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Multisubject decomposition of event-related positivities in cognitive control: tackling the age-related anterior shift

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Abstract:	Electroencephalographic (EEG) research focuses usually rather on individual features than on the interplay of different EEG parameter. This study characterizes for the first time the associations between topographies and source space, as well as between event-related potentials and oscillations of independent functional networks which underlie cognitive aging. Three different age groups (30 young: 18-26 years, 30 mid-aged: 49-58 years, 30 elderly: 65-75 years) took part in an EEG switching task. Neural data was analyzed by means of group independent component analysis and with respect to targets following a distractor- in the single-task block, or switch- and repeat cue in the mixed-task block. As expected, behavioral performance slowed down with increasing age, especially in conditions of the mixed- compared to the single-task block. Further, a total of 10 functionally independent networks were detected. Nearly all of them were affected by age as indicated by two main changes in older compared to young participants: first, reduced amplitudes of event-related potentials; second, by reduced power in frequency bands which span from delta to gamma, but is consistently observed in beta. Crucially, in two of these networks the prominent posterior-to-anterior age-related topography shift was detected. Corresponding positivities peaked at 400 ms and its analyses revealed brain-behavior associations: fast correct behavioral performance was associated with high activity at posterior- and low anterior topographies, as well as with high beta power in general cognitive and executive functioning. Hence, the results speak in favor of an age-related failed compensation. By providing a synopsis of age-related EEG changes, this study extends previous findings and opens new prospects in understanding aging in reactive control.
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Dear Editors,

We herewith submit our manuscript “Multisubject decomposition of event-related positivities in cognitive control: tackling the age-related anterior shift” for the special issue “Multisubject decomposition of EEG –methods and applications” organized by the guest editors Vince Calhoun and René Huster. We kindly ask you to review the paper for possible publication in "Brain Topography".

One of the most prominent observations in cognitive neuroscience and biopsychology is the posterior-anterior shift, a phenomenon that reflects higher prefrontal activity in older participants than in younger subjects. Although this shift has been a known fact, it is yet outstanding under which constellations this phenomenon represents successful, attempted or failed compensatory mechanisms. In the current study, three different age groups (30 young: 18-26 years, 30 mid-aged: 49-58 years, 30 elderly: 65-75 years) took part in an EEG task switching experiment. The current study extends previous findings on set-shifting and aging by drawing for the first time a critical line between topographies (FPz, Fz, Cz, Pz) and source space (independent components), as well as between prominent ERPs (e.g., P300) and less known underlying mechanisms of brain communications as reflected in EROs (from delta to gamma band) in functionally connected networks using group-ICA. By further assessing brain-behavior relations, we open new prospects in understanding aging in reactive control. Since our novel findings demonstrate the associations between different EEG parameter and behaviour, we strongly believe that our manuscript is of general interest for the wide readership of “Brain Topography”.

The findings have not been published previously and are not under consideration for publication elsewhere.

We would like to thank you for taking the time to consider our submission. Correspondence regarding our paper should be sent to Dr. Stefanie Enriquez-Geppert at the address indicated on the first manuscript page.

We are looking forward to hearing from you.
On behalf of all authors,
Yours sincerely,

Dr. Stefanie Enriquez-Geppert

Multisubject decomposition of event-related positivities in cognitive control: tackling the age-related anterior shift

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ABSTRACT

Electroencephalographic (EEG) research focuses usually rather on individual features than on the interplay of different EEG parameter. This study characterizes for the first time the associations between topographies and source space, as well as between event-related potentials and oscillations of independent functional networks which underlie cognitive aging. Three different age groups (30 young: 18-26 years, 30 mid-aged: 49-58 years, 30 elderly: 65-75 years) took part in an EEG switching task. Neural data was analyzed by means of group independent component analysis and with respect to targets following a distractor- in the single-task block, or switch- and repeat cue in the mixed-task block. As expected, behavioral performance slowed down with increasing age, especially in conditions of the mixed- compared to the single-task block. Further, a total of 10 functionally independent networks were detected. Nearly all of them were affected by age as indicated by two main changes in older compared to young participants: first, reduced amplitudes of event-related potentials; second, by reduced power in frequency bands which span from delta to gamma, but is consistently observed in beta. Crucially, in two of these networks the prominent posterior-to-anterior age-related topography shift was detected. Corresponding positivities peaked at 400 ms and its analyses revealed brain-behavior associations: fast correct behavioral performance was associated with high activity at posterior- and low anterior topographies, as well as with high beta power in general cognitive and executive functioning. Hence, the results speak in favor of an age-related failed compensation. By providing a synopsis of age-related EEG changes, this study extends previous findings and opens new prospects in understanding aging in reactive control.

INTRODUCTION

We are currently facing periods of demographic change, which are characterized by pronounced aging due to higher life-expectancy worldwide (United Nations Development Programme, 2004). While analyzing the implications for health management, a crucial aspect is the cognitive decline associated with aging. Affected domains are for instance episodic memory (Glisky, Rubin, & Davidson, 2001), processing speed (Salthouse, 1996), and executive functions (EFs) (Kramer, Hahn, & Gopher, 1999; Bialystok, 2006; Watson et al., 2010). EFs are defined as a bundle of higher functions controlling lower functions. Of those, motor inhibition, conflict monitoring, memory updating and task switching are the most important and most independent functions (Miyake et al., 2000; Brydges et al., 2014; Adrover-Roig, Sesé, Barceló, & Palmer, 2012). EFs are regarded as especially imperative for success in daily life since they enable adaptive goal-oriented behavior (Seiferth et al., 2007). In terms of aging, declines of EFs are known to reduce the success in everyday activities (Vaughan & Giovanello, 2010) and to narrow the functional status in older adults (Bell-McGinty et al., 2002). Thus, it is clearly apparent, that the investigation of age-related changes in executive functioning and its underlying neural mechanisms is imperative in order face the challenges of main trends in society.

Age-related cognitive decline has frequently been associated with brain changes such as reduced brain weight and volume (e.g., van Petten et al., 2004). White matter integrity of axonal bundles has been shown to be decreased mostly in frontal regions (Moseley, 2002; Pfefferbaum et al., 1994) and has been associated with poorer EF performance (Grieve, Williams, Paul, Clark, & Gordon, 2007). The network implementing EFs seems to be affected alike, as observed in grey matter declines of the highly interconnected midcingulate cortex (MCC) (Mann et al., 2011), which is considered as a network hub (Cavanagh, et al., 2012). It therefore comes as no surprise that apart from structural changes, functional changes take also place in aging. One of the most prominent observations in cognitive neuroscience and biopsychology is the reduced hemispheric asymmetry (Cabeza et al., 2002), and the posterior-anterior shift (PASA) (Davis et al., 2008). The latter reflects higher prefrontal activity in older participants than in younger subjects (e.g., review Grady, 2012), as it was shown via functional magnetic resonance imaging (fMRI). Interestingly, the anterior shift has also been reported in task switching (e.g., Hakun et al., 2015), which represents a single EF enabling a flexible shift of cognitive tasks and is triggered by a diversity of stimuli in order to reach goals in everyday tasks (Monsell, 2003). Although the anterior shift has been a known fact for a long time, it is yet outstanding under which constellations this phenomenon represents successful, attempted, or failed compensatory mechanisms or even neural inefficiency (e.g., Reuter-Lorenz & Park, 2014), as this depends on the experimental task, the cognitive function, as well as on the structural and functional brain characteristics. Thus, studies combining the investigation of functional, structural and behavioral changes can be considered as a significant step towards addressing this issue.

One of the few studies combining corresponding methods as fMRI and diffusion tensor imaging (DTI), have brought mechanisms as reduced inter-hemispheric prefrontal signaling into play. As such, Zuh et al. (2015) studied task switching with fMRI-DTI in a cross-sectional study. Thereby they observed lower integrity of white matter paths connecting frontal brain structures, which in turn reflected enhanced activity in elderly compared to younger participants. In a longitudinal study with elderly, Hakun and colleagues (Hakun et al., 2015) measured fMRI-DTI even twice. At the second measurement after three years, they reported increased activations in the prefrontal cortex (PFC) during task switching compared to the first measurement. These changes were furthermore associated with declines of white matter integrity in the corpus callosum, the fiber bundle connecting the PFC of both hemispheres. Interestingly, increased activity in the left ventro-lateral PFC was associated with increased response latencies. Thus, such PFC activity changes have been interpreted as functional attempts to overcome structural declines underlying brain communication. Concerning the interpretation of these observations, different concepts emerged, such as the compensation-related utilization of neural circuits hypothesis (CRUNCH) and the scaffolding theory of aging and cognition (STAC) (Reuter-Lorenz & Park, 2010. However, dysfunctional accounts point to declines in regional functional specificity and age-related reductions in efficiency (Rypma & D'Esposito, 2000). Nevertheless, from fMRI it is not clear which stages of information processing and evaluation are affected, as this method has a relatively low time resolution compared to the fast brain dynamics during neural communication.

Interestingly, with electro-encephalography (EEG), a method with high temporal resolution, age-related anterior shifts have also been observed. These include event-related potentials (ERPs), of which the P300 has received a lot of scientific attention. Although there is much debate on what the P300 is exactly reflecting, there is broad scientific consensus that this potentially indexes aspects of cognitive information processing. Mostly in oddball tasks, the anterior shifts of the P300 have been observed (e.g., Friedman, Nessler, Johnson, Ritter, & Bersick, 2008). Apart from that, further age-sensitive P300 aspects are known. Among those are the P300 latency prolongations with age (Rossini et al., 2007), age-amplitude correlations of the posterior P300 (Walhovd & Fjell, 2001), and even age-related associations of amplitude reduction and poor performance (Ashford, Coburn, Rose, & Bayley, 2011). In a meta-analytic study, van Dinteren et al. (2014b) considered latency, amplitude and behavior in auditory oddball tasks, and modeled the parietal P300 development by curve fitting procedures across the whole lifespan. A P300 amplitude maximum was reported around the age of 21, which was followed by a pronounced amplitude decrease, but accompanied with stable behavioral performance. Based on the assumption that the frontally measured P300 would reflect compensatory mechanisms by frontal networks, van Dinteren and colleagues combined the parietal with anterior P300 trajectories in a following large cross-sectional investigation (van Dinteren et al., 2014a). It turned out that the anterior P300 peaked much later with 46 years on average, and more importantly that a joined consideration of the anterior and posterior P300 trajectory is better in explaining behavioral performance across life. Against this background the P300 may indeed reflect an index of neurocognitive aging as already suggested by Polich in 1996 (Polich, 1996).

Crucially, concerning EFs and more precisely with task switching, age-related posterior-anterior P300 shifts have also been reported (Kopp, Lange, Howe, & Wessel, 2014; Whitson et al., 2014). However, here much less is known about the neural mechanisms underlying cognitive aging. Furthermore, the P300 has not been the only positivity in focusing on cognitive aging. Later positivities peaking around 600-800 ms after stimulus onset, as well as sustained positivities have also been shown to be affected by age and were demonstrated to play important roles during task switching (e.g., Adrover-Roig & Barceló, 2010; Karayanidis et al., 2011).

However, it is important to note that EEG parameters like ERPs, which are measured at different electrode locations, reflect a composition of multiple dynamics of temporally and regionally overlapping, and functionally separable sub-processes (Arieli et al., 1996; Kiehl et al., 2005). ERPs thus mirror cumulative neural activation related to multiple processes involved in stimulus processing and evaluation (e.g., Luck, 2005). EEG-decomposition by time-frequency reveals synchronous processes that are supposed to coordinate neuronal spiking between and within brain circuits, namely the so-called brain oscillations that link neural activity with behavior and thoughts (e.g., Buzsáki et al., 2001). Mainly because of anatomical constraints as slow axon conduction velocity, lower frequency bands are predestinated for neural communication between long-distance brain areas and higher frequencies for local communication (Varela et al., 2001; Buzsáki & Watson, 2012). Every ERP component can thus be regarded as event-related oscillations (ERO) of a single frequency or a superposition of multiple EROs with different frequencies. Interestingly, brain oscillations are suggested to be physiologically better interpretable than conventional ERPs, as higher accuracies are demonstrated in predicting subject's behavioral performance (e.g., Cohen & Donner, 2013). Concerning brain oscillations and aging, scientific literature reports of changes in the peak and amplitude of oscillations in the alpha (Klimesch, 1999), beta- (Karrasch et al., 2004), as well as theta/delta band (Kardos et al., 2014; Schmiedt-Fehr & Basar-Eroglu, 2011; Cummins & Finnigan, 2007). Specifically, age-related changes regarding event-related frontal-midline (fm) theta is in focus, since these oscillations have been proposed as a neural working language of EFs and are generated in the MCC (Cavanagh et al., 2012). Fm-theta oscillations have been furthermore shown to fall into the time-range of ERPs associated with EFs such as the N200/P300 complex (Huster et al., 2013; Nigbur et al., 2011; Başar-Eroglu et al., 1992).

Anyhow, in order to tackle the underlying independent networks, that are involved in the generation of ERPs, a powerful tool for the decomposition of EEG data is the blind source separation by means of independent component analysis (ICA) (Bell & Sejnowski, 1995). ICA solves a two-dimensional linear mixing problem of spatially and/or temporally independent sources. Applied to EEG data, ICA thus identifies functionally coherent brain networks (Hyvärinen, 2013). In this way, Debener et al. (2005) demonstrated the involvement of different brain sources to the novelty P3, which fits to findings from intracranial, lesion and fMRI-EEG studies (Linden, 2005), as well as studies with low resolution electromagnetic tomography all pointing toward multiple neural generators of the P300 (Mulert et al., 2004). Regarding an attention switch paradigm, Onton et al. (2006) demonstrated that the P300 consisted of multiple underlying independent components. Hence, the application of ICA methods in EEG is a well-suited informative approach regarding the investigation of functional connectivity, tracking fast brain dynamics at different stages of processing rather than only the final end results.

However, the basic ICA model applies to single subject data and is limited in typical multi-subject EEG studies as it has to resolve generalization questions from single subject to a group level. While clustering techniques come with the challenge of an increased likelihood of equivocal results due to differences in the selection of algorithms, feature selection and the user bias, group-ICA seem to reflect a much more parsimonious approach to match independent components across individuals (Calhoun et al., 2009; Eichele et al., 2011; Huster et al., 2015). By the usage of the group-ICA approach, data containing observations from all subjects are aggregated, and components are estimated that are consistently expressed across subjects. Especially in context of subjects that are known to show differences in ERPs and are therefore also expected to differ concerning the components due to age-related changes, group-ICA reflects an appropriate and powerful tool.

The aim of the current study was to systematically investigate, for the first time, the independent functional networks underlying positivities at different levels (ERP, EROs) by performing a group-ICA to obtain a more complete delineation of aging effects in set-shifting. Therefore, we tracked the EEG of three different age groups, namely a young, a mid-aged and an elderly group while they were performing a switch task, which required the categorization of Gabor stimuli regarding color and thickness. Concerning the behavioral performance, we expected the known slowing effects of RTs mainly in conditions demanding EFs, as reflected in the mixed-tasks block, which requires the switch between two categorizations, as compared to the single-task block without switching. Additionally, higher costs such as mixing, restart, and local switch costs were anticipated with increasing age. As ERPs measured at the scalp surface are known to reflect cumulated neural activation related to multiple processes, we expected several independent components underlying the known positivities. Based on the compensation theories, successful age-related compensations would be reflected in increased frontal activation and improved performance, attempted compensation by an anterior shift without effects on behavior, and failed compensation or dys-functioning by an increased frontal activation associated with reduced behavioral performance (see review Grady, 2012). Along with this, we expected reduced amplitudes of the positivities based on oscillatory changes, most of all in fm-theta as neural working language of EFs. This study makes a major contribution to research on age-related neurocognitive changes by integrating previous findings with the outcome of the current investigation of functional networks which are revealed by EEG and its brain-behavior associations in a complex highly demanding cognitive function.

METHODS

Participants

30 young (20 female, mean age: 21.2 years, SD: 2.5 years), 30 mid-aged (17 female, mean age: 53.6 years, SD: 2.9 years), and 30 elderly (16 female, mean age: 68.6, SD: 2.4 years) took part in the present study. Participants provided a self-report regarding their neurological and psychiatric conditions. According to the Edinburgh Handedness Inventory (Oldfield, 1971) all participants were right-handed apart from one who was considered to be ambi-handed. All participants had normal or corrected-to normal vision. The participants were recruited via the University of the Balearic Islands and public announcements and gave informed consent prior to study participation. In return for their participation, young participants received course credits or payment (20 Euro), while elderly received a detailed report on their cognitive results. The study was approved by the ethics committee of the University of the Balearic Islands, which is in accordance with the Declaration of Helsinki on good scientific practice. All participants were part of a larger trial examining additionally an Oddball task and a neuropsychological test battery of EFs (e.g., a Stroop test).

Stimuli and task

Participants performed a cued switching task (color/thickness), while seated in a sound and light attenuated cabin. All task stimuli were presented on a 27-inch TFT screen with a viewing distance of 150 cm. Task presentation and performance was controlled by using Presentation (version 0.61, Neurobehavioral Systems). Responses were given with the thumb finger on a two button box. For the color/thickness switching task, a variant of the intermittent-instruction paradigm (Monsell, 2003; Rushworth et al, 2002) was used. Each stimulus had a visual angle of about 1° and consisted of Gabor patches with horizontally oriented gratings that were red, blue or gray and of either four or ten cpd thickness. Participants had to classify the gratings‘ colors into red (right button press) and blue (left button press) or the gratings‘ thickness into thin (right button press) and thick (left button press). Before the start of the experiment, participants received 73 test trials. The experiment consisted of two parts. First, the single-task block was presented, which is not supposed to require EFs at all. Here only the color task had to be performed and gray Gabor gratings had to be ignored. Then, participants continued with the mixed-task block, in which the color and thickness tasks alternated. Tasks were cued by the task-associated orientation of gray colored Gabor patches: horizontal and vertical gratings instructed to repeat or switch the task. Participants started the mixed-task block with the color classification task. Cue-task assignments were counterbalanced across subjects. Participants were instructed to respond as fast and as accurate as possible.

All stimuli were presented on a gray background. Each trial began with the presentation of a Gabor patch displayed for 100 ms either on the left or right of a centrally presented fixation cross, afterwards a gray screen appeared. Participants had to respond within 1200 ms, and whenever their responses were late or wrong or they responded after the cue, a feedback (Spanish "mal" for "wrong" or "tarde" for "too late") was presented for 400 ms. In sum, the stimulus onset asynchrony (SOA) was 1900 ms for correct trials and 2000 ms for incorrect trials. In the single and the mixed-tasks block each, 976 trials were presented within six blocks which were separated by self-paced blocks. All trials were presented on a semi-randomized offline procedure to ensure that in-between the gray Gabor stimuli, four to eight coloured patches were presented.

EEG recording and preprocessing

EEG data was recorded from 60 channels using SynAmps RT amplifiers (NeuroScan, TX, USA). Electrodes were mounted on a flexible electrode cap according to the 10-10 system for electrode placement (Syncamp2 Quickcap, Compumedics, TX). In addition, the electro-oculogram (EOG) was recorded from four channels placed above and below the left eye and on the outer canthi of both eyes. EEG and EOG recordings were taken continuously from 0.05 – 100 Hz bandpass at a sampling rate of 500 Hz. Impendences were kept below 10 kΩ. All data were referenced against the left mastoids, as ground electrode AFz was used.

For pre-processing, the MATLAB (version R2010a) based toolbox EEGLAB (Delorme & Makeig, 2004, version 13.4.4b) was used. First, data was high (50 Hz) and low-pass filtered (0.5 Hz), then down-sampled to 250 Hz, and re-referenced to a common average. ICA (runica algorithm) was used to correct for eye artefacts (Bell & Sejnowski, 1995; Miyake et al., 2000). Components suggesting eye blinks or horizontal eye movements were identified by comparing the independent components (ICs) activity to the eye blink artefacts in the EOG. The corresponding topographical maps of putative ICs had to show a frontal distribution. Eye-blink related ICs were then excluded from back-projection the EEG channels. Next, data was epoched from -1600 ms to 1600 ms relative to stimulus onset and baseline corrected for -200 pre-stimulus to 0 ms. Based on the epoched data, a semi-automatic correction procedure was used to correct for residual artefacts. Single trials crossing a self-set threshold of 60 µV were marked automatically for visual inspection and rejection.

Functional connectivity analysis: Group-ICA

To decompose EEG data into underlying functionally coherent networks, blind source separation was performed by group-ICA using the MATLAB based toolbox GIFT (Eichele et al., 2011). Single subject matrices were therefor adjusted concerning the number of trials, as the group-ICA requires the same number for each subject and condition. A minimum of 40 trials per condition were randomly selected from each subject's available data, leading to a selection of 240 trials per subjects in total. As three subjects showed less trials (< 20) in at least one of the conditions, these were excluded from further analysis. For each subject, data were restricted to a two-dimensional matrix with rows corresponding to channels and columns to the time-course data.

The intrinsic data-dimensionality was estimated based on two approaches. First, a Principal Component Analysis (PCA) on a single subject level suggested a nine or ten model order, explaining more than 95% of the single-subject data. Second, in order to estimate the reliability and stability of group-ICs, the group-ICA algorithm was run 100 times for each of both models using the ICASSO software (Himberg et al., 2004). This procedure revealed the 10 model order as sufficient, reliable and stable.

The group-ICA procedure itself includes two data reduction steps. On a single-subject level, data were pre-whitened and reduced by extracting most relevant and orthogonal time-courses resulting in first-level principal components that were further used as variables in a second, group-level PCA, which in turn estimated the most-relevant and orthogonal principal component time courses capturing the activity patterns correlated across subjects. In a last step, single-subject activations of the group-ICs were reconstructed by matrix multiplication of the weight matrices resulting from the group-ICA.

Time frequency analysis

To analyze the time-frequencies of the ICs, event-related spectral perturbations (ERSPs) were calculated for each trial per IC and subject. ERSPs represent log-transformed changes of power in dB relative to the baseline (Delorme & Makeig, 2004). A Morlet-wavelet was applied with an increasing number of cycles for higher frequencies between 1 and 50 Hz, using a resolution of 150 frequency steps and 300 time point. The number of cycles started at 1 Hz and increased by 0.5 per frequency increase. The average power across the trials was divided by the frequency specific baseline values separately for each frequency to visualize power changes relative to the pre-stimulus activity.

Data analysis: behavioral performance

To investigate the effects of aging on the behavioral performance, mean RTs and accuracies were extracted from the

EEG data using MATLAB for the first and third target position after a gray Gabor stimulus, which itself generally did not require a response. However, depending on the context, the gray Gabor represented either a distractor, which was task irrelevant in the single-task block or two cue types (switch or repeat) indicating the switch or the repetition of the current task classification in the mixed-task block. Further analyses were done in SPSS 15.0 (IBM Corp. Released 2013. IBM SPSS Statistics for Macintosh, Version 22.0. Armonk, NY: IBM Corp). Three types of costs were calculated: first, restart costs, calculated as the RT difference between the first and third target after a cue regardless of the type in the mixed-task block; second, mixing costs were calculated as RT difference between the third targets of the mixed-task block and the third targets in the single-task block; local switch costs were calculated as the difference in the mixed-task block between the first target after a switch and the first target after a repeat cue.

Only correct responses within a correct stream (between two gray Gabor stimuli) of stimuli were taken into consideration. A 3 x 3 x 2 mixed-model ANOVA with the between group factor GROUP (young, mid-aged, elderly), and the two within-group factors TASK-RULE which refers to targets after switch-, repeat-cues or the distractor (switch, repeat, distractor) and POSITION (first, third) was set up for RTs (see Table 1). Further post-hoc tests were calculated as well as effect-sizes by Cohen's d ($M1 - M2 / \sqrt{[(s_1^2 + s_2^2) / 2)}$). Because local switch costs were reversed and appeared as switch benefits, age-related effects were analyzed by independent t-tests. Regarding the remaining costs, a 2 x 3 mixed-model ANOVA with the within-group factor COST-TYPE (restart, mixing) and the between group factor GROUP (young, mid-aged, elderly) was set up. In cases of sphericity violations, Greenhouse–Geisser corrections were performed; corrected p-values as well as ε-values are reported.

Please insert Table 1about here

Data analysis: functional connectivity

Statistical analyses: Topography effects of positivities

To analyze the frontalization effects, values of the weights matrix of the four midline electrode positions were extracted for each participant. A mixed ANOVA with the in-between factor GROUP (young, mid-aged, elderly) and within factor TOPOGRAPHY (FPz, Fz, Cz and Pz) was calculated for each of the ten ICs. An age-related anterior-shift was indicated by decreased activity projections to Pz and increases to more frontal electrodes with the older participant groups. Therefore, only interaction effects of GROUP x TOPOGRAPHY will be reported.

Statistical analyses: independent component's ERPs and ERSP

For each event-related positivity of each ICs, time values of the positivities' peak +/- 50 ms were identified based on grand-means. Regarding the sustained positivity, grand means suggested a large interval between 340 and 940 ms post stimulus. Then, mean ERPs and ERSPs were calculated across trials and extracted for each subject and condition of each IC for the above indicated positivity peak-interval. Delta (1-3.9 Hz), theta (4-7.9 Hz), alpha (8-12 Hz), beta (12.1-29.9 Hz), low gamma (30-40 Hz), and high gamma (40.1-49.9 Hz) frequencies were taken into account. For statistical analyses of ERPs and each frequency, a mixed ANOVA with the in-between factor GROUP (young, mid-aged, elderly), and the two within factors TASK-RULE (switch, repeat, distractor), POSITION (first, third) was performed.

Statistical analyses: brain-behavior associations

In order to assess the associations of neural changes due to age and behavioral performance, a Pearson product-moment correlation was calculated between significant effects concerning ERPs, ERSPs and RTs. To correct for multiple comparisons, a false discovery rate (FDR) correction was applied on the resulting p-values with a FDR rate of $\alpha = .05$.

RESULTS

Behavioral Performance

Concerning all conditions and groups, Table 2 provides the means and standard deviations (SDs) for the RTs, while Table 3 depicts the means and SDs for all costs. As accuracies were all very high (mean across conditions: 0.93, SD: 0.09) these were considered as ceiling effects and excluded from further analysis.

Age-independent characteristics: Typical task-switching behavior was statistically confirmed by a main effect of TASK-RULE ($F_{(2,168)} = 11327$, ε=.993, p<.001). As expected, the fastest RTs were shown in the single-task block (distractor > switch: t(86) = -102.3; p < .001; distractor > repeat: t(86) = -112.3; p <.001). However, RTs of repeat targets were longer than switch targets (repeat > switch: t(86) = 51.9; p < .001), thereby explaining the so-called switch benefits. A further main effect of POSITION ($F_{(1,84)} = 5184$, p < .001) showed the expected slowing effect of RT at the first target position. The two way interaction TASK-RULE x POSITION ($F_{(1,84)} = 207$, ε=.712, p < .001) did not change this picture.

Age-dependent effects: A main effect of GROUP ($F_{(2,84)}$ = 57.4, p < .001) and the expected three-way interaction TASK-RULE x POSTION x GROUP ($F_{(1,84)}$ = 4.43, ε=.095, p < . 01) was observed. The younger showed fastest RTs, RTs mid-aged followed, while the elderly showed longest RTs in all conditions [(young < older group: 1st switch: t(56) = -11.713, p < .001, d = -2.97; 3rd switch: t(56) = -10.886, p < .001, d = -2.83; 1st repeat: t(56) = -12.046, p < .001, d = -3.05; 3rd repeat: t(56) = -9.53; p < .001, d = 2.58; 1st distractor: t(56) = -5.893, p < .001, d = -1.51; 3rd distractor: t(56) = -7.575, p < .001, d = -1.94), (young vs mid-age: 1st switch: t(56) = -4.372, p < .001, d = -1.15; 3rd switch: t(56) = -4.466, p < .001, d = -1.18; 1st repeat: t(56) = -4.209, p <.001, d = -1; 3rd repeat: t(56) = -3.39, p < .001, d = -0.93; 1st distractor: t(56) = -3.034, p <.001, d = -0.8; 3rd distractor: t(56) = -3.448, p <.001, d = -0.85)), (mid-aged < elderly group: 1st switch: t(56) = -8.352, p < .001, d =; -2.18; 3rd switch: t(56) = -7.929, p < .001, d = -2.1; 1st repeat: t(56) = -6.917, p < .001, d = -1.8; 3rd repeat: t(56) = -8-.47, p < .001, d = -2.25; 1st distractor: t(56) = -6.829, p < .001, d = -1.58; 3rd distractor: t(56) = -8.701, p < .001, d = -2.28)]. Thus, based on the effect size differences of Cohen's d, differences between the young and both older groups were strongest in the conditions requiring EFs (mixed-task block: switch and repeat) and less in the conditions of the single-task block.

Please insert Table 2 about here

A main effect of COST-TYPE ($F_{(2,168)}$ = 7240.538, p < .01) was revealed. Mixing cost were significantly larger than restart costs (t(86) = 66.079, p < .001). A further main effect of GROUP ($F_{(2,84)}$ = 16.603, p < .001) showed that elderly showed higher costs than the younger (t(56) = -2.656, p <.05) and the mid-aged (t(56) = -3.336, p < .01). Switch benefits were investigated separately by independent t-tests, which revealed that the elderly did not benefit as much as compared to the mid-aged (t(56) = -2.715, p <.01) and to the youngest (t(56) = -2.972, p <.01).

Please insert Table 3 about here

Functional Connectivity, topography, ERP and ERSPs

General overview: The multi-trial multi-subject EEG decomposition resulted in ten ICs which are characterized by the event-related time-courses, ERSPs and their topographies. Supplementary Figure 1-5 displays an overview of each IC and its features for the young, mid-aged and elderly group. Table 4 summarizes the most important effects. The focus will be put on the positivities, which result as the multiplication of the time-course times the corresponding topography of the specific IC each respectively. Five independent networks were peaking around 300 and 400 ms (IC1, IC2, IC3, IC6, IC7). Two independent networks showed P700s (IC8, IC10), slightly later the P800 was revealed in the network IC4, and the very late P1000 in IC9. IC5 reflected a late sustained positivity (IC5-SP). The ICs which are specifically sensitive to the mixed-task block (EF conditions) were: IC1-P400, IC5-SP, IC8-P700, IC10-P700. IC2-P400 and IC4-P800 were specifically sensitive to the single-task block. A third type of ICs was observed regarding the sensitivity of target positions (IC3-P300; IC6-P400, IC7-P400, IC9-P1000). Time-frequency decompositions of the positivities in each IC revealed sustained delta/theta activity accompanied with activity of higher frequency bands, such as beta and gamma band as reported in Enriquez-Geppert et al. (Enriquez-Geppert, Huster, Figge, & Herrmann, 2014).

Apart from IC3, all independent networks were affected by age. However, age-related posterior-to-anterior shifts were observed in only two networks (IC1, IC2) affecting the P400s. These were accompanied with aging effects in the neural processing reflected in the peak amplitudes of the positivities as well as in the time-frequency decomposition and showed, more importantly, brain-behavior relations. However, other age-related topography effects were observed as well in IC4, IC5, IC8, and IC9. But only IC5 (and IC10) reflected further significant brain-behavior associations. The most consistent time-frequency age related effect was reduced beta power with increasing age (IC1, IC2, IC3, IC5, IC6, IC7, and IC8).

Please insert Table 4 about here

Independent Component 1 exhibits a positivity at about 400 ms (IC1-P400) and a topography with a parietal maximum, which is strongly frontalized in both older groups (see Figure 1).

Age-independent characteristics: Concerning the IC1-P400, a main effect of TASK-RULE ($F_{(2,168)}$ = 55.081, p < .001) was detected. IC1-P400 amplitudes were strongly increased regarding targets of the mixed-task compared to the single-task block (switch > distractors: t(86) = -8.321, p < .001; repeat > distractor: t(86) = -7.745, p < .001). However, the IC1-P400 is furthermore sensitive to the target position (main effect: POSITION $F_{(1,84)}$ = 10.182, p < .001). Amplitudes in the first were stronger than in the third target position (t(86) = -2.924, p < .01).

Time-course effects are accompanied by effects in three frequency domains, which were reflected in a significant main effect of TASK in delta ($F_{(2,168)}$ = 6.738, p < .01), an interaction of TASK-RULE x POSITION in theta ($F_{(2,168)}$ = 3.588, p<.05), as well as two main effects of TASK-RULE ($F_{(2,168)}$ = 4.681, p < .05) and POSITION ($F_{(2,168)}$ = 9.194, p < .01) in beta oscillations.

Age-dependent effects: The age-related frontalization effect is confirmed by an interaction of GROUP x TOPOGRAPHY ($F_{(6,252)}$ = 7.55, p < .001). As expected, the young group showed stronger Pz activity than the elderly (t(56) = -3.37; p < .01). The reversed topography pattern was demonstrated at frontal electrode positions (elderly > younger: Fz: t(56) = 4.94, p <.001; FPz: t(56) = 5.21, p < .001). Interestingly, the mid-aged showed stronger Fz activity compared to the younger (Fz: t(56) = 2.592, p < .05; FPz: t(56) = 2.597, p < .05), while they did not differ concerning Pz. Compared to the elderly, mid-aged revealed stronger Pz activity (t(56) = -2.03, p < .05).

Importantly, the above described time-course effects were strongly affected by age (main effect: GROUP ($F_{(2,84)}$ = 18.448, p < .001). The interaction of TASK-RULE x GROUP ($F_{(4,168)}$ = 3.481, p < .01) and associated post-hoc tests revealed that these effects were driven by reduced amplitudes in the young compared to both older groups in the repeat (young > mid-aged: t(56) = 2.576, p < .05; young >. elderly: (t(56) = 2.508, p < .05) and the distractor condition (young > mid-aged: t(56) = 5.887, p < .001; young > elderly: t(56) = 3.945, p < . 001). Additionally, an POSITION x GROUP interaction was detected ($F_{(2,84)}$ = 9.192, p < .001), which was mainly driven by the mid-aged (t(28) = -3.992, p < .001). Age-related time-frequency effects were revealed by a three way interaction in alpha TASK-RULE x POSITION x GROUP ($F_{(2,168)}$ = 55.081, p < .001). However post-hoc test did not reach significance. Regarding beta oscillations, a main effect of GROUP ($F_{(2,84)}$ = 5.858, p<.01) was detected. The young group showed higher beta power than the mid-aged (t(56) = 3.112, p < .01) and elderly (t(56) = 3.112, p < .01). The mentioned position effect in the beta frequency band was furthermore also affected by age (interaction: GROUP x POSITION, $F_{(2,84)}$ = 4.881, p < .05). Indeed, the position effects were only observed in the younger (t(28) = 2.24, p < .05) and the elderly (t(28) = 3.257, p < .01).

Brain-behavior associations: Further statistical analyses were conducted by taking into account the behavioral results (mean RTs for the switch, repeat and distractor conditions), frontalization effects (activity at Pz, Fz and FPz), IC1-P400 (switch, repeat and distractor amplitudes) and time-frequency effects (high gamma and theta activity in the switch, repeat and distractor condition; mean beta over all conditions). Statistical significant FDR corrected effects are set out in Supplementary Table 1. Interestingly, fast RTs of the switch condition is associated with less activity at Fz (1st position: r = .414, p < .001; 3rd positions: r =.384, p < .001). Further brain behavior associations have been observed in the first target position after repeat, here faster RTs are associated with higher activity at Pz (r = -.389, p < .001), higher general beta power (r = -.402, p < .001) and higher specific beta power in the first target position (r= -.4, p < .001).

Please insert Figure 1 about here

Independent Component 2 depicts a positivity at about 500 ms (IC2-P500) that is augmented by targets in the single-task block. Its topography exhibits a parietal maximum, which is frontalized in both older groups (see Figure 1).

Age-independent characteristics: The IC2-P400 reflected a main effect of TASK-RULE ($F_{(2,168)}$ = 336.334, p < .001), that was explained by stronger amplitudes of targets after distractors in relation to targets in the switch (t(86) = -10.35, p < .001) or repeat conditions (t(86) = -11.37, p < .001), which both nearly did not reflect a positivity at all. Furthermore, delta and high gamma oscillations revealed a main effect of TASK-RULE (delta: $F_{(2,168)}$ = 17.49, p<.001; high gamma: $F_{(2,168)}$ = 3.073, p<.05) and theta oscillations an interaction of TASK-RULE x POSITION ($F_{(2,168)}$ = 4.992, p<.01).

Age-dependent effects: The frontalization effect was statistically confirmed by an interaction of GROUP x TOPOGRAPHY ($F_{(6,252)}$ = 3.803, p < .001). As expected, young participants showed stronger Pz activation than the elderly (t(56) = 2.657, p < .05). At frontal electrode positions (FPz, Fz), amplitudes are stronger for the elderly compared to the younger (FPz: t(56) = -2.642, p < .05; Fz: t(56) = -3.283, p <.01). However, trends reflecting slight differences between the mid-aged and elderly are apparent at frontal electrodes (FPz: t(56) = -1.9, p = .063; Fz: t(56) = -1.8, p = .077). Age-dependent effects were furthermore reflected in the beta oscillations by a main effect of GROUP ($F_{(2,84)}$ = 9.256, p<.001). Younger participants elicited higher beta power than the mid-aged (t(56) = 3.069, p < .01) and elderly (t(56) = 4.091, p < .001).

Brain-behavior associations: Based on the significant behavioral results (mean RTs for the switch, repeat and distractor condition), frontalization (topography values at Pz, Fz and FPZ), IC2-P400 (switch, repeat and distractor amplitudes) and time-frequency effects (mean beta over all conditions), further statistical analyses were conducted. Statistical significant FDR corrected correlations are summarized in Supplementary Table 1. It is shown that faster

RTs are associated with increased beta (correlations are between -.49 > r -.34, all $p < 0.001$) activity in all conditions and increased amplitudes at Pz (correlations are between -.31 > r -.25, all $p < 0.001$). However, the slowing of RTs was associated with increased amplitudes measured at frontal electrode positions FCz and Fz (correlations are between .39 > r .23, all $p < 0.001$).

Independent Component 3 exhibits a positivity at about 300 ms (IC3-P300), which is sensitive to the target position in the mixed-task block and has a frontal age-independent topography (see Figure 2).

Age-independent characteristics: IC3-P300 effects were revealed concerning two main effects of TASK-RULE ($F_{(2,168)} = 11.717$, $p < .001$) and POSITION ($F_{(2,168)} = 11.613$, $p < .001$), as well as the interaction of TASK-RULE x POSITION ($F_{(2,168)} = 8.03$, $p < .001$). Higher amplitudes of the first position targets compared to the third were observed in the mixed-target block only (switch: $t(86) = -3.737$, $p < .001$; repeat: $t(86) = -3.75$, $p < .001$) .

The time-course effects were reflected in theta oscillations. Two main effects of TASK-RULE ($F_{(2,168)} = 3.79$, $p <. 05$), POSITION ($F_{(2,168)} = 5.19$, $p < .05$), as well as an interaction of TASK-RULE x POSITION ($F_{(2,168)} = 5.268$, $p < .01$) were revealed. However, also delta oscillations demonstrated a main effect of TASK-RULE ($F_{(2,168)} = 4.45$, $p < .05$), while beta showed a main effect of POSITION ($F_{(1, 48)} = 27.26$, $p < .001$). Concerning alpha oscillations a main effect of POSITION ($F_{(1,84)} = 8.35$, $p < .01$) and the interaction TASK-RULE x POSITION ($F_{(4,168)} = 34.622$, $p < .01$) was detected.

Age-dependent effects: IC3 reflected differences regarding beta oscillations as demonstrated by the main effect of GROUP ($F_{(2,84)} = 6.031$, $p < .01$). Younger participants demonstrated higher beta power than mid-aged ($t(56) = -3.377$, $p < .001$) and elder participants ($t(56) = 3.122$, $p < .01$). No significant correlations between brain activity and behavioral performance were detected.

***Independent Component* 4** reflects a late positivity at about 800 ms (IC4-P800), which is mainly enlarged by targets in the single-task block. This component is characterized by a fronto-central topography that is increased in amplitude with increasing age (see Figure 2).

Age-independent characteristics: A main effect of TASK-RULE ($F_{(2,168)} = 99.83$, $p < .001$) indicated highest amplitudes in targets of the single-task block (distractor > switch: $t(86) = -12.06$, $p < .001$; distractor > repeat: $t(86) = -11.52$; $p < .001$). An interaction of TASK-RULE x POSITION ($F_{(2,168)} = 3.8$, $p < .05$) revealed that position differences were mainly driven by the repeat condition ($t(86) = -2.78$, $p < .01$).

Time-course effects were accompanied by oscillatory effects in the delta frequency (main effects TASK: $F_{(2,168)} = 19.043$, $p<.001$, POSTION: $F_{(1,84)} = 5.857$, $p < .05$, and an interaction TASK-RULE x POSITION: $F_{(2,168)} = 6.146$, $p < .01$), as well as in the beta frequency range (main effect of TASK: $F_{(2,168)} = 4.028$, $p < .05$, POSITON: $F_{(1,84)} = 22.25$, $p<.001$; and an interaction of TASK-RULE x POSITION: $F_{(2,168)} = 3.107$, $p < .05$).

Age-dependent effects: The age-related topography effects were reflected by a significant interaction of GROUP x TOPOGRAPHY ($F_{(6,252)} = 2.778$, $p < .05$). The elderly showed stronger Cz activity than the younger ($t(56) = -1.8$, $p < .05$). A trend for stronger activity of mid-aged compared to younger was also apparent ($t(56) = -1.7$, $p = .095$).

The age-related effects in the IC4-P800 were reflected by a main effect of GROUP ($F_{(2,84)} = 3.42$, $p<.05$) and an interaction of GROUP x POSITION ($F_{(2,84)} = 5.59$, $p < .01$). Elderly showed generally reduced IC4-P800 amplitudes in the third target position compared to younger ($t(56) = 5.41$, $p < .001$) and mid-aged ($t(56) = 3.59$, $p < .01$).

Interestingly, age-related effects were observed in low gamma oscillations and were reflected by a three-way interaction of TASK-RULE x POSTION x GROUP ($F_{(4,168)} = 2.882$, $p < .05$). However, post-hoc tests did not reach significance.

Please insert Figure 2 about here

Independent Component 5 mirrors a late sustained positivity (IC5-SP) which is augmented in third target positions of the mixed-task block. The component shows age-related frontal to central topography shifts (see Figure 2).

Age-independent characteristics: The sustained positivity of IC5 is modulated by target positions (main effects: POSITION $F_{(1,84)} = 182.597$, $p<.001$). Only third position targets elicited positivities (mean= .87µV) at all, while first position targets let to negativities (mean=.-7 µV; $t(86) = 13.05$, $p < .05$). A further main effect of TASK-RULE ($F_{(2,168)} = 9.092$, $p<.001$) revealed that switch targets elicited higher activity than repeat ($t(86) = -3.7$, $p < .05$) and distractor targets ($t(86) = -4.13$, $p < .05$). Post-hoc results of the interaction TASK-RULE x POSITION ($F_{(2,168)} = 3.93$, $p<.05$) did not change the described picture ($1^{st} > 3^{rd}$ switch: $t(86) = -5.712$, $p < .001$; $1^{st} > 3^{rd}$ repeat: $t(86) = -7.2$, $p < .001$; $1^{st} > 3^{rd}$ distractor: $t(86) = -3.175$, $p < .01$). Amplitude effects were accompanied by main effects of TASK-RULE ($F_{(2,168)} = 8.809$, $p < .001$), POSITION ($F_{(1,84)} = 7.063$, $p < .01$) and the interaction TASK-RULE x POSITION ($F_{(2,168)} = 3.87$, $p<.05$) in the slow delta oscillations. Similar beta frequency effects were revealed by a main effects of TASK-RULE ($F_{(2,168)}$ = 9.553, p<.01) and POSTION ($F_{(1,84)}$ = 23.046, p < .001).

Age-dependent effects: Age-related topography maxima shifts from frontal to central were confirmed by a significant interaction of GROUP x TOPOGRAPHY ($F_{(6,252)}$ = 3.83, p<.01). Younger showed significantly higher activity at FPz (t(56) = 2.24, p < .05), less activity at Cz (t(56) = -1.8, p < 0 .01) and Pz (t(56) = -3.46, p < .01) than elderly. Similarly, mid-aged participants showed less activity at Pz (t(56) = -2.04, p < .05) compared to the elderly. Concerning the IC5-SP, the position effects were affected by age (interaction: GROUP x POSITION ($F_{(2,84)}$ = 4.12, p<.05). In elderly no position differences were revealed in the distractor condition, and only a trend was shown in the mid-aged (t(86) = -2.007, p = .055). Interestingly, age-related effects were revealed in beta oscillations by a main effect of GROUP ($F_{(2,84)}$ = 7.699, p < .01). Higher beta power was observed in younger compared to the mid-aged (t(56) = 2.801, p < .01) and elderly (t(56) = 3.828, p < .001).

Brain-behavior associations: Further statistical analyses were conducted by including significant results in behavior (mean RT for the switch, repeat and distractor condition), concerning topography effects (topography values at Pz, Fz and FCz), and regarding IC5-SP (first and third target amplitudes) as well as time-frequency effects (mean beta over all conditions). Statistical significant FDR corrected effects are summarized in Supplementary Table 1. In all conditions, faster RTs are highly correlated with increased beta power and increased activity at FCz, while slower RTs are correlated with reduced activity at Pz. Furthermore, slower RTs in the first position targets of the mixed-task block (switch, repeat) were correlated with increased amplitudes of the IC-SP in the first target position.

Independent Component 6 depicts a relatively early positivity at about 300 ms (IC6-P300) with an age-independent frontal topography (see Figure 3).

Age-independent characteristics: No statistical significant effects were revealed in the time-course, however analysis on ERPs revealed an interaction of TASK-RULE x POSITION ($F_{(2,168)}$ = 3.933, p < .05) in theta, and a main effect of POSTION ($F_{(1,84)}$ = 14.507, p < .001) in beta oscillations.

Age-dependent effects: Age-related effects were revealed in theta oscillations. Planned comparisons revealed expected higher theta power of younger participants compared to mid-aged participants when they had to switch tasks (S1 effects: t(56) = 2.735, p < .01). However, also beta oscillations revealed a main effect of GROUP ($F_{(2,84)}$ = 5.835, p<.01). Younger elicited higher beta power than mid-aged (t(56) = 2.142, p < .05) and elderly (t(56) = 3.178, p < .01). Further age-related effects were revealed in low gamma (interaction of TASK-RULE x GROUP: $F_{(4,168)}$ = 3.152, p < .05), which was driven by group differences between the young and the elderly in the distractor condition (t(56) = -2.135, p < .05). Young participants showed less low gamma power than the elderly. Finally, compared to mid-aged participants the elderly showed also lower low gamma power, but in the switch condition only (t(56) = 2.663, p < .05). There were no further significant correlations between brain activity and behavioral performance.

Please insert Figure 3 about here

Independent Component 7 reflects a further positivity at 400 ms (IC7-P400) related to first position targets with an age-independent weak central topography (see Figure 3).

Age-independent characteristics: Concerning the time-course of the IC7-P400 a main effect of POSITION ($F_{(1,56)}$ = 18.737, p < .001) was detected. First position targets elicited a P400 at all (t(86) = 2.982, p < .01). However, an interaction of TASK-RULE x POSITION ($F_{(2,112)}$ = 6.434, p < .01) and post-hoc tests revealed, that this effects was mainly driven by the position differences between repeat targets (1^{st} repeat vs 3^{rd} repeat: t(57) = 5.08, p < .001). Concerning ERSPs main effects of TASK-RULE was revealed in delta ($F_{(2,168)}$ = 6.74, p < .01), and in beta oscillations ($F_{(2,168)}$ = 4.681, p < .05) and a further main effect of POSTION ($F_{(2,168)}$ = 9.194, p < .01) in beta oscillations. Furthermore, an interaction of TASK-RULE x POSITION was shown in the theta ($F_{(1,84)}$ = 3.588, p < .05) domain as well.

Age-dependent effects: In terms of the IC7-P400 an interaction of TASK-RULE x GROUP ($F_{(2,112)}$ = 3.393, p < .05) was found. Concerning the alpha oscillations an interaction of TASK-RULE x POSTION x GROUP ($F_{(4,168)}$ = 2.788, p < .05) was also detected. With respect to beta, a main effect of GROUP ($F_{(2,84)}$ = 5.858, p < .01) was detected with the typical effect of higher beta power in young compared to the mid-aged (t(56) = 2.481, p < .05) and elderly (t(56) 3.327, p < .01). Further, an interaction of POSITION x GROUP ($F_{(2,84)}$ = 4.881, p < .05) showed that the effect described before, was observed identically in the first target position, however in the third position, there was no such difference between the young and the mid-aged subjects (1^{st} beta position: young vs. mid-aged: t(56)=3.736, p < .001; 1^{st} beta: young vs. older group: t(56) 3.921, p < .001; 3^{rd} beta position: young vs. older group: t(56) = 2.16, p < .05). Apart from that differences regarding high gamma oscillation were observed (interaction: POSTION x GROUP ($F_{(2,84)}$ = 4.728, p < .05; TASK-RULE x POSITION x GROUP $F_{(4,168)}$ = 2,49, p < .05). No correlations between brain activity and behavioral performance were detected.

Independent Component 8 This network shows a late positivity about 700 ms (IC8-P700) that is apparent in the mixed-task block. Its topography shows a central maximum, which is accompanied by an additional effect at fronto-central positions in young participants only (see Figure 4).

Age-independent characteristics: The task effect of the IC8-P700 is confirmed by a main effect of TASK-RULE ($F_{(2,168)}$ = 86.172, p < .001). Targets in the mixed-task block elicited the IC8-P700 at all, the repeat condition elicited strongest amplitudes (repeat > switch: t(86)= 6.711, p < .001; repeat > distractor: t(86) = -10.9, p < .001), followed by the switch condition (switch > distractor: t(86) = -6.347, p < .001). Additionally a main effect of POSTION ($F_{(1, 84)}$ = 11.503, p < .01) was observed which was explained by stronger amplitudes in the first position compared to the third (t(86) = 2,955, p < .01). These effects were reflected in the beta and delta oscillations which showed the same main effects of TASK-RULE (delta: $F_{(2,168)}$ = 3.584, p < .05; beta: $F_{(2,168)}$ = 9.642, p < .001), and POSTION (delta: $F_{(1,84)}$ = 5.297, p < .05; beta: $F_{(6,252)}$ = 29.179, p < .001). However, alpha oscillations were also sensitive to TASK-RULE as revealed by the according main effect ($F_{(1, 84)}$ = 4.357, p < .05).

Age-dependent effects: Age-related topography effects were confirmed by a significant interaction of GROUP x TOPOGRAPHY ($F_{(6,252)}$ = 3.95, p < .01). Younger subjects showed stronger frontal activity than elderly (FPz: t(56) = 2.95; p < .01; Fz: t(56) = 3.39, p < .01) and mid-aged (FPz: t(56) = 3.115, p < .01) Fz: t(56) = 3.25, p < .01). IC8-P700 is affected by several interactions as TASK-RULE x GROUP ($F_{(4,164)}$ = 8.115, p < .001), POSITION x GROUP ($F_{(2,84)}$ = 14.642, p < .001), and the three-way interaction TASK-RULE x POSITION x GROUP ($F_{(4,168)}$ = 3,426, p < .05). Regarding the ERSPs, alpha reflected an interaction of TASK-RULE x GROUP ($F_{(4,168)}$ = 2.901, p < .05). Furthermore, beta showed a main effect of GROUP ($F_{(2,84)}$ = 3.319, p < .05), the younger showed higher beta power only compared to the mid-aged (t(56) = 2.806, p < .01). No significant correlations were found between brain activity and behavioral performance.

Independent Component 9 is characterized by an enhancement at 1000 ms post stimulus (IC9-P1000), reflecting high amplitudes related to the third target positions. The topography reflects age-related differences; increasing age leads to increased parietal activity (see Figure 4).

Age-independent characteristics: Time-course effects were observed regarding a main effect of TASK-RULE ($F_{(2,164)}$ = 14.726, p<.001), both conditions of the mixed-task block elicited higher amplitudes than the single-task block (switch > distractor: t(86) = 5.541, p < .001; repeat > distractor: t(86) = 4.041, p < .001). Additionally, the main effect POSTION ($F_{(1,84)}$ = 27.078, p < .001) reflected higher amplitudes in the third target position compared to the first (t(86) = -7.571, p < .001).

Age-dependent characteristics: Age-related topography effects were demonstrated by a significant interaction of GROUP x TOPOGRAPHY ($F_{(6,252)}$ = 4.084, p < .01). Interestingly, elderly and mid-aged participants showed stronger amplitudes at Cz and Pz (Cz: elderly > younger: t(56) = -3.318, p < .01, PZ: elderly > younger; t(56) = -3.566, p < .01; Cz: mid-aged > younger: t(56) = -2.196, p < .05; Pz: mid-age > younger: t(56) = -2.082, p < .05) compared to young participants.

Brain-behavior associations: Significant behavioral results (mean RTs for the switch, repeat and distractor condition) and topography effects (topography values at Pz, Cz) were taken into account for statistical analyses of correlations. Statistical significant FDR corrected effects are summarized in Supplementary Table 1. Faster RTs are associated with decreased activity at Pz in all conditions. Short RTs of the mixed-task block (switch, repeat) are furthermore associated with decreased activity at Cz.

Please insert Figure 4 about here

Independent Component 10 reflects a later positivity at 700 ms (IC10-P700), which is enhanced after first position targets in the mixed-task block. IC10-P700 has a parietal age-independent topography (see Figure 3).

Age-independent characteristics: IC10-P700 effects were confirmed by a main effect of TASK-RULE ($F_{(2,168)}$ = 43.567, p < .001). The switch condition elicited strongest amplitudes, followed by the repeat condition, whereas distractor targets reflected the weakest amplitudes (switch > repeat: (t(86)= -4.534, p < .001): switch > distractor (t(86) = -9.491, p < .001) : repeat > distractor (t(86) = -4.662, p < .001). However, a further main effect of POSTION ($F_{(1,84)}$ = 141.473, p < .001) demonstrated that targets of the first position generally elicited higher amplitudes than targets of the third position (t(86)= -11.760, p < .001). Additionally, an interaction was detected TASK-RULE x POSTION ($F_{(4,168)}$ = 1.136, p < .01). The main effect of TASK-RULE was furthermore observed in beta ($F_{(2,168)}$ = 7.002, p < .01), and high gamma ($F_{(2,168)}$ = 4.619, p < .05) oscillations. The main effect of POSITION was only reflected in beta oscillations ($F_{(1,84)}$ = 11.444, p < .01).

Age-dependent effects: Main effects of GROUP were revealed in the slow oscillations: delta ($F_{(2,84)} = 6.27$, $p < .01$) and theta ($F_{(2,84)} = 4.427$, $p < .05$). Interestingly, young participants showed lower power than mid-aged (delta: $t(56)= -3.575$, $p < .01$; theta: $t(56)= -3.146$, $p < .01$). No brain-behavioral associations were observed.

DISCUSSION

The current study extends previous findings on task switching and aging by drawing for the first time a critical line between topographies (FPz, Fz, Cz, Pz) and source space (ICs), as well as between prominent ERPs (e.g., P300) and certain less known underlying mechanisms of brain communications as reflected in EROs (from delta to gamma band). By further assessing brain-behavior relations, we open new prospects in understanding aging in reactive control. Concerning the general behavioral performance, the expected step-wise decline in aging was observed most pronounced in conditions that require EFs. Mixing and restart costs and switch benefits were similarly affected. As a main result of group-ICA, a total ten functionally independent networks were identified during set-shifting. Each had a distinctive frequency profile and different sensitivity to the experimental conditions and age. As expected, several ICs peaked at about 300/400 ms, few more at 700/800 ms, one peaked at 1000 ms and another reflected a sustained late activity. Surprisingly, nearly all networks were affected by age as reflected by reduced amplitudes of the positivities and decreased power in different frequency bands. Although these age-related changes included also the expected theta reduction, the beta frequency was commonly affected. Most importantly, two of these networks (IC1, IC2) showed the expected posterior-to-anterior age-related topography shift which was associated with decreased behavioral performance. In the following, the two main findings concerning the topography shifts and the age-related beta power reductions will be discussed in more detail before the less known phenomenon of switch benefits will be outlined.

One of the most interesting finding of the current study is the age-related posterior-to-anterior shift which is observed in two (IC1, IC2) of ten functional networks. The age-related shift in both networks was accompanied by reductions of the P400s' amplitudes, as well as by power decreases in the beta frequency and behaviorally by slowed performance. However, concerning IC1 highest P400 amplitudes were mostly revealed in aspects of reactive control in the mixed-task block (switch and repeat conditions); whilst network IC2 reflected its highest ERP peaks in the single-task block (distractor condition). The P400 in network IC1 might thus rather seem to reflect working memory aspects of EFs or executive attention than specific set-shifting aspects, as the encountered brain-behavior associations hold both for reactive control in targets following switch and repeat cues. The P400 in IC2, however, seems to reflect more general cognitive aspects, since neural functioning is associated to behavioral performance in all experimental conditions. A central issue described in literature is furthermore the interpretation of the topography shift with regard to the brain-behavior links. Here, three aspects are found to be associated with decreased behavioral performance and increasing age: stronger frontal, but reduced parietal activity accompanied with reduced beta power. The current findings support the idea of failed compensation or dysfunctional accounts underlying the implementation of a high-demanding task. The high demands of the color-form switching tasks seem to exceed the resources of both reorganized P400 networks in elder participants (see Reuter-Lorenz & Cappell, 2008). Nevertheless, Grady (Grady, 2012) points out that behavioral performance could be even worse without posterior-to-anterior shifts. In view of the fact that age-related topography shifts are primarily observed in Oddball tasks (e.g., Juckel et al., 2012; O'Connell et al., 2012) both with EEG and fMRI, whereas in complex switching tasks this phenomenon is just recently assessed with fMRI (Hakun et al., 2015a, 2015b), the electroencephalographic investigation provides insightful findings into the timing and type of oscillatory communication and marks on this way a necessary next step.

Interestingly, the observed effects in both networks, IC1 and IC2, may hint to a different trajectory of neural changes during aging regarding the topography shifts and oscillatory power changes. With regard to the EF-related network IC1, the posterior-anterior shift is revealed in the mid-aged by increased frontal activity, which is observed additionally to the pronounced posterior activity. Further topography changes are visible in the elderly, the former posterior activity is considerably reduced and a marked frontal topography evolved. In contrast, the anterior-shift to a central topography maximum in IC2, which reflects general cognitive processes, might evolve later, as these deviations were only apparent between the youngest and oldest group. With regard to the oscillatory changes, beta power reductions seem to rather emerge earlier in life and especially before 50 years of age in both networks IC1 and IC2, since a marked divide is already evident between the young and the mid-aged group, whereas both older groups cannot be distinguished. Thus, in this cross-sectional study, reduced neural communication in the beta frequency range is observed before topographical reorganization in the subsequent course of development. These two effects contribute in the end to less efficient neuronal processing. Importantly, in both functional networks fast correct behavioral performance is firstly associated with high posterior activity and low anterior positivity as reflected in the

topographies, and secondly also with high beta power.
Nevertheless, the observation of further topography effects with increasing age should be mentioned. Age-related augmented central activity is, for instance, visible in functional network IC4, which includes a positivity peaking at 800 ms. Additionally, IC8 reflects vanished anterior activity with advance aged. Further brain –behavior associations were detected in IC5 and IC9. In IC5, which comprised a sustained positivity beginning at about 600 ms, an age-related central shift was identified. IC9, which included a late positivity complex, reflected increased parietal activity with increasing age. These results demonstrate that age-related changes affect different processing stages and include also later stages of information processing.

Further remarkable observations that emerges from the EEG decomposition into EROs are the age-related beta reductions which underlie task switching. The fact, that these beta power reductions were found across most functional networks, fits to findings which show that beta oscillations are observed all over the brain (Uhlhaas, et al., 2008) in all cortical areas and numerous subcortical structures (Uhlhaas & Singer, 2013). Its generation has been linked to Glutamate, NMDA receptor -, and GABAa receptor activity (Traub et al., 2004; Yamawaki et al., 2008). In general, the functional role of beta is less analyzed compared to other frequency bands (see review Huster et al., 2013). Beta oscillations have primarily been associated with somatosensory and motor functions (Pfurtscheller, et al., 1996; Pfurtscheller & Klimesch, 1991, review Kilavik et al., Riehle, 2013). However, concerning the functional role in cognition, beta oscillations have also been linked to working memory and working memory load (Pesonen, et al., 2006; Pesonen et al. 2007) as well as to attention and cognitive control (Stoll et al., 2015). Among others, Tallon-Baudry et al. (2004) demonstrated how large coordination of distributed neural activity in two sites over the posterior infero-temporo cortex is synchronized in the beta frequency range during correct trials, which require working memory, whereas synchrony failed with incorrect responses. Similarly, long-range synchronization and beta-band activity has been shown in attention control (Schnitzler & Gross, 2005). Transient long-range phase synchronization in the beta-band has been interpreted as communication within the fronto-parieto-temporal attention network. Interestingly, healthy aging has been related to oscillatory beta responses in working memory (e.g., Karrasch et al., 2004) and to attention, as shown by reduced beta power associated with reduced behavioral performance in older compared younger people (Gola et al., 2012). Pathological aging, nevertheless, stands also in connection with decreased beta power. Missionnier and colleagues (2007) reported, for example, a continued reduction of beta power in progressive mild cognitive impairment as well as in Alzheimer´s disease observed in a two-back task compared to healthy elderly. Along the same line, Kurimoto et al. (Kurimoto et al., 2012) reported reduced beta synchrony in the right central area of patients with Alzheimer's disease during a Sternberg's visual memory task. Hence, the current results add to the growing body of evidence that age-related beta power reductions are not only observable in Sternberg-, n-back- and detection tasks, but also in more complex switching tasks. Taking the above mentioned aspects concerning the brain-behavior associations in IC1 and IC2 into account, beta oscillations may indeed reflect a sensitive marker of rapid cognitive decline as suggested by Missionnier et al. (2007).

Turning to the so-called switching benefits, we observed the expected age-related differences in behavioral performance. However, in the current cued switching task with long cue-task SOAs, we surprisingly found so-called switching benefits instead of (absent) costs. It is a well-known fact, that the increase of SOA reduces switching cost as presented with long SOAs (e.g., 900 ms in Logan & Bundesen, 2003). Such cost reductions are expected in the current design that even includes SOAs of 1900 ms. Nonetheless, the vanishing or reversing of switch costs is less familiar, although already reported earlier in literature (e.g., Cherkasova et al., 2002; Barton et al., 2006, both studies utilized SOAs of 2000 ms). Among others, Hunt and Klein (2002) used a cued pro- and anti-saccadic switching task including long SOAs (200, 500, and 1100 ms) and reported switch costs with the shortest SOA, the vanishing of switch costs in the 500 ms SOA condition and switch benefits with the longest SOA. According to this, they brought up the idea of alertness drifts as a possible explanation for switch benefits. With long SOAs, task reconfigurations may at least be mostly completed before target presentation. In the repeat condition the renewed implementation of the same task set would be faster than in the case of switching. This would lead to an increased likelihood to drift alertness during the cue-target interval of this experimental condition and could subsequently end in increased RTs at the time of the actual target presentation. In contrast, longer lasting task set reconfigurations during the cue-target interval in the switch condition may result in a reduced chance of alertness drifts, which would appear as switch benefits in the end. Such an explanation might seem plausible, but is still rather speculative; anyhow, regardless of the exact source for switching benefits, this phenomenon has been shown to be age-sensitive. Reduced switching benefits in both older groups are possible due to consequences of age-related slowing on reduced alertness drifts when repeating the same task-set.

To conclude, the results of the multisubject decomposition of ERPs in task switching open new prospects in understanding aging in reactive control, but comprise also several implications for future studies related to basic and translational research. A next important step is, for instance, to analyze the associations between reduced neural communication in the beta frequency domain and age-related anatomical changes, similar to Zuh et al. (2015), who combined functional with anatomical data. Interestingly, the usage of DTI (Giorgio et al., 2010)) revealed widespread decrease of white matter microstructure from young adulthood on, including posterior regions such as the splenium of the corpus callosum and the posterior limb of the internal capsule. As it was shown for gamma band activity and the corpus callosum, better myelinated pathways facilitate efficient inter-hemispheric information transfer (Zaehle & Herrmann, 2011). Hence, it yet remains to be investigated whether the integrity of abnormal signal transmission may also be a neuroanatomical prerequisite for efficient synchronization for beta oscillations in general, and further, what specific pathways are associated with beta oscillations in the networks underlying set-shifting. The current study results, thus, offer a starting point for the application of scientific knowledge into health benefits. Although cognitive declines and age-related neural changes are known in older adults, current concepts as the life span theory propose that cognitive enhancement is possible throughout the whole life span (Baltes et al., 2006). The decomposition of EEG into independent neural networks and the analyses of relevant ERPs and EROs, as well as the assessment of brain-behavior relations provide specific neural targets for neuroscientific brain trainings, such as neurostimulation or – feedback, in order to maintain and enhance set-shifting in the elderly.

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TABLE LEGENDS:

Table 1 Overview of the within-factor conditions
This table depicts an overview of all within-factors POSITION, which specifies the exact target position after a cue (1st, 3rd) and TASK-RULE, which instructs participants to switch or repeat the task classification (Switch, Repeat, Distractor). The between-factor GROUP (young, mid-aged, elderly) is not depicted.

Table 2 RTs of all conditions
This table gives an overview over all the mean RTs (and SD) of all conditions: first and third target positions after a switch, repeat, distractor cue for each group (young, mid-aged, elderly).

Table 3 Behavioral costs
This figure illustrates restart, mixing costs, as well as switch benefits in ms (incl. SD) for each group (young, mid-aged, elderly).

Table 4 Overview of the network effects
The table summarizes the positivity effects of all ten ICs. The first column gives the name of the network, the second the specific positivity, the third the age-related topography effects. In the fourth column age-related effects concerning the positivities' amplitudes and the power of the underlying time-frequency effects are given. In case of significant brain-behavior associations, the fifth column classifies the specific compensation effects, whereas the last column summarizes the general sensitivity of the network concerning the experimental conditions.

FIGURE LEGENDS:

Figure 1 Independent component time-courses and age-related effects of IC1 and IC2
This figure gives an overview of the results concerning network IC1 (**A**-**C**) and IC2 (**D**-**F**). **A** and **D** show the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor), and group (young, mid-aged, elderly), respectively. For IC1 and IC2 an age-related effect can be observed (posterior-to-anterior shift). Note, for back reconstruction to the electrode space, the weight topography matrix has to be multiplied with the time-course of the respective IC. Therefore, both IC1 and IC2 reflect positivities peaking at about 400 ms post stimulus (IC1-P400, IC2-P00). **B** and **E** show (* = statistical significant) differences regarding the power of beta oscillations during the positivities. As can be seen, young participants show stronger beta power than both older groups. **C** and **F** reflect the brain-behavior correlations between the significant age-related effects of IC1 and IC2. Associations of RTs with beta power and RTs electrodes are depicted (the more power the faster the RTs in both IC1 and IC2). Furthermore, regarding IC1 faster RTs in first target positions of Repeat is related to enhanced Pz activity, whereas in Switch faster RTs are observed with less Fz activity. These effects are seen very similar in IC2, but across all conditions. Thus, the age-related anterior shift is accompanied with worsened behavioral performance. Note, for illustration reasons only correlations of IC2 are summarized as mean of over all conditions (RTs in the first and third position after Switch, Repeat, and Distractor).

Figure 2 Independent component time-courses and age-related effects of IC3. IC4 and IC5
This figure presents an overview of the results concerning network IC3 (**A**, **B**), IC4 (**C**) and IC5 (**D**-**F**). **A**, **C** and **D** show the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor), and group (young, mid-aged, elderly), respectively. Only IC4 and IC5 depict age-related topography shifts (IC4: increased central activity with age; IC5 central shift with age). Note, for back reconstruction to the electrode space, the weight topography matrix has to be multiplied with the time-course of the respective IC. Therefore, the components reflect positivities peaking at about 300 ms post stimulus (frontal IC3-P300), a late IC4-P800, and the sustained positivity of IC5. **B** and **E** show (* = statistical significant) differences regarding the power of beta oscillations during IC3-P300 and IC5-SP. Here again, young participants show stronger beta power than both older groups. **F** reflects the brain-behavior correlations between the significant age-related effects of IC5. Associations of RTs with beta power and RTs electrodes are

depicted (the more power the faster the RTs). However, here reduced Pz activity and higher FCz activity are related to faster responses irrespectively the condition. Thus, age-related topography effects are accompanied with worsened behavioral performance. Note, that these correlations are presented as a mean over all conditions (RTs in the first and third position after Switch, Repeat, and Distractor) for illustration reasons only.

Figure 3 Independent component time-courses and age-related effects of IC6 and IC7
This figure gives an overview of the results concerning network IC6 (**A** and **B**), and IC7 (**C** and **S**). **A** and **C** show the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor), and group (young, mid-aged, elderly), respectively. No age-related topography effects are observed. Note, for back reconstruction to the electrode space, the weight topography matrix has to be multiplied with the time-course of the respective IC. Thus, the components reflect positivities peaking at about 300/400 ms post stimulus (frontal IC6-P300, IC7-P400). **B** and **D** show (* = statistical significant) differences regarding the beta power oscillations underlying the positivities. Once again, young participants show stronger beta power than both older groups (**D** reflects further position effects of IC7). Additionally, age-related power differences in gamma oscillations of Switch, Repeat and Distractor conditions are also depicted (low gamma in IC6 and high gamma of IC7).

Figure 4 Independent component time-courses and age-related effects of IC8, IC9 and IC10
This figure summarizes the results concerning networks IC8 (**A-B**), IC9 (**C-D**), and IC10 (**E-F**). **A, C** and **E** show the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat 3; green line: 1st Distractor; dotted green line: 3rd Distractor), and group (young, mid-aged, elderly), respectively. Only in IC8 and IC9, age-related topography changes are observed (IC8: additional frontal activation in the young; IC9 parietal changes with age). Note, for back reconstruction to the electrode space, the weight topography matrix has to be multiplied with the time-course of the respective IC. Therefore, the components reflect late peaking positivities at about 700 ms (frontal IC8, IC10), at 1000 ms (IC9) post-stimulus. **B** and **F** show (* = statistical significant) differences regarding the power of beta oscillations during IC8 (higher beta power of young compared to mid-aged) and power differences of delta and theta oscillations in IC10. Part **D** of IC9 reflects the brain-behavior correlations between the significant age-related effects. Associations of RTs with activity at Pz and with Cz are shown. Interestingly, faster RTs are associated with less activity at Pz and Cz. Thus, age-related topography effects are accompanied with worsened behavioral performance. Note, that these correlations are summarized as a mean over all conditions (RTs in the first and third position after Switch, Repeat, and Distractor) for illustration reasons only.

SUPLLEMENTARY FIGURE LEGENDS:

Supplementary Figure 1 Independent component features of IC1 and IC2
A presents the features of IC1 and **B** of IC2. Shown are the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor) and group (young, mid-aged, elderly) of each component respectively. Additionally, each column shows further the time-frequency plots (ERSP) of all conditions (S1: 1st Switch; S3: 3rd Switch; R1: 1st Repeat; R3: 3rd Repeat; D1: 1st Distractor; D3: 3rd Distractor) for the specific group and for all frequency bands (delta, beta, theta, alpha, low- and high gamma).

Supplementary Figure 2 Independent component features of IC3 and IC4
A gives the features of IC3 and **B** of IC4. Depicted are the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor) and group (young, mid-aged, elderly), of each component respectively. Additionally, each column presents further the time-frequency plots (ERSP) of all conditions (S1: 1st Switch; S3: 3rd Switch; R1: 1st Repeat; R3: 3rd Repeat; D1: 1st Distractor; D3: 3rd Distractor) for the specific group and for all frequency bands (delta, beta, theta, alpha, low- and high gamma).

Supplementary Figure 3 Independent component features of IC5 and IC6

A gives the features of IC5 and **B** of IC6. Shown are the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor) and group (young, mid-aged, elderly), of each component respectively. Additionally, each column shows further the ERSPs of all conditions (S1: 1st Switch; S3: Switch 3rd; R1: 1st Repeat; R3: 3rd Repeat; D1: 1st Distractor; D3: 3rd Distractor) for the specific group and for all frequency bands (delta, beta, theta, alpha, low- and high gamma).

Supplementary Figure 4 Independent component features of IC7 and IC8

A shows the features of IC7 and **B** of IC8. Presented are the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: 1st Switch; dotted blue line: 3rd Switch; pink line: 1st Repeat; dotted pink line: 3rd Repeat; green line: 1st Distractor; dotted green line: 3rd Distractor) and group (young, mid-aged, elderly), of each component respectively. Additionally, each column depicts further the time-frequency plots (ERSP) of all conditions (S1: 1st Switch; S3: 3rd Switch; R1: 1st Repeat; R3: 3rd Repeat; D1: 1st Distractor; D3: 3rd Distractor) for the specific group and for all frequency bands (delta, beta, theta, alpha, low- and high gamma).

Supplementary Figure 5 Independent component features of IC9 and IC10

A provides the features of IC9 and **B** of IC10. Shown are the time-courses including the source topographies (negative weights are shown in blue, neutral in green and positive in red) of each IC, condition (blue line: Switch 1; dotted blue line: Switch 3; pink line: Repeat 1; dotted pink line: Repeat 3; green line: Distractor 1; dotted green line: Distractor 3) and group (young, mid-aged, elderly), of each component respectively. Additionally, each column shows further the time-frequency plots (ERSP) of all conditions (S1: 1st Switch; S3: 3rd Switch; R1: 1st Repeat; R3: 3rd Repeat; D1: 1st Distractor; D3: 3rd Distractor) for the specific group and for all frequency bands (delta, beta, theta, alpha, low- and high gamma).

TABLES

Table 1

		Target position	
		1st	3rd
Task-rule	Switch:	1st Switch	3rd Switch
	Repeat:	1st Repeat	3rd Repeat
	Distractor:	1st Distractor	3rd Distractor

Table 2

Group	Switch		Repeat		Distractor	
	1st	3rd	1st	3rd	1st	3rd
Young	563 ms (SD: 14 ms)	535 ms (SD: 12 ms)	585 ms (SD: 11 ms)	551 ms (SD: 13 ms)	489 ms (SD: 23 ms)	447 ms (SD: 17 ms)
Mid-aged	577 ms (SD: 10 ms)	547 ms (SD: 8 ms)	596 ms (SD: 11 ms)	561 ms (SD: 8 ms)	503 ms (SD: 9 ms)	458 ms (SD: 7 ms)
Elderly	595 ms (SD: 6 ms)	561 ms (SC: 5 ms)	612 ms (SD: 6 ms)	576 ms (SD: 5 ms)	514 ms (SD: 4 ms)	471 ms (SD: 4 ms)

Table 3

Group	Restart	Mixing	Local
Young	31 ms (SD: 7 ms)	97 ms (SD: 10 ms)	22 ms (SD: 8 ms)
Mid-aged	33 ms (SD: 5 ms)	95 ms (SD: 3 ms)	20 ms (SD: 5 ms)
Elderly	35 ms (SD: 1 ms)	97 ms (SD: 2 ms)	17 ms (SC: 2 ms)

Table 4

Component	Positivity	Topography effects	Aging-effects	Brain-behavior associations	Characteristics
IC1	P400	Anterior shift	ERP & α,β	Failed compensation	Mixed-tasks
IC2	P400	Anterior shift	ERP & β	Failed compensation	Single-task
IC3	P300	/	β	/	Position
IC4	P800	Increased central activity	ERP & low γ	/	Single-task
IC5	Sust. Pos.	Central shift	ERP & β	Failed compensation	3rd position: mixed-tasks
IC6	P300	/	θ, β, low γ	/	Unspecific
IC7	P400	/	ERP & α,β, high γ	/	1st target position
IC8	P700	Vanished anterior activity	ERP & α,β	/	Mixed-tasks
IC9	P1000	Increased parietal activity	/	Failed compensation	3rd target position
IC10	P700	/	δ, θ	/	1st position: mixed-tasks

Figure 1

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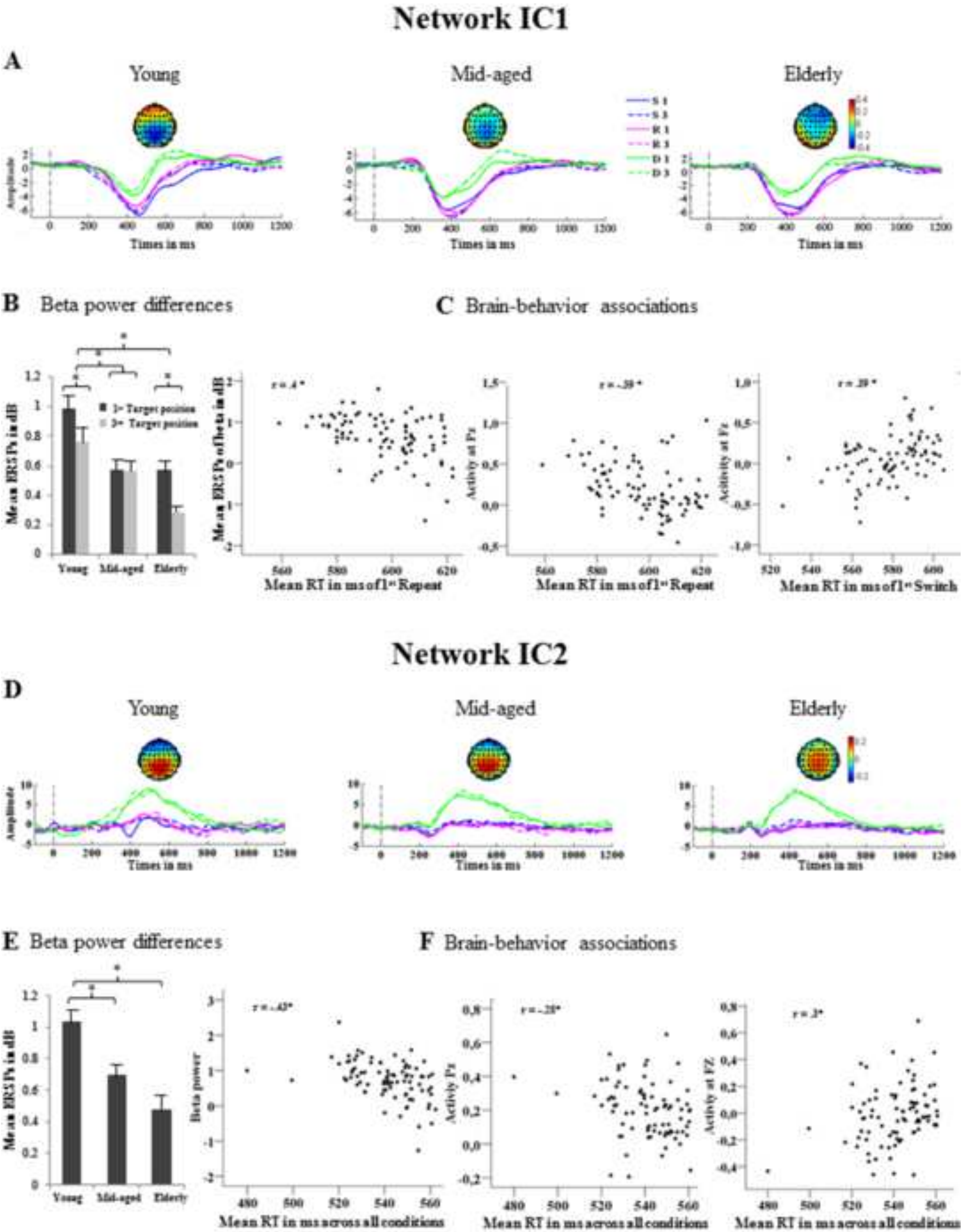

Figure 2 Click here to download Figure Figure 2.TIF

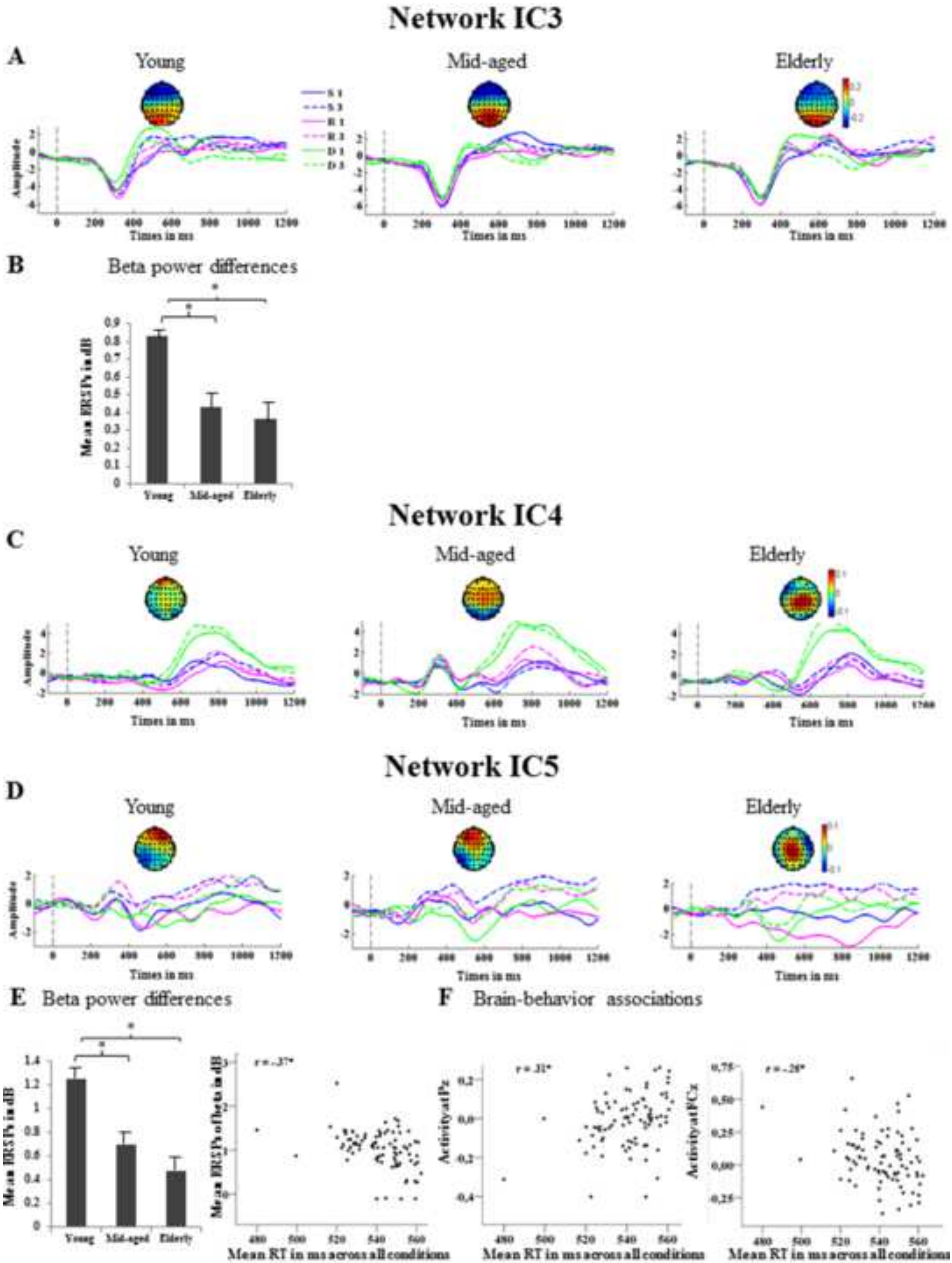

Figure 3

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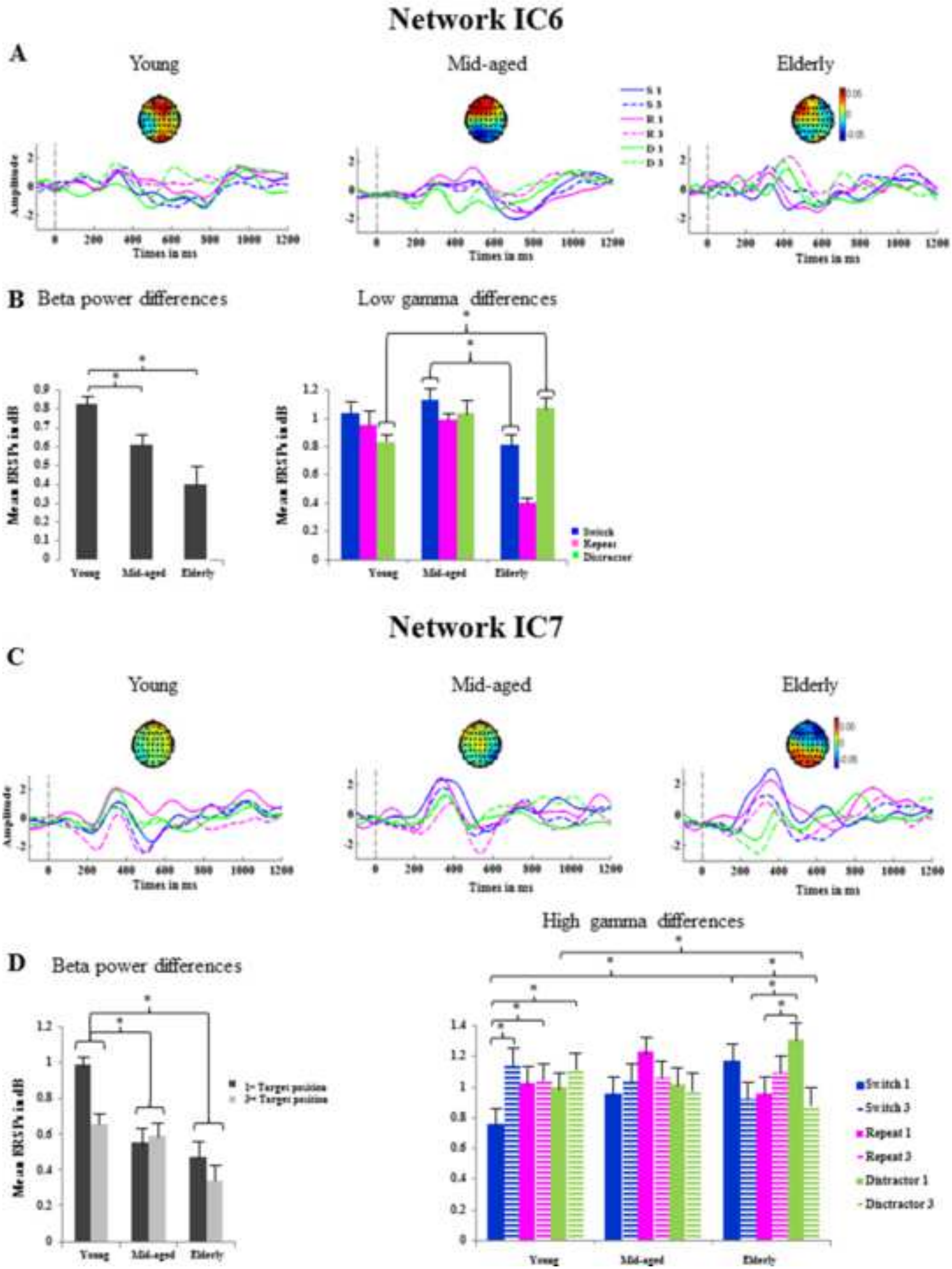

Figure 4

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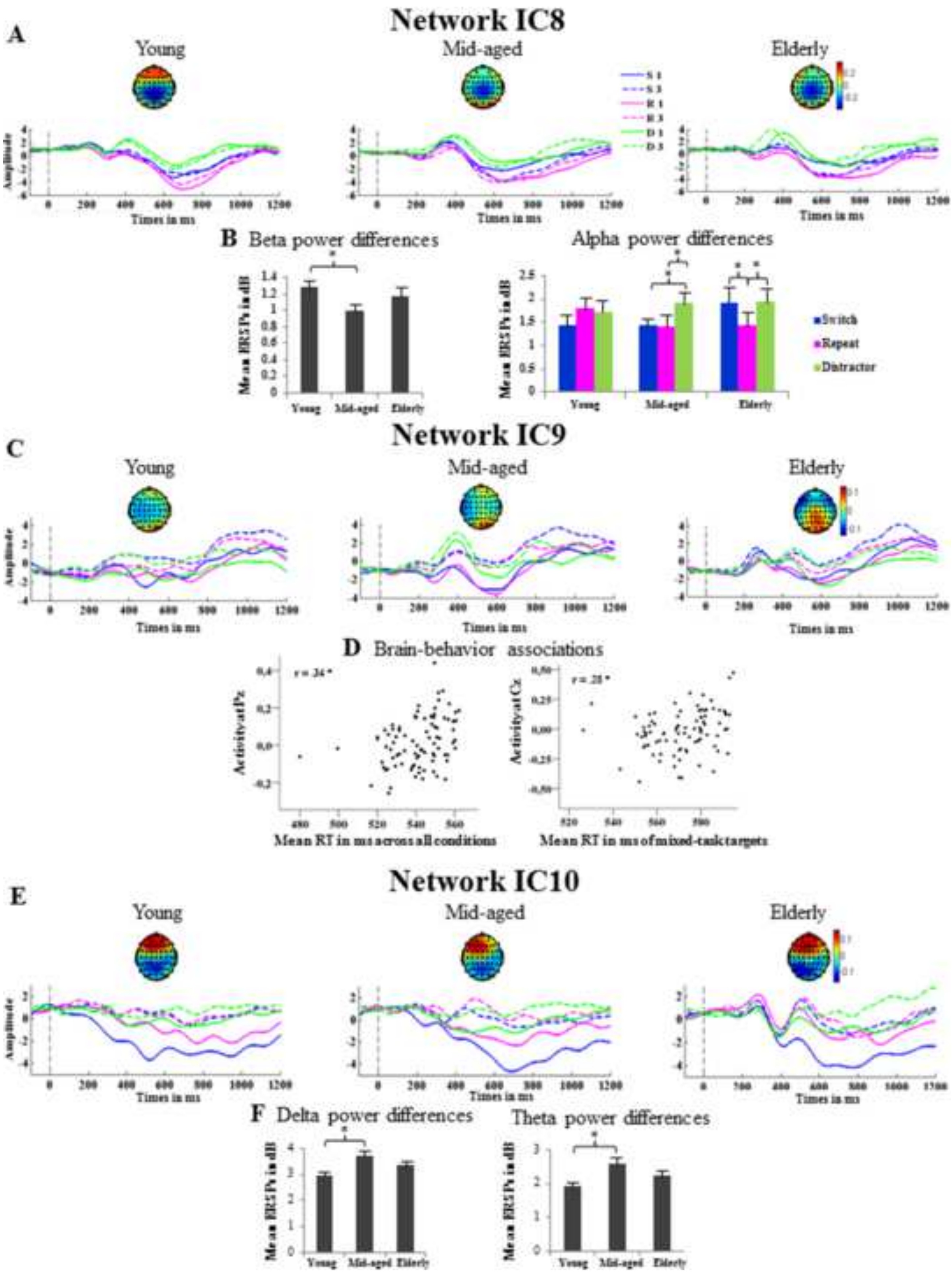

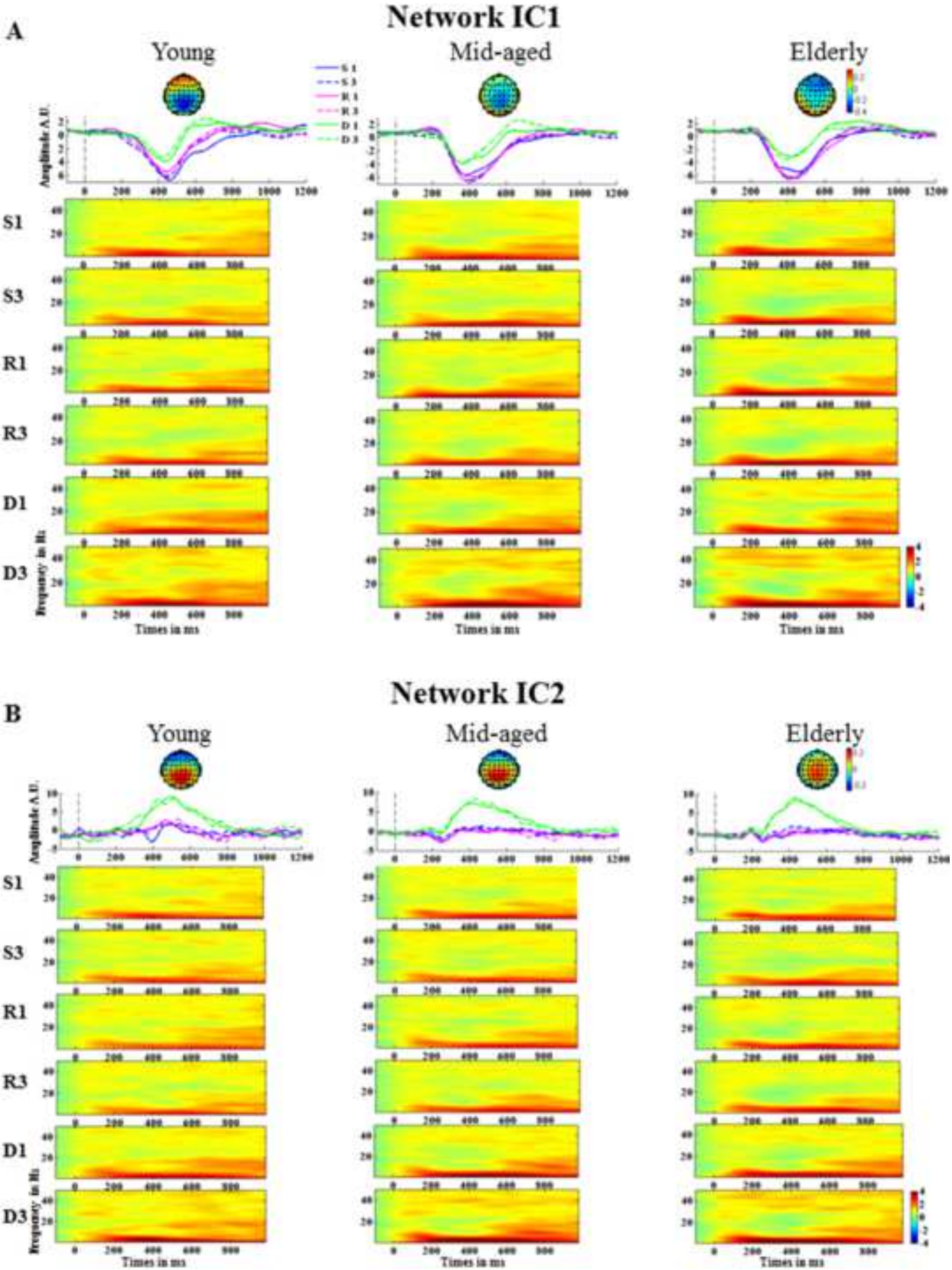
Network IC1
A
Young
Mid-aged
Elderly
S 1
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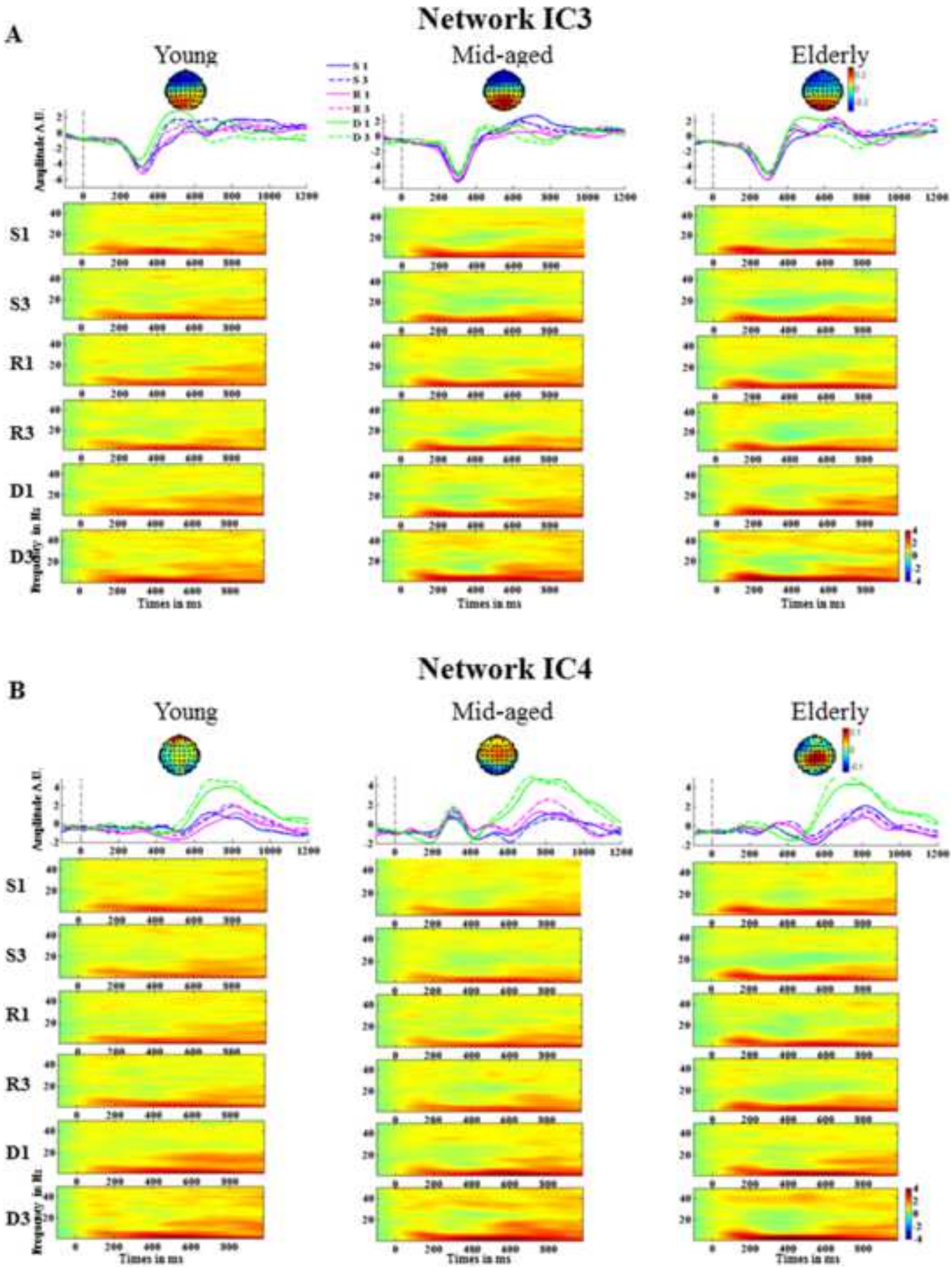
R 1
R 3
D 1
D 3
Amplitude A.U.
S1
S3
R1
R3
D1
D3
Frequency in Hz
Times in ms
Network IC2
B
Young
Mid-aged
Elderly
Amplitude A.U.
S1
S3
R1
R3
D1
D3
Frequency in Hz
Times in ms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Mid-aged
Elderly
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S 3
R 1
R 3
D 1
D 3
Amplitude A.U.
S1
S3
R1
R3
D1
D3
Frequency in Hz
Times in ms
Network IC4
B
Young
Mid-aged
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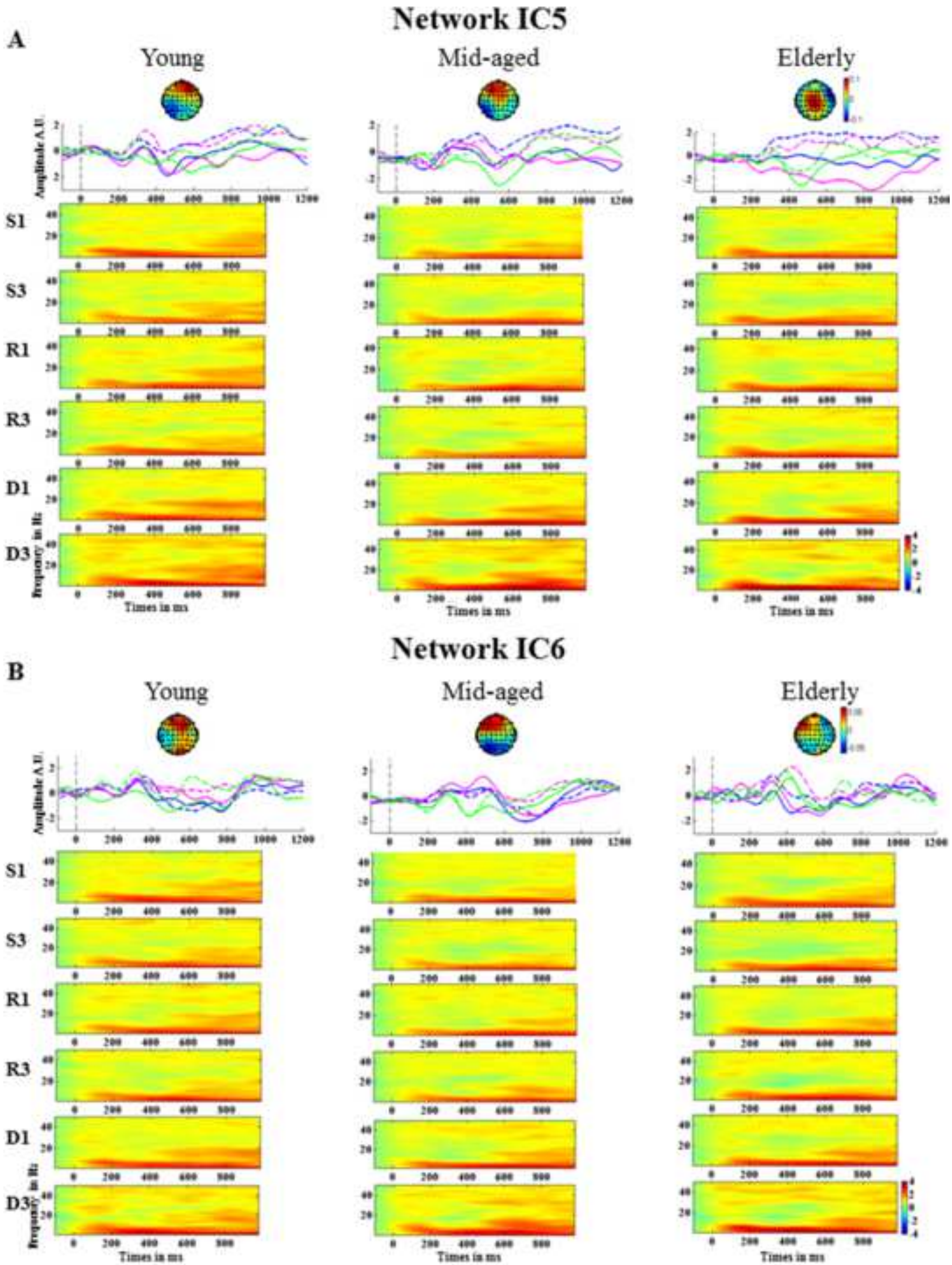
Amplitude A.U.
S1
S3
R1
R3
D1
D3
Frequency in Hz
Times in ms


Network IC5
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Frequency in Hz
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Network IC6
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Amplitude A.U.
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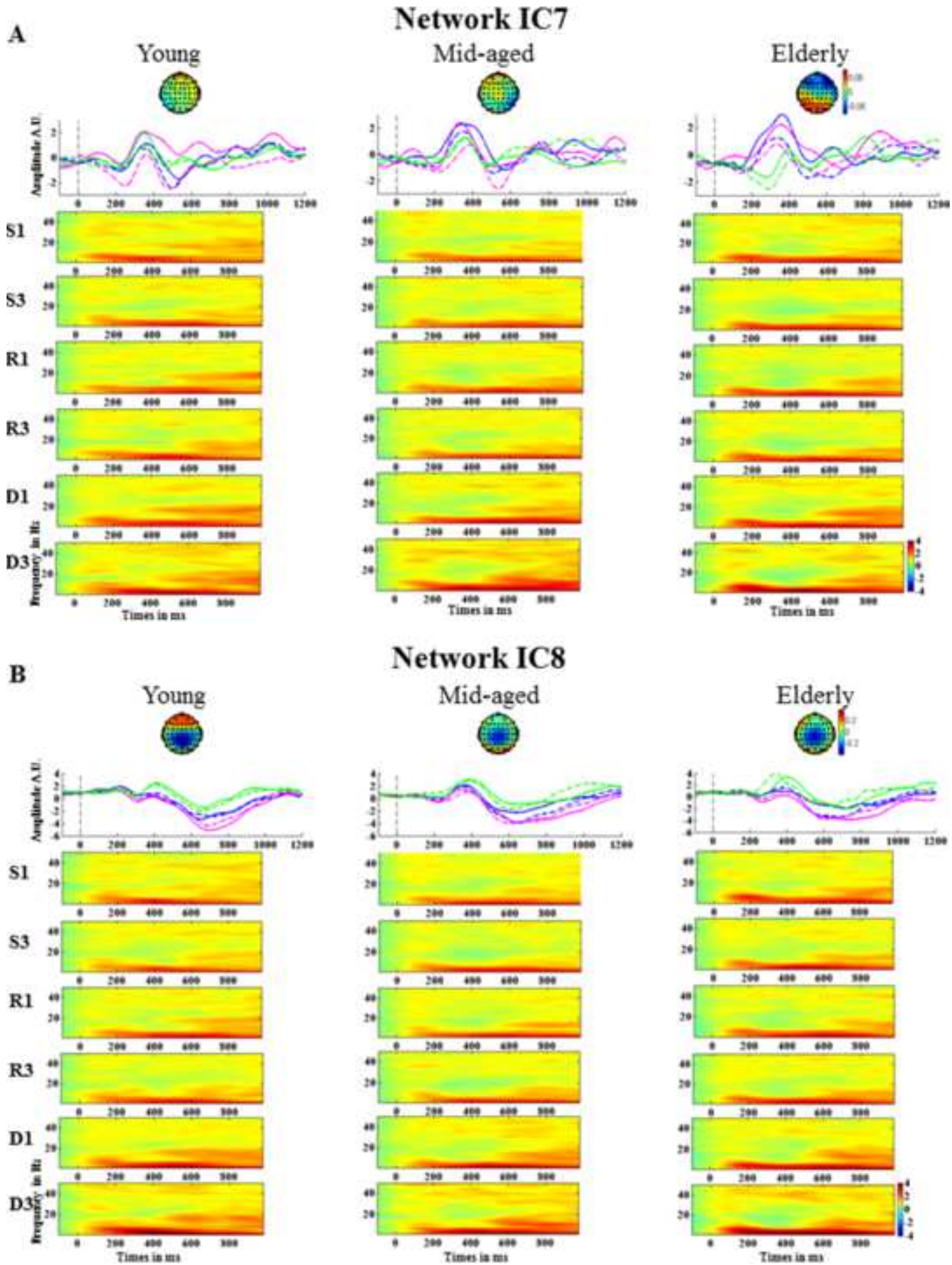
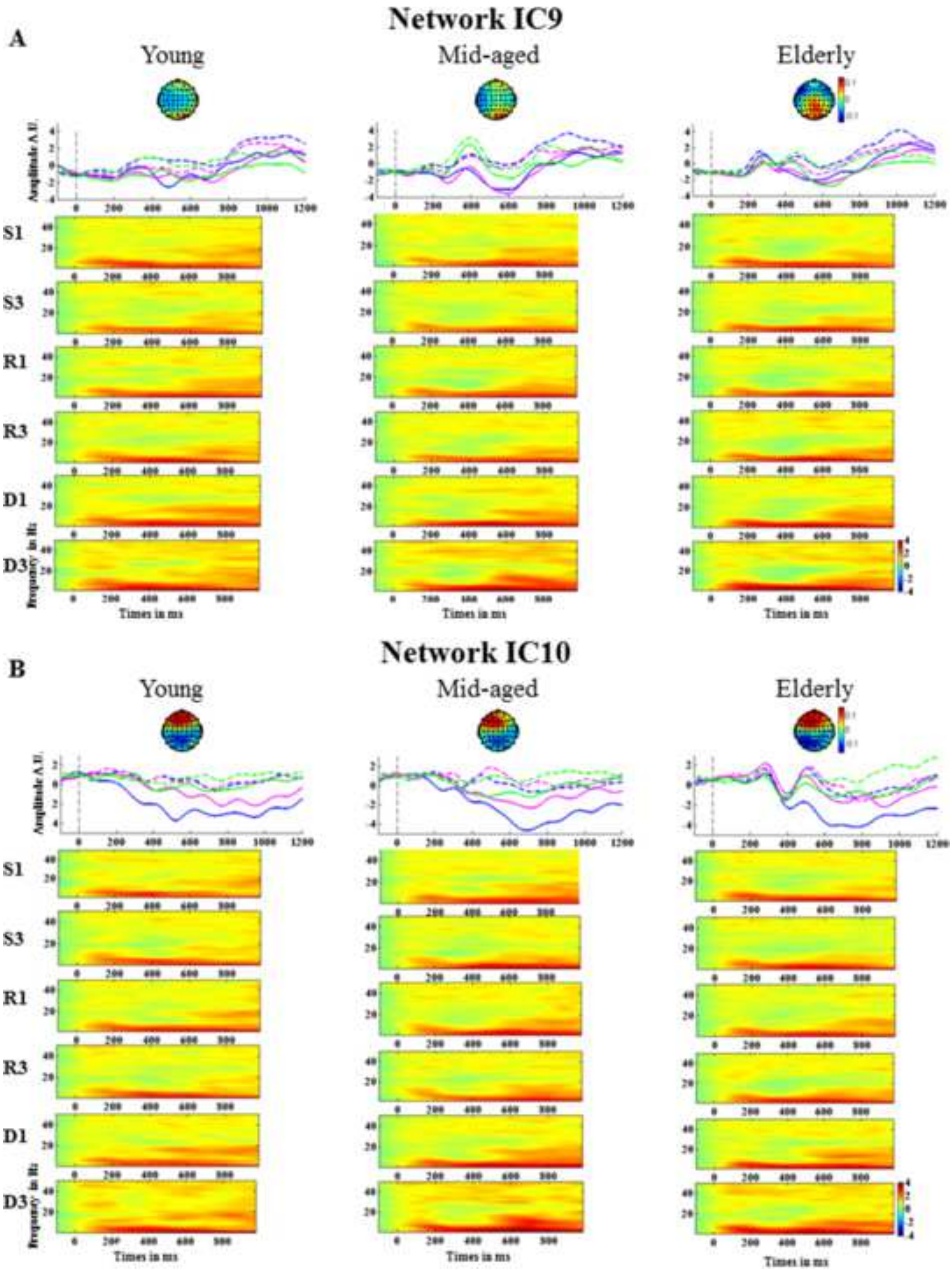
Times in ms

Supplementary Material 4 Click here to download Supplementary Material S4_IC7_IC8.TIF




Network IC9
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Network IC10
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Amplitude A.U.
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R1
R3
D1
D3
Frequency in Hz
Times in ms