degradation beyond a simple temporal echo. Third, transition probability changes represent sequence-level syntax that has no direct analogue in single-channel peak latency. Taken together, the microstate findings add mechanistic specificity beyond what delayed P300 latency alone can convey.

*Spatial resolution and source attribution.* The 33-channel montage limits inverse source localization. Microstate topographies here reflect sensor-level electric field configurations; establishing cortical and subcortical generators will require high-density EEG (128–256 channels) with individual MRI co-registration or simultaneous EEG–fMRI [Murray et al. \(2008\)](#); [Michel and Koenig \(2018\)](#); [Brechet et al. \(2024\)](#).

## 5 Conclusion

This study demonstrates that age-group differences in P300 electrophysiology during cross-modal attention shifting are embedded in systematic alterations of the temporal organisation, spatial fidelity, and transition syntax of whole-scalp EEG microstates. Three primary sets of findings converge:

1. **Modality-Specific ERP Phenotype (H1 supported):** Older adults showed large-effect P300 latency delays for visual targets across focused and shifting conditions, and attenuated amplitude during auditory attention shifting, consistent with reduced stimulus evaluation speed and resource allocation under cross-modal demand.
2. **Delayed Microstate Recruitment and Reduced Fidelity (H2 supported):** During auditory attention shifting, Class B emerged later and was expressed with lower spatial precision in older adults, providing the whole-scalp structural basis for the sensor-level P300 attenuation beyond what a single-electrode peak can reveal.
3. **Constrained Transition Syntax and Dynamical Inertia (H3 supported):** Older adults exhibited reduced forward switching into Classes B and C and elevated self-loop persistence within Class A, the signature of diminished dynamical flexibility during attentional reconfiguration.

Healthy aging is associated not merely with delayed P300 peaks, but with altered temporal coordination of large-scale electrophysiological states supporting attentional reconfiguration, a structured dynamical constraint that single-electrode ERP analysis cannot resolve. Applying this integrated ERP–microstate framework to high-density recordings and clinical cohorts promises to reveal how large-scale brain state dynamics support, and ultimately fail to support, cognitive flexibility across the adult lifespan.

**Supplementary information.** Supplementary Table [A1](#) reports all exploratory, uncorrected age effects ( $p < .050$ ) to support future hypothesis-driven replications.

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788 for publication.  
789

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791 ysis of a de-identified, publicly available dataset from the OpenNeuro repository  
792 (ds002893). The original data collection protocols were approved by the institutional  
793 review boards of the host institutions, and all participants provided written informed  
794 consent in accordance with the Declaration of Helsinki.

795 **Consent for Publication.** Not applicable (de-identified secondary public data  
796 analysis).  
797

798 **Data Availability.** The raw EEG datasets supporting the conclusions of this article  
799 are openly accessible in the OpenNeuro repository under accession identifier ds002893  
800 (version 2.0.0; <https://openneuro.org/datasets/ds002893>).

801 **Code Availability.** The signal-processing, microstate segmentation, and statisti-  
802 cal analysis pipelines were developed in Python (using MNE-Python v1.6.0) and are  
803 publicly available upon final publication(<https://github.com/shivom7>).  
804

805 **Authors' Contributions.** **Shivom Gupta:** Conceptualization, Methodology,  
806 Software, Data curation, Formal analysis, Investigation, Visualization, Writing – orig-  
807 inal draft.

808 **Jyotiranjana Beuria:** Supervision, Project administration, Resources, Funding acqui-  
809 sition, Conceptualization, Validation, Writing – review & editing.

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## Appendix A Supplementary Table

**Table A1** Comprehensive uncorrected statistically significant age effects ( $p < .05$ ) across P300 electrophysiology, canonical microstates, temporal parameters, and transition dynamics.  $g$  denotes Hedges'  $g$  (older minus younger);  $p$  denotes the uncorrected Welch  $t$ -test  $p$ -value;  $n_Y/n_O$  gives the numbers of contributing younger/older participants. AUC, area under the curve; CV, coefficient of variation; FA, focused-auditory; FV, focused-visual; SF, shift-focus.

| Domain            | Condition/contrast | Outcome                        | Direction<br>older adults | in | $n_Y/n_O$ | $g$   | $p$  |
|-------------------|--------------------|--------------------------------|---------------------------|----|-----------|-------|------|
| P300              | FA auditory        | Peak latency                   | Later                     |    | 15/11     | 1.06  | .014 |
| P300              | FV visual          | Peak latency                   | Later                     |    | 15/14     | 1.41  | .001 |
| P300              | SF auditory        | Area under curve (AUC)         | Lower                     |    | 15/15     | -0.94 | .014 |
| P300              | SF auditory        | Mean amplitude                 | Lower                     |    | 15/15     | -0.94 | .013 |
| P300              | SF auditory        | Peak amplitude                 | Lower                     |    | 15/15     | -0.75 | .047 |
| P300              | SF visual          | Peak latency                   | Later                     |    | 15/15     | 0.96  | .013 |
| State A           | FA auditory        | Spatial correlation            | Lower                     |    | 15/11     | -0.78 | .045 |
| State A           | SF auditory        | Time coverage                  | Higher                    |    | 15/15     | 0.83  | .028 |
| State A           | SF auditory        | Mean duration (ms)             | Higher                    |    | 15/15     | 0.80  | .032 |
| State A           | SF visual          | Time coverage                  | Higher                    |    | 15/15     | 0.89  | .019 |
| State A           | SF visual          | Mean duration (ms)             | Higher                    |    | 15/15     | 0.80  | .033 |
| State B           | FA auditory        | Spatial correlation            | Lower                     |    | 15/11     | -0.94 | .017 |
| State C           | FA auditory        | Spatial correlation            | Lower                     |    | 15/11     | -0.77 | .045 |
| State C           | SF auditory        | Occurrence rate                | Lower                     |    | 15/15     | -0.77 | .040 |
| State C           | SF visual          | Occurrence rate                | Lower                     |    | 15/15     | -0.82 | .029 |
| State C           | SF visual          | Time coverage                  | Lower                     |    | 15/15     | -0.77 | .040 |
| ERP Temporal      | FA auditory        | State B Mean  corr             | Lower                     |    | 15/11     | -1.20 | .011 |
| ERP Temporal      | FA auditory        | State C Onset (ms)             | Later                     |    | 15/11     | -0.82 | .048 |
| ERP Temporal      | FA auditory        | State C Mean  corr             | Lower                     |    | 15/11     | -1.07 | .017 |
| ERP Temporal      | FA auditory        | State D Mean  corr             | Lower                     |    | 15/11     | -1.04 | .042 |
| ERP Temporal      | SF auditory        | State A Duration (ms)          | Longer                    |    | 15/15     | 0.82  | .032 |
| ERP Temporal      | SF auditory        | State B Onset (ms)             | Later                     |    | 15/15     | 1.06  | .009 |
| ERP Temporal      | SF auditory        | State B Center of gravity (ms) | Later                     |    | 15/15     | 1.07  | .005 |
| ERP Temporal      | SF auditory        | State B Mean  corr             | Lower                     |    | 15/15     | -1.11 | .004 |
| ERP Temporal      | SF visual          | State C Mean  corr             | Lower                     |    | 15/15     | -0.88 | .024 |
| ERP Temporal      | SF visual          | State D Mean  corr             | Lower                     |    | 15/15     | -0.95 | .023 |
| Sequence dynamics | FA auditory        | Markov entropy, no self        | Higher                    |    | 15/11     | 0.75  | .044 |
| Sequence dynamics | FA auditory        | Sequence entropy               | Higher                    |    | 15/11     | 0.75  | .040 |
| Sequence dynamics | FA auditory        | Sequence entropy normalized    | Higher                    |    | 15/11     | 0.75  | .040 |
| Sequence dynamics | SF visual          | Dwell-time CV                  | Lower                     |    | 15/15     | -0.78 | .038 |
| Transition        | FA auditory        | B→C                            | Lower                     |    | 15/11     | -0.87 | .024 |
| Transition        | FA auditory        | D→C                            | Lower                     |    | 15/11     | -1.00 | .013 |
| Transition        | SF auditory        | B→C                            | Lower                     |    | 15/15     | -1.06 | .006 |
| Transition        | SF auditory        | C→B                            | Lower                     |    | 15/15     | -0.75 | .044 |
| Transition        | FV visual          | C→B                            | Lower                     |    | 15/14     | -0.79 | .036 |
| Transition        | SF visual          | B→C                            | Lower                     |    | 15/15     | -0.77 | .041 |
| Transition        | SF visual          | D→C                            | Lower                     |    | 15/15     | -0.78 | .036 |

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