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Cortical correlates in upright dynamic and static balance in the elderly

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ABSTRACT

Falls are the second leading cause of injury for the elderly worldwide. Physiological aging processes alter the ability to address unexpected balance perturbations and increase the probability of falling. Indeed, approximately 30% of adults older than 65 years experiences up to one fall/year. Investigating the neurophysiological patterns of static and dynamic balance in the elderly is an emerging area of research. This knowledge will provide a mechanistic basis to implement novel rehabilitation strategies and assistive devices to eventually reduce the risk of falls.
Our aim was to identify cortical and muscular correlates of static and dynamic balance in a cohort of younger and old healthy adults. We quantified cortical and muscular activation in 9 elderly and 8 younger healthy participants during a task of upright stance in static and dynamic (core board) conditions. To simulate real-life double-tasking while maintaining posture, a second set of experiments incorporated a visual oddball task.
During static balance, we observed high electroencephalographic (EEG) delta rhythm over the anterior cortex in the elderly and more diffused fast rhythms (i.e., alpha, beta, gamma band) in younger participants. By adding a visual oddball, the elderly increased theta activation over sensorimotor and occipital cortices.
During dynamic balance, the elderly recruited sensorimotor areas and increased muscle co-contraction, suggesting a preferential motor strategy to maintain posture. This strategy was exasperated during the oddball task. The younger participants showed an overall reduced cortical and muscular activation compared to the elderly, with the noteworthy difference of a preferential activation of occipital areas reinforced during the oddball task, hinting to a likely visual strategy to maintain dynamic balance. These results support the hypothesis of a different strategy during the life-span in addressing postural tasks as cognitive load increases. This knowledge will aid in tailoring age-specific rehabilitative and assistive interventions.

Introduction

Falls are usually caused by a combination of risk factors that increase with age. Indeed, adults older than 65 years of age suffer the greatest number of fatal falls each year[1].

In the optimally functioning nervous system, the maintenance of upright stance is an automatic involuntary task, predominantly under control of cortical and spinal networks. The cortical contribution is challenged with increased cognitive load, depending on the postural task, the age of the individuals and their balance abilities[2].

In the last decades, effective quantification of complex balance task by using different kinds of perturbations, e.g., either a platform perturbation or a cognitive task (e.g., double tasking), was mainly assessed by computerized dynamic posturography (CDP)[3]. This kind of research demonstrated that elderly – when performing a cognitive task concurrently during a challenging balance recovery – prioritize balance recovery. CDP was also quantified in virtual-reality based scene: visual interference induced a significantly larger postural sway[4,5]. Other studies exploring this relationship between attention, posture and gait in younger and older adults proved that postural control appears to be more cognitively demanding in older adults compared to younger adults and that the performance of a dual-task appears to have a more deleterious effect on postural control in the elderly compared to younger adults[6,7,8,9,10,11,12,13]. In fact, it is not still clear if these differences are due to shift of attention between two different tasks, the reduction in attention capacity or the increased demand due to impairments in the postural control system in the ageing nervous system[2].

Understanding the neurophysiological control of balance in increasingly challenging balance tasks (static, dynamic, during dual-task) may help to clarify age-relate differences. Dual-task experiments[14] are usually designed to represent real-life situations of instability and to try to introduce it in experimental settings. The quest for neural predictors of dynamic balance instability (i.e., during gait) while double-tasking (i.e., texting or conversing) in younger participants suggests a leading role of the posterior parietal cortex (PPC), involved in the processes of sensorimotor integration and gait control[14]. Indeed, experiments in younger healthy volunteers showed that, when walking naturally without engaging in any secondary tasks, PPC is active in the theta range (4–7 Hz). When a double-task is added, a positive predictive relationship could be identified between PPC activity in the alpha frequency band and walking pace[14,15,16]. The existence of neural detectors of postural instability that could trigger the compensatory adjustments to avoid falls was also supported by a burst of gamma activity that preceded the initiation of compensatory backward posture[17].

To our knowledge, there is a paucity of studies investigating the cortical activation during balance in healthy elderly, in particular using in parallel high-density electroencephalographic (EEG) systems and electromyographic (EMG) sensors[6]. The scarce number of studies addressing this issues[18,19], show that the scalp EEG power distribution increases in both elderly and younger adults control group in delta EEG frequency band during challenging postural conditions; theta rhythms, on the other hand, were more responsive to cognitive tasks in both groups, with more marked increases in younger subjects, and gamma oscillations increased in the elderly primarily over central and central-parietal cortices during challenging postural tasks.

The majority of studies analysing power spectral density changes associated with postural control are based on younger participants[4]. An increase in frontal and parietal midline theta power is observed with demanding continuous balance control[20] and fronto–central and centro–parietal theta power resulted associated with balance performance[20]. Specifically, significant increases in theta band spectral power in the left sensorimotor cortex played a larger role in sensing loss of balance during walking than the right sensorimotor cortex[21]. Cortical alpha rhythms resulted correlated with body sway during quiet open-eyes standing[22] and beta band power of the sensorimotor cortex reflected muscle contraction[23].

Despite the wide heterogeneity in experiments, protocols, and data analyses[6], findings on EMG data are more consistent: EMG latency, amplitude and muscular co-contraction are usually larger in the elderly compared to younger participants during walking and upright stance[24,25,26,27,28,29]. Increased activation of antagonist muscles in old adults seems a change associated with normal healthy aging[30].

In this study, we monitored both EEG source waveform spectral power distribution estimated by high-density (i.e., 256 electrodes) EEG recordings, and EMG amplitudes recorded by 8 wireless loggers on the main muscles of the leg and the trunk, during single postural tasks (i.e., standing on a 0%, +22%, -22% inclined planes and on a core board) and dual postural-visual tasks (adding a visual oddball – i.e., the participant is asked to count the odd stimuli presented on a screen that differ from the more frequent stimuli – to the previous conditions) in 9 healthy elderly ($>$ 64 y) and 8 younger ($<$ 35 y) adults. The main aim is to investigate cortical and muscular activation underlying age-related differences in postural control. Studying both the EEG and EMG signals while engaging in a secondary task in healthy subjects mimics a real-life situation of distraction that might lead to elderly instability. We chose a visual task because visual and proprioceptive inputs seem to play dominant roles in maintaining postural stability[5].

The aim of the study is to answer to the following research questions: **(Q1)** Which are the age-related differences in cortical and muscular activations during static and dynamic balance and **(Q2)** How they are modified during dual postural-visual tasks. Toward this aim, we identified EEG power spectral content and source generators of brain regions active during different postural conditions and dual-tasking in a cohort of younger and old healthy adults and estimated EEG spectral power and EMG amplitudes differences among the two groups.

Results

Behavioral tests. To evaluate visual attention and task switching, before the dual-task experiment, participants underwent the Trail Making Test (TMT) A and B. The time in *s* needed for performing both TMT-A (assessing cognitive processing speed) and TMT-B (assessing executive functioning) is reported in Figure1 and in Table1 (2nd and 4th columns). Since performance on TMT-A and TMT-B is affected by both age and education[31], we computed the cut-off for each one of our participants considering these two covariates[32] (3rd and 5th columns of Table1). No one of our participants showed an impaired performance considering her/his age and level of education comparing the time needed to perform the tasks (2nd and 4th columns of Table1) and the cut-offs (3rd and 5th columns of Table1). The time needed to perform the tests was normally distributed for both the groups, and significantly higher in the TMT-B compared to the TMT-A execution in particular for the elderly ($p_{value} < 0.001$) and overall in the elderly ($p_{value} < 0.01$). TMT performance declines, on average, during healthy aging[33] with performance on TMT-B declining significantly more than TMT-A in older adults[34].

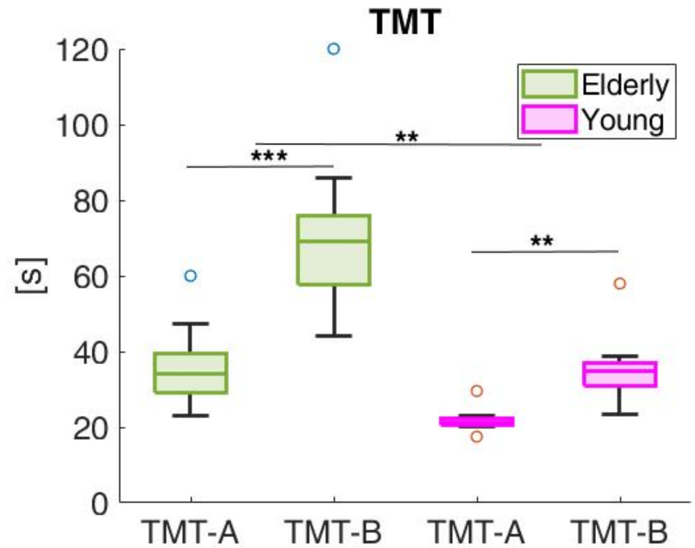

Figure 1. Time in seconds to perform the Trail Making Test (TMT) A and B for the elderly (in green) and for the younger adults (in pink). On each box, the central red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the 'o' symbol. Asterisks indicates statistical significant difference ('**' stands for $p_{value} < .01$; '***' stands for $p_{value} < .001$).

Cortical and muscular activation underlying age-related differences in postural control (Q1). To emphasize the differences in cortical and muscular activation between younger adults and elderly under the different conditions, we reported the results during static and dynamic balance in Figure 2. In the baseline condition, static balance (i.e., undisturbed upright standing), elderly (Figure 2a) exhibit a shift to lower rhythms compared to younger adults (Figure 2c): indeed higher values in the low frequency rhythms (delta band) are present in the elderly whereas higher values in frontal and midline regions in higher frequency rhythms (i.e., beta, low and high gamma) are present in the younger adults. Significant differences (p < 0.05) between the two groups are localized over frontal regions in delta band (higher values in elderly) and over frontal and sensorimotor regions in beta and gamma bands (higher values in younger adults). During dynamic balance (i.e., on the core board), the motor/occipital theta is increasing in the elderly (Figure 2b) compared to the younger adults (Figure 2d) as confirmed by statistical tests (Wilcoxon test (Figure 2f)).

Cortical activations underlying age-related differences during dual postural-visual tasks (Q2) To emphasize the differences in cortical activation in the two groups, we reported the results during the dual-task (mental counting the odd stimuli) during static and dynamic balance in Figure 4 and 5.

Figure 4 shows the median values for each ROI computed among the elderly whereas Figure5 for the younger adults. In particular, in Figure 4 and in 5, we reported the difference of the power spectra between the 0.5 s-epoch post-odd stimulus and the 0.5 s-epoch pre-odd stimulus in the same postural conditions of Figure 2. The p-values of the statistical significant differences between the younger and the elderly group were reported in Figure 4c during static balance (simple standing) and in Figure 5c during dynamic balance.

During static balance (simple standing) double-tasking, the elderly (Figure 4a) increased the values on their midline theta compared to the younger adults (Figure 5a) and showed higher values on their frontal regions in high-gamma. During dynamic balance double-tasking, the elderly (Figure 4b) increase their midline delta and high gamma compared to younger adults (Figure 5b). Comparing cortical activations in the elderly during static and dynamic balance, significantly higher cortical activations are localized over sensorimotor regions in alpha and beta bands and over frontal region in high gamma during dynamic balance (Figure 4c). A different pattern is observed in younger adults, with an increase in gamma band localized over occipital regions (Figure 5c).

Interestingly, only in the younger adults delta power in the centro-parietal areas significantly increased during dynamic balance. When double-tasking, only the elderly showed a decrease in delta rhythm in the centro-parietal area parallel to an increase in theta rhythm in the occipital area during dynamic balance compared to static balance.

Comparing the performance (Figure6a and Figure6b) in dual-tasking between elderly (Figure4) and younger (Figure5)

Table 1. TMT-A and TMT-B: Results

Young adults				
Subject	*TMT-A*	*Cut-off (TMT-A)*	*TMT-B*	*Cut-off (TMT-B)*
CTRL002	21.24	45	38.66	120
CTRL003	13.88	45	21.00	120
CTRL004	21.36	45	23.30	120
CTRL005	17.50	45	28.00	120
CTRL006	20.01	45	57.97	120
CTRL007	22.95	45	35.32	140
CTRL008	29.56	45	34.43	120
CTRL009	22.05	45	34.91	140
Elderly				
Subject	*TMT-A*	*Cut-off (TMT-A)*	*TMT-B*	*Cut-off (TMT-B)*
ELD001	34.04	68	60.07	200
ELD002	25.30	68	44.20	200
ELD003	37.00	68	86.00	200
ELD004	60.00	85	120.00	220
ELD005	23.00	68	51.00	200
ELD006	36.10	68	69.04	200
ELD007	30.58	68	69.85	200
ELD008	31.99	85	72.61	220
ELD009	47.22	68	62.44	200

Table 2. MVC median values

Elderly						
ES	*RF*	*VL*	*BF*	*TA*	*PL*	*GL*
29.4 μV	56.4 μV	95.3 μV	65.4 μV	214.4 μV	123.5 μV	82.4 μV
Young adults						
ES	*RF*	*VL*	*BF*	*TA*	*PL*	*GL*
66.3 μV	98.5 μV	99.1 μV	84.2 μV	216.7 μV	129.2 μV	95.4 μV

adults, we observe a significant increase in frontal and occipital theta rhythms and frontal high gamma in the elderly compared to the younger adults in dual-tasking already in static balance (Figure6a).

During dual-tasking static balance over the inclined plane (-22%), the elderly show higher cortical activations in alpha and gamma bands over occipital and frontal regions respectively. This pattern is similar to that observed in younger adults during dynamic balance, suggesting a similar cognitive load in elderly and younger adults in these two different postural conditions. Higher cortical activation in younger adults are observed, during dual-task static balance over the inclined plane (+22%) over frontal regions in theta and low gamma bands, similar to the pattern observed during static balance. During the same task, the elderly show higher activation of frontal and central regions in beta range. We refer the reader to the Supplementary material for the results of all the statistical tests for the EEG power spectra.

In Figure3, we reported the RMS values of muscular activation signal normalized by the median RMS value of the maximum voluntary contractions (Table 2) among subjects of the same group for each assessed muscle: Erector spinae (ES); Rectus femoris (RF); Vastus lateralis (VL); Biceps femoris (BF); Tibialis anterior (TA); Peroneus longus (PL) and Gastrocnemius lateral head (GL). In particular, each barplot represents the median values computed among the elderly participants (first row, in green, of Figure3) and the younger adults (second row, in pink, of Figure 3).

RMS values for the Erector spinae significantly differ in all the postural conditions between the two groups: elderly show higher values compared to the younger adults and an increasing trend from 0% inclined plane to the core board (first column of Figure3). The RMS values for the RF were significantly higher in the elderly participants than in the younger adults on the -22% inclined plane and on the core board. The RMS of the GL was significantly higher on the 0% plane and on the core-board in the elderly compared to the younger adults.

The activity of the PL and GL in -22% condition revealed a plantar-flexion action, which is similar in the two groups but it is complemented by two different knee strategies between elderly and younger adults: elderly showed higher co-contraction of RF and BF, whereas younger adults prefer recruiting the knee flexors.

When looking at the results obtained for the +22% condition, results suggested a different ankle strategy to keep balance: elderly showed higher co-contraction of TA, PL and GL than younger adults, with the higher difference in the recruitment of TA; at the upper leg, extensors activity is higher than BF for both groups.

Interestingly, the task on the core board highlighted a further co-contraction of plantarflexors and dorsiflexors of the ankle joint in the elderly (i.e., higher co-contraction of TA, PL and GL) than in the younger adults, who prefer the recruitment of the PL for fine movement control. The activity of the RF, which serves both as knee extensor and hip flexor, was also found to be significantly higher in the elderly than in the younger adults on the core board.

No significant differences were found in comparing the EMG data during the postural task with and without the visual oddball.

Discussion

Our findings provide evidence of different motor control strategies to maintain static and dynamic balance in the elderly compared to younger healthy adults.

During static balance, delta power over frontal regions was higher in the elderly, whereas younger participants had higher activation of frontal and occipital regions in the fast frequencies. Both groups showed a mid-line fronto-central theta rhythms, a neural signature of the attentive process of maintaining posture. During dynamic balance, the elderly increased theta rhythms over sensorimotor and occipital areas. When adding a visual oddball task, during static balance the elderly showed stronger activations over the sensorimotor areas compared to the non-double tasking condition. Dynamic balance only magnifies these findings. In the younger group, static balance during double tasking induces an occipital theta and gamma rhythm, associated with frontal alpha increase, which again are magnified during dynamic balance.

Although the different cortical activation strategies are more evident during the dual-task, they emerged already during quite static balance. The elderly showed high delta activation over the frontal areas, a process hypothesized to contribute the maintenance of posture[18,19]. The younger adults showed prevalent fast frequencies over the frontal and occipital areas, suggesting an ongoing attentive task to maintain upright posture supported by a visual fixation strategy identified by the activation over the occipital lobes.

Dual-task is a well-known strategy to increase the cognitive load in experimental conditions and mimics real-life settings in which balance maintenance is coupled with tasks such as speaking or texting. A common paradigm is the visual oddball, during which the participant is asked to count the stimuli presented on a screen that differ from the more common one. In our experiment, the double task addressed the issue of the competing cognitive resources the elderly deploy during stance. In line with previous research[2,3,4], we expected an increase of cortical recruitment to keep up performance in the elderly. The observed activation of posterior areas in theta band supports this hypothesis; it is coupled with a recruitment of sensorimotor cortices, confirmed by the muscle activation pattern hinting to an increased muscular firing to maintain posture.

In the younger adults, we observed during dynamic postural double tasking a strong activation of the occipital and frontal areas, congruent with the oddball task (visual stimulus and counting). While we cannot definitely disentangle the components of the visual activation, it is likely that younger participants adopt a visual fixation strategy during this more challenging task, as they did already during unchallenged static balance.

It is noteworthy that the main differences in cortical activations between elderly and younger adults appear during double-task, suggesting that they were able to recruit adaptive reserve. This finding contrasts with previous work[35] which described increased cortical activation during double tasking static posture to be suggestive of a defective compensatory mechanism in the elderly. It is also possible that the different nature of the task – static vs dynamic – may render these findings not directly comparable.

In normal aging structural and functional physiological brain changes occur. Structural changes (i.e., cortical thinning, local brain atrophy, etc.) together with functional maladaptive brain activity, namely decreased functional specificity and loss of functional lateralization, trigger the activation of compensatory mechanisms[36]. This has been referred in literature as compensatory cognitive scaffolding, whose efficacy largely depends on each one's cognitive reserve[37]. This model explains older individual's level of cognitive functioning: this relies on compensation mechanisms by which supplementary higher level cortical loops are recruited to accomplish also those tasks supposed to be highly automatized, as the control of upright stance[38]. Thus, the increased allocation of attention sources to handle a challenging postural task (as in the core board condition), together with a cognitive oddball paradigm, lead the older group to necessarily increase recruitment of cortical areas to keep balance. This is not needed by younger adults who relay on more automatized and less central processes to maintain balance, having more cognitive sources available to easily accomplish the task.

The elderly showed higher muscular activity than younger adults. The higher co-contraction of ankle plantarflexors and dorsiflexors in the elderly suggest a stiffening action at the ankle joint already during static balance and magnified in dynamic tasks. In both groups, PL shows a strong activation already during static balance, confirming the need for a greater stabilization over the mediolateral plane[39]. However, the elderly tend to complement PL action with TA and GL, whereas in challenging postural tasks (i.e., the core board) younger adults prefer to control the ankle joint mainly with the PL for fine movement control.

These mechanisms are integrated by a higher co-contraction of knee extensors (RF and VL) and flexors (BF) during dynamic balance in the elderly, most likely to add stiffness to the knee. The young adults, instead, prefer a strategy that allows lowering their center of mass to increase their stability when needed.

We can notice that the RMS values for the Erector spinae significantly differ in all the postural conditions between the two groups: elderly show higher values compared to the younger adults and an increasing trend from 0% inclined plane to the core board (first column of Figure 3). The activity of the RF, which serves both as knee extensor and hip flexor, was also significantly higher in the eldelrly during dynamic balance and complemented by a significant higher ES activity.

Overall, the elderly seem to prefer a stiffening strategy of the lower limb with a compensatory mechanism of the trunk to keep balance, whereas younger subjects work on their stabilization of the mediolateral plane, recruiting the PL for fine movement control, and lower their center of mass, i.e., a combination of ankle and knee strategy.

Our findings indicate that the elderly need to increase cortical recruitment during postural challenging tasks with additional cognitive load. Dynamic postural control during double tasking needs the involvement of the whole sensory-motor network: the correlate of this cortical finding is the preferred motor control strategy, which in the elderly sees a muscle co-contraction to stiffen lower limb and trunk. Younger subjects are apparently undisturbed by the double tasking, with a possible visual fixation strategy to maintain dynamic balance which can only be inferred from our data. Their motor strategy seems more efficient and less energetically demanding, given the overall lower contraction levels and reduced number of involved muscles.

These observations may guide future rehabilitative interventions, which need to be targeted to the compensatory mechanism in each population, as well as provide insight into the neural processes underlying postural control.

Methods

Participants

Nine healthy right-handed elderly ([64-76] y) and 8 healthy right-handed younger ([24-34] y) adults were included in this study. Exclusion Criteria were: 1) Already diagnosed neuropathy or sensation of tingling in the legs or feeling of having reduced sensitivity to feet or legs; 2) Diabetes mellitus; 3) Any rheumatological pathology; 4) Orthopedic problems (e.g., arthrosis); 5) History of fractures of the lower limbs or feet; 6) History of spinal surgery; 7) History of hip and/or knee prosthesis operations; 8) History of stroke even if completely recovered. Hypertension was not considered a contraindication if under drug treatment and with good control.

This study was carried out in accordance with the recommendations of Ethics Committee of the Teaching Hospital of Padua (n.AOP2025) with written informed consent from all subjects.

Behavioral tests

As first task, participants were asked to perform the Trail Making Test, i.e., a neuropsychological test of motor speed and visual attention composed by two parts. In part A, i.e., TMT A, the subject's task is to quickly draw lines on a page connecting 25 consecutive numbers without lifting the pen from the paper. In case errors occur, participants are alerted and correction is allowed. The performance is assessed by the time taken to complete the trial correctly. In part B, i.e., TMT B, it is tested how fast the participant can connect numbers and letters in alternating increasing sequence (i.e., 1-A-2-B, etc.). Part B is more difficult than Part A not only because it is a more difficult cognitive task, but also because of its increased demands in motor speed and visual search[40]. Thus, TMT B evaluates visual attention, motor speed, and cognitive alternation.

Data acquisition

High-density EEG recordings were acquired at Padova Neuroscience Center inside a dimly lit sound-attenuated and electrically shielded room with the Geodesic Sensor Net with 256 electrodes (Electrical Geodesic Inc., Eugene, OR, USA). Electrode-skin impedances were maintained $< 40\ k\Omega$. The recordings were sampled at 500 Hz, referenced to Cz. In parallel, synchronized EMG recordings were acquired from the following muscles in the right leg (Figure 3a)): Rectus femoris (RF), Vastus lateralis (VL), Tibialis anterior (TA), Peroneus longus (PL), Gastrocnemius lateral head (GL), Biceps femoris (BF); and from Erector spinae (ES) with Cometa MiniWave Waterproof EMG sensors (Cometa srl, Milan, Italy). An expert researcher individualized the minimal crosstalk areas for the EMG electrode placement[41] as suggested by[42,43]. Skin preparation was performed removing dead cells and humidifying the areas if participants had a dry skin, or rubbing it with alcoholic wipes when they had a oily skin[43]. Electrode-skin impedances were maintained $< 74\ k\Omega$. The recordings were sampled at 2 kHz.

Baseline. Before performing the dual-task experiment, 3 minutes of quiet upright and barefoot standing in front of a black screen were acquired for each participant at the beginning and at the ending of the experiment.

The dual-task experiment consisted in a static or dynamic postural task while performing a visual task. Both the static and dynamic postural tasks were tested with and without the cognitive perturbation, i.e., a visual oddball. In particular, 30 s of standing before and after the visual oddball were recorded.

Static postural conditions. Participants were standing upright and barefoot on a plane - feet position was maintained consistent from trial to trial and at shoulder distance - inclined at different angles: 0% +22% (i.e., 12 °) and -22%.

Dynamic postural condition. Participants were keeping balance on a $50cm^2$ wooden core board with a 12° front-to-back tilt.

Visual oddball. Participants were asked to focus on a series of coherent pictures (i.e., red squares) presented on a screen in front of them with about 0.5 Hz rate. One incoherent picture (i.e., a yellow square) appeared at a random time during each trial. Participants were instructed to keep their gaze in front of them. Each block contained circa 80 standard (frequent) stimuli, and circa 20 incoherent (odd) stimuli. The total experiment included four blocks (3 for the static postural conditions, i.e., 0% +22% and -22%, and one for the dynamic postural condition) of 100 stimuli presented in a pseudo-randomized order. Each block lasted about 3 minutes. Stimulus duration was 500 ms and was presented centrally on a black background. Inter-stimuli interval was varying between 500 ms and 1 s. Participants were asked to count the incoherent pictures. A short pause between each block was offered to participants.

Data processing

EEG processing. EEG data were zero-phase-filtered in the interval [1-70] Hz through a 4 order Butterworth filter avoiding phase distortion. Channels in the cheeks and in the neck were discarded (204 channels left). EEG epochs were then extracted from the continuous dataset and time-locked from -500 to 500 ms relative to the onset of each image whereas the 30-s recorded before and after the dual-task were divided in non-overlapping epochs of 1 s. Noisy channels were identified by visual inspection and were interpolated using the nearest-neighbor spline method (average percentage of channels interpolated: 1.5%). Individual epochs containing non-stereotyped artifacts, peri-stimulus eye blinks and eye movements (occurring within $\pm$ 500

ms from stimulus onset) were also identified by visual inspection and removed from further analysis (average percentage of epochs removed: 10%). Data were cleaned from remaining physiological artifacts (eye blinks, horizontal and vertical eye movements, muscle potentials and other artifacts) through a Principal Component Analysis (PCA)-informed Independent Component Analysis (ICA) algorithm implemented in EEGLAB (average percentage of components removed: 9.1%).
We applied the LAURA algorithm implemented in Cartool[44] to compute the source reconstruction taking into account the patient's age to calibrate the skull conductivity[45][46][47]. The method restricts the solution space to the gray matter of the brain. Then, the cortex was parcellated into 45 brain regions of interest (ROIs)[48]: *(Right and Left:) Precentral gyrus; Superior frontal gyrus, dorsolateral; Superior frontal gyrus, orbital part; Inferior frontal gyrus, opercular part; Inferior frontal gyrus, triangular part; Inferior frontal gyrus, orbital part; Rolandic operculum; Superior frontal gyrus, medial; Superior frontal gyrus, medial orbital; Superior occipital gyrus; Middle occipital gyrus; Inferior occipital gyrus; Postcentral gyrus; Superior parietal gyrus; Inferior parietal, but supramarginal and angular gyri; Supramarginal gyrus; Angular gyrus; Paracentral lobule* and *Occipito-temporal gyrus; Supplementary motor area; Median cingulate and paracingulate gyri; Posterior cingulate gyrus; Calcarine fissure and surrounding cortex; Anterior cingulate and paracingulate gyri; Cuneus; Lingual gyrus; Precuneus*.
The dipoles in each ROI were represented with one unique time-series by a singular-value decomposition[49].
For each time-series represented the activity in each ROI, we computed the absolute and the relative power spectra in the canonical EEG frequency bands, i.e., delta [1-4] Hz, theta]4-8] Hz, alpha]8-12] Hz, beta [14-24] Hz, low gamma [30-50] Hz, high gamma]50-70] Hz.
Lastly, we performed two-sided Wilcoxon rank sum tests on the relative power spectra values for each ROI under the same postural/dual-task condition between the two groups (i.e., elderly and younger adults) to find the significant different activation between elderly and younger adults. Moreover, we performed two sided paired samples Wilcoxon signed rank tests inside the same group to compare relative power spectra values for each ROI between the different postural/dual-task condition to emphasize the seeds of each task. In particular, as input of the statistical tests, we used the relative power spectral values during the baseline condition (i.e., simple standing in front of a black screen) and we computed the difference between the relative power spectral value post-stimulus (i.e., 500 ms after the stimulus onset) and pre-stimulus (i.e., 500 ms before the stimulus onset) for the odd and frequent stimuli.

EMG processing. EMG data (time-locked with the EEG recordings) were zero-phase-filtered in the interval [20-250] Hz through a 4th-order Butterworth filter. EMG segments containing artifacts were identified by a threshold ($|EMG| > 5 * standard\ deviation$) and removed from further analyses (percentage of data-points removed: < 3.5 % for the elderly; < 3% for the younger adults).
We computed the Root Mean Square (RMS) value for each EMG signal. In order to compare the muscular activity between the two groups (i.e., elderly and younger adults), the RMS of each muscle activation during each task was divided by the within-group median RMS value of the same muscle while performing a Maximum Voluntary Contraction (MVC). Due to constraints of the experimental setup, MVCs were performed with the participants standing in the shielded room and equipped with the EEG cap. Not all the participants were able to perform a true MVC and normalizing the RMS within-subjects would lead to unreliable results. However, RMSs obtained from each muscle and within groups showed low variability and we can trust median values to be representative of the muscular activity for elderly and younger groups.
We then compared the normalized RMS value of each muscle under the same postural condition (i.e., $0\%, \pm 22\%$, core board) between the two groups through two-sided Wilcoxon rank sum tests and among all the four different postural conditions within each muscle and group through paired samples two sided Wilcoxon signed rank tests.

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Author contributions statement

A.D.F. wrote the initial project and granted financial support, contributed to manuscript writing and critical revision; M.R., R.D.M, E.F., P.B., A.D.F. conceived the experiment; M.R., R.D.M., E.F. recorded the data; M.R. analysed the data; P.B. supervised analysis of EMG data; M.R. and M.B. conceived, set up and analysed cognitive task experiment; M.R., E.F. and M.C. run the statistics; M.R. drafted the manuscript; S.M. reviewed the manuscript.

Ethics statement

All participants gave their written informed consent prior to the experiment and the study received the approval of the Ethics Committee of the Teaching Hospital of Padua, Padova, Italy (n.AOP2025). All experiments of this study were performed in accordance with relevant guidelines and regulations.

Additional information

Competing interests. The authors declare no competing interests.

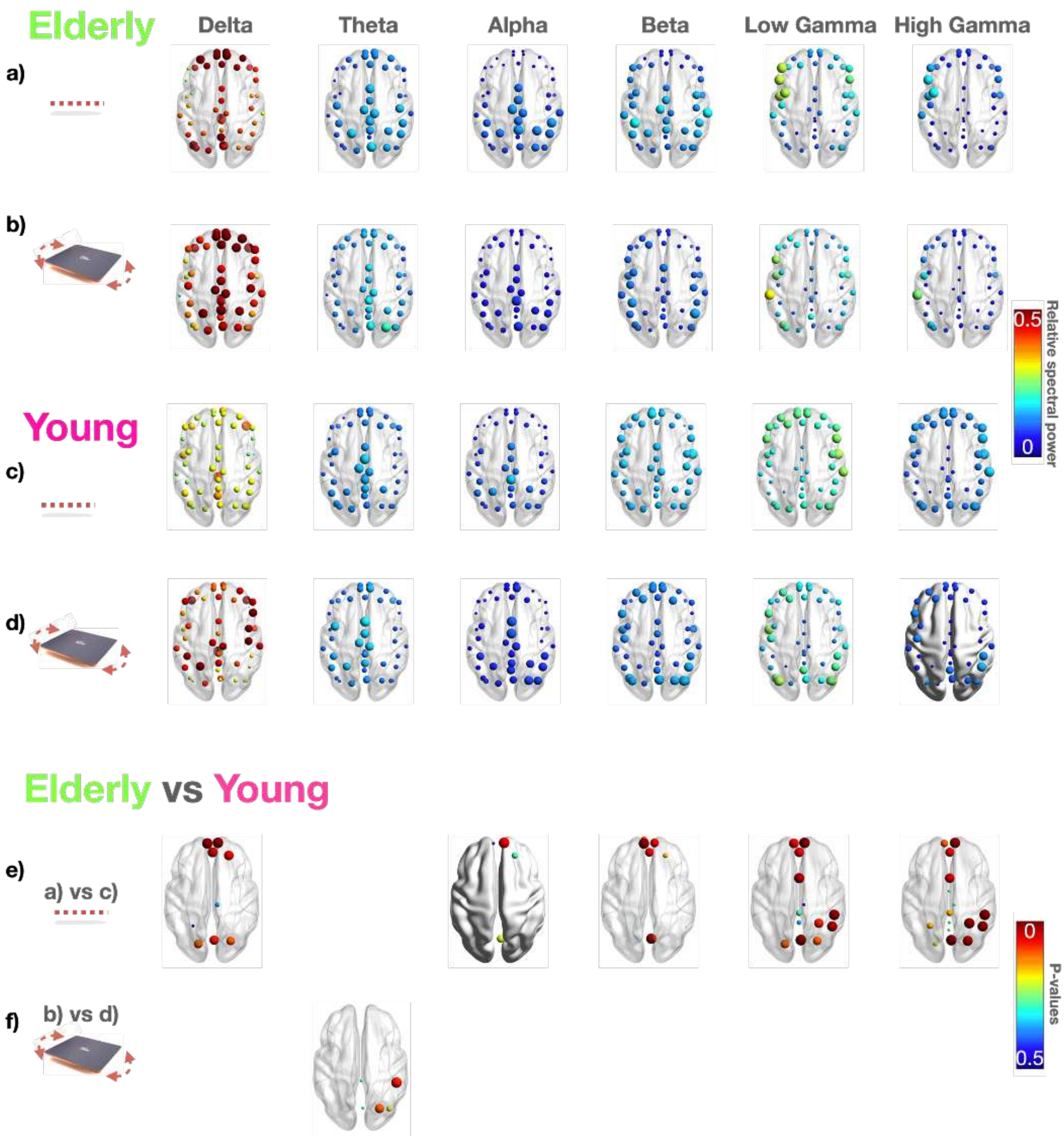

Figure 2. EEG power spectra during static (0%) and dynamic (core board) balance. Median values computed among the elderly in a) and b) and among the younger adults in c) and d) for each ROI represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude. Such information is also coded through a color scale. In particular, we reported the power spectra values for each EEG frequency band (ordered per columns) during static balance (0%) in a) and c) and during dynamic balance on the core board in b) and d). The p-values of the statistical significant differences between the younger and the elderly group were reported in panel e) during static balance (0%) and f) during dynamic balance (core board). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

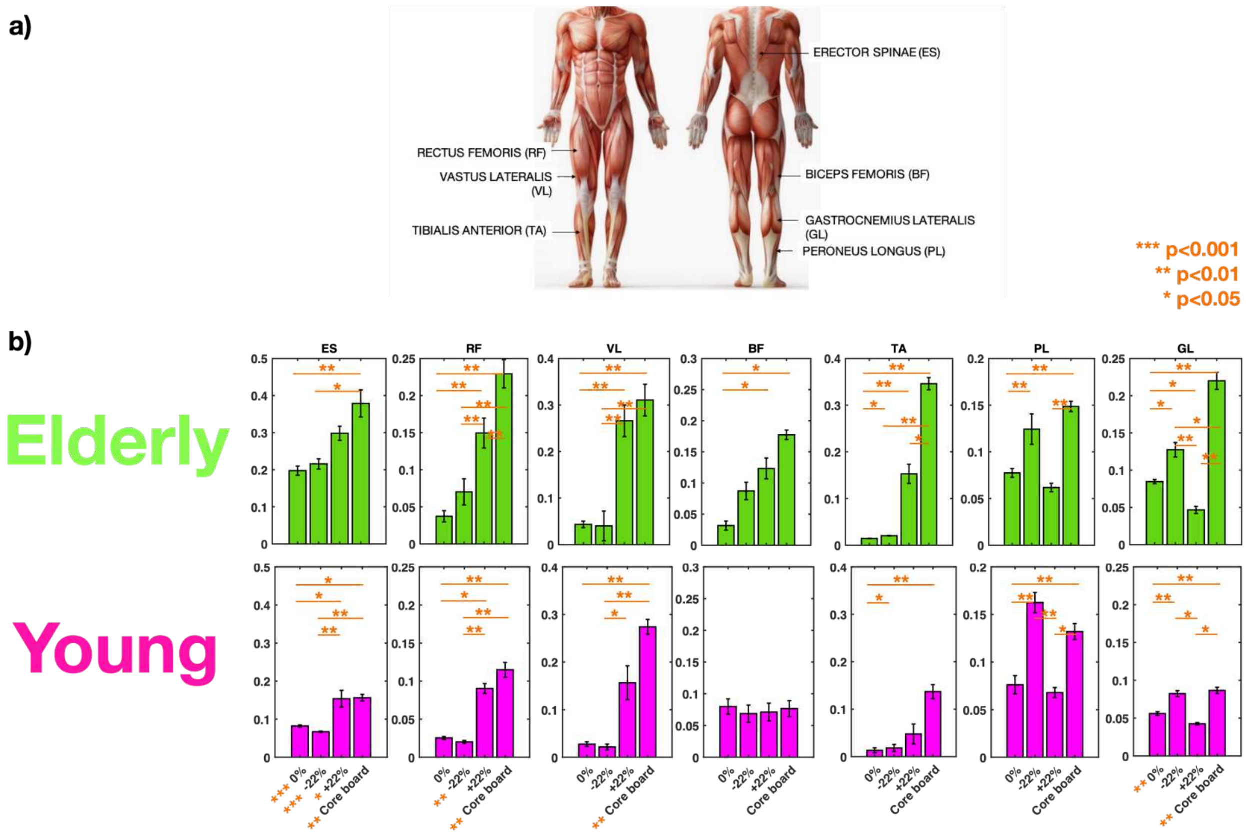

Figure 3. **a) Muscles measured by the EMG sensors. b)EMG results.** Median values among the elderly (in green) and the younger adults (in pink) of the RMS of each muscle (ordered in column), respectively from Erector spinae (ES), Rectus femoris (RF), Vastus lateralis (VL), Biceps femoris (BF), Tibialis anterior (TA), Peroneus longus (PL) and Gastrocnemius lateral head (GL) in static ($0\% \pm 22\%$) and dynamic (core board) balance. P-values are represented by asterisks. In each box, p-values represent statistically significant differences among postural conditions inside the same group. P-values reported in the x-axis represent statistically significant differences between the two groups under the same postural condition.

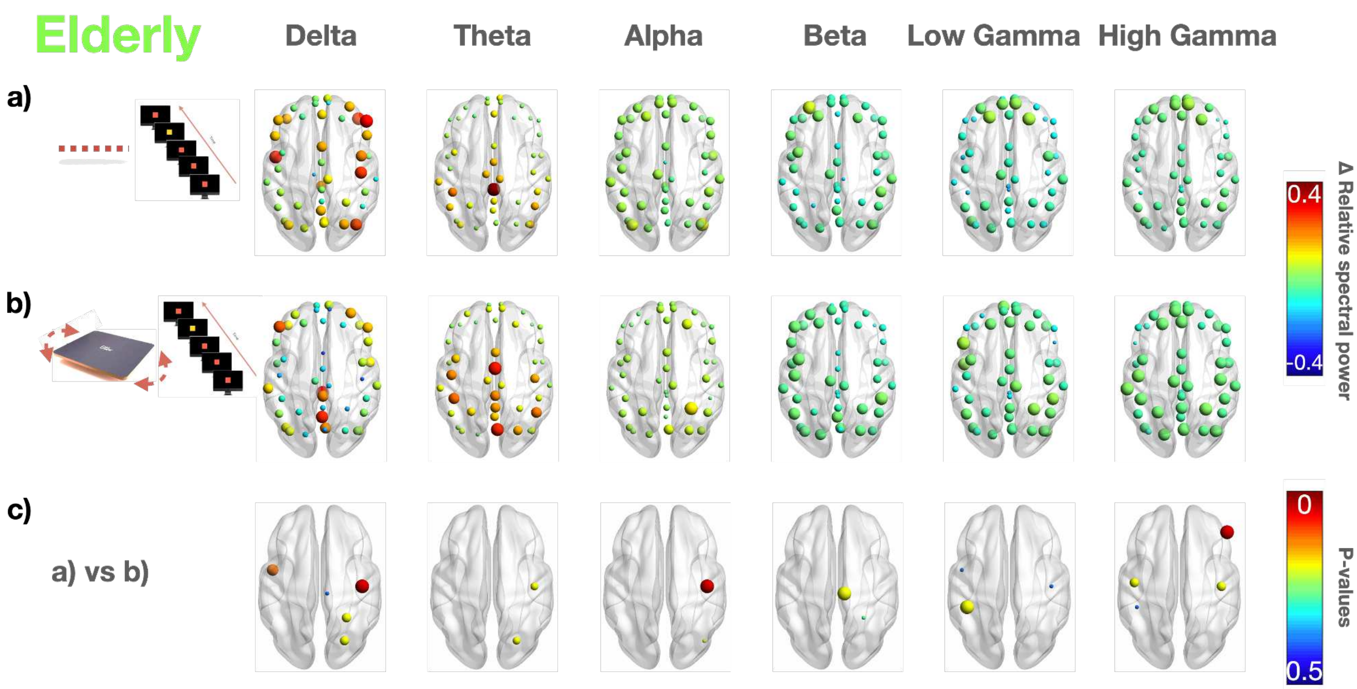

Figure 4. **EEG power spectra during dual-tasking in static (0%) and dynamic (core board) balance in the elderly**. Median values computed among elderly for each ROI represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude. Such information is also coded through a color scale. We reported the difference (Δ) of the power spectra between the 0.5 s-epoch post-odd stimulus and the 0.5 s-epoch pre-odd stimulus in the same postural conditions of Figure 2. The p-values of the statistical significant differences between a) and b) condition are reported in c). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

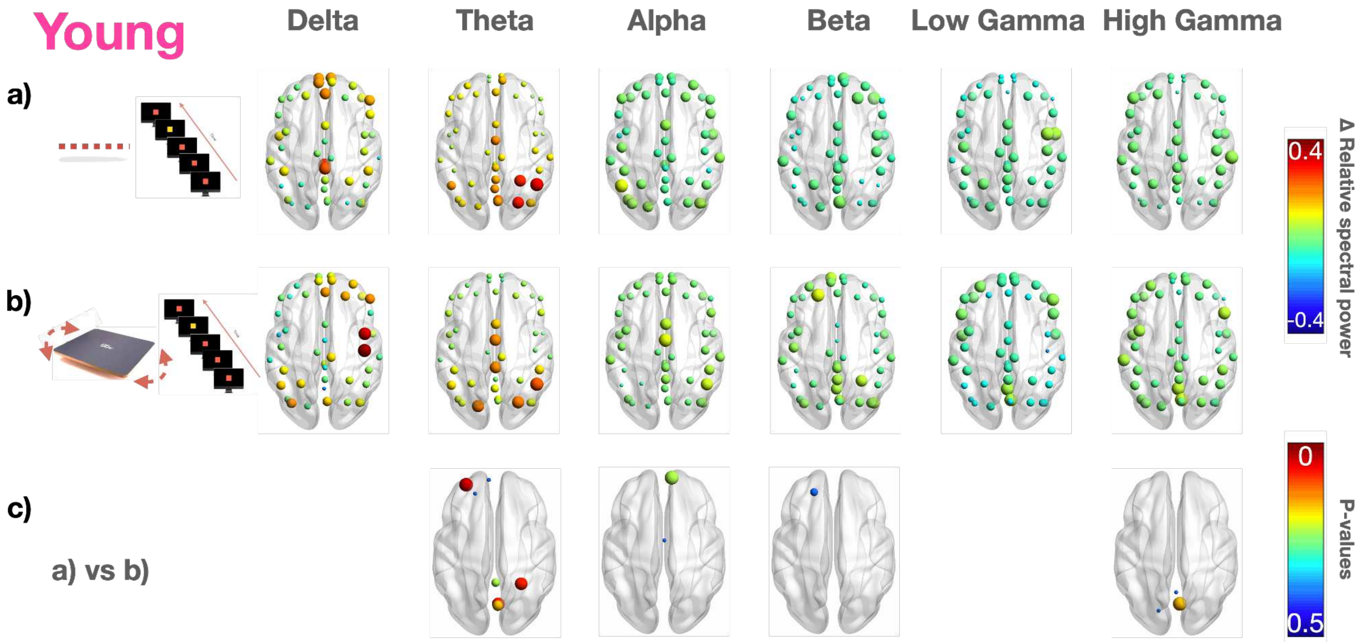

Figure 5. EEG power spectra during dual-tasking in static (0%) and dynamic (core board) balance in the younger adults. Median values computed among younger adults for each ROI represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude. Such information is also coded through a color scale. We reported the difference (Δ) of the power spectra between the 0.5 s-epoch post-odd stimulus and the 0.5 s-epoch pre-odd stimulus in the same postural conditions of Figure 2. The p-values of the statistical significant differences between a) and b) condition are reported in c). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

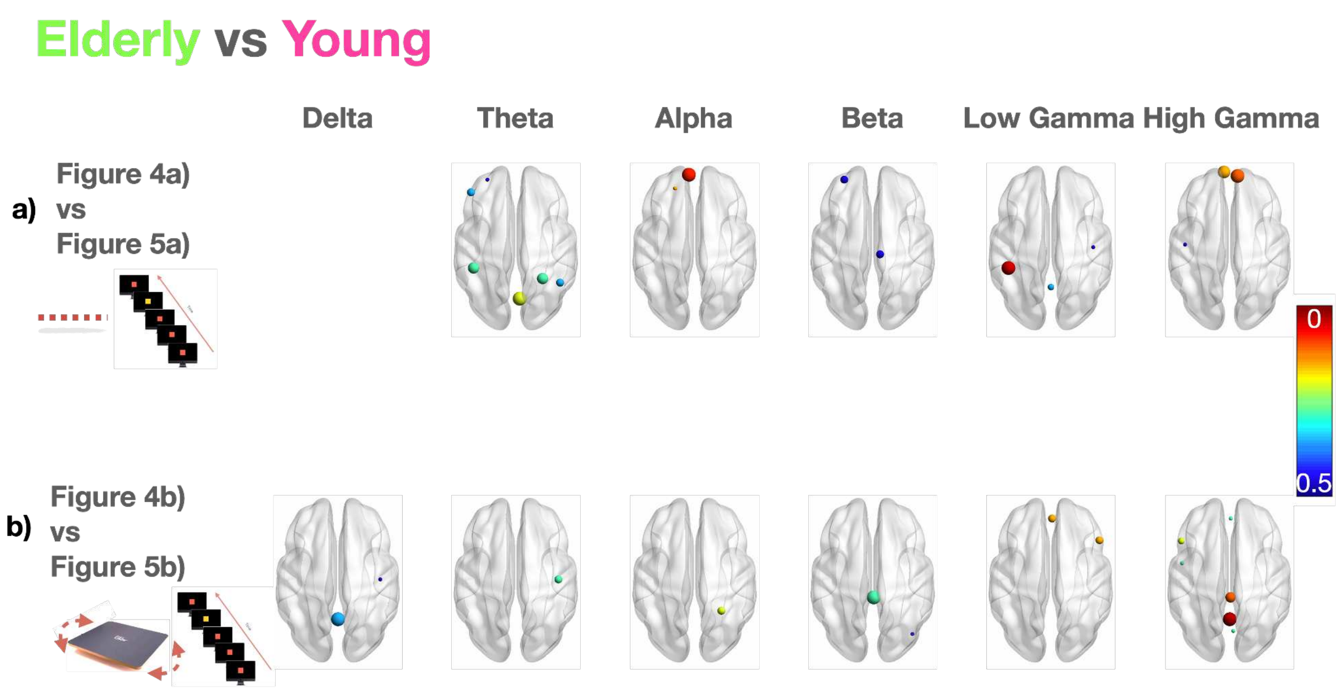

Figure 6. Statistics in elderly vs younger adults during odd stimuli in static (0%) and dynamic (core board) balance. The p-values of the statistical significant differences between the younger and the elderly group during a) visual odd stimuli and static balance (0%) and b) during visual odd stimuli and dynamic balance (core board). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

Figures

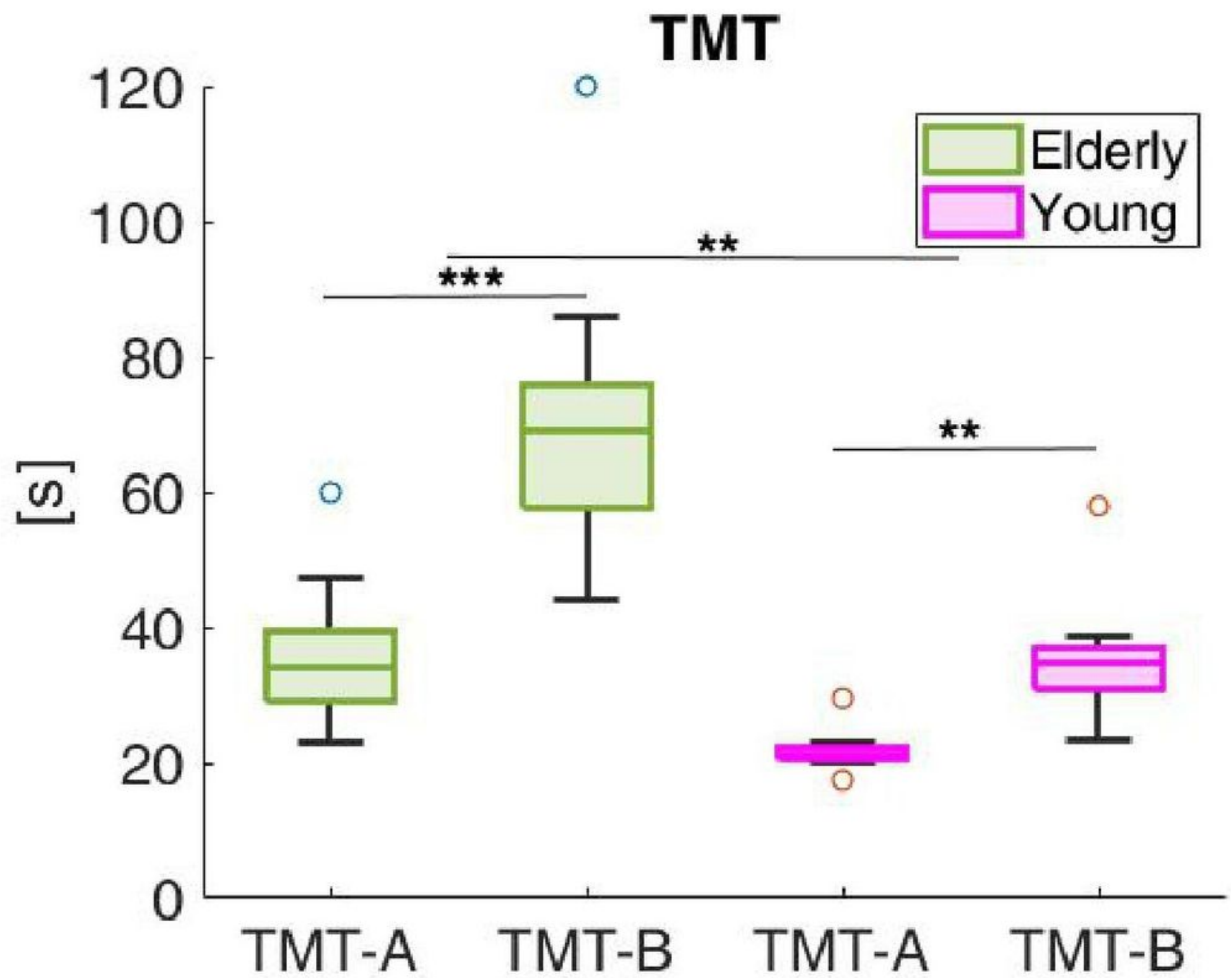

Figure 1

Time in seconds to perform the Trail Making Test (TMT) A and B for the elderly (in green) and for the younger adults (in pink). On each box, the central red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the 'o' symbol. Asterisks indicates statistical significant difference ('**' stands for pvalue < .01; '***' stands for pvalue < .001).

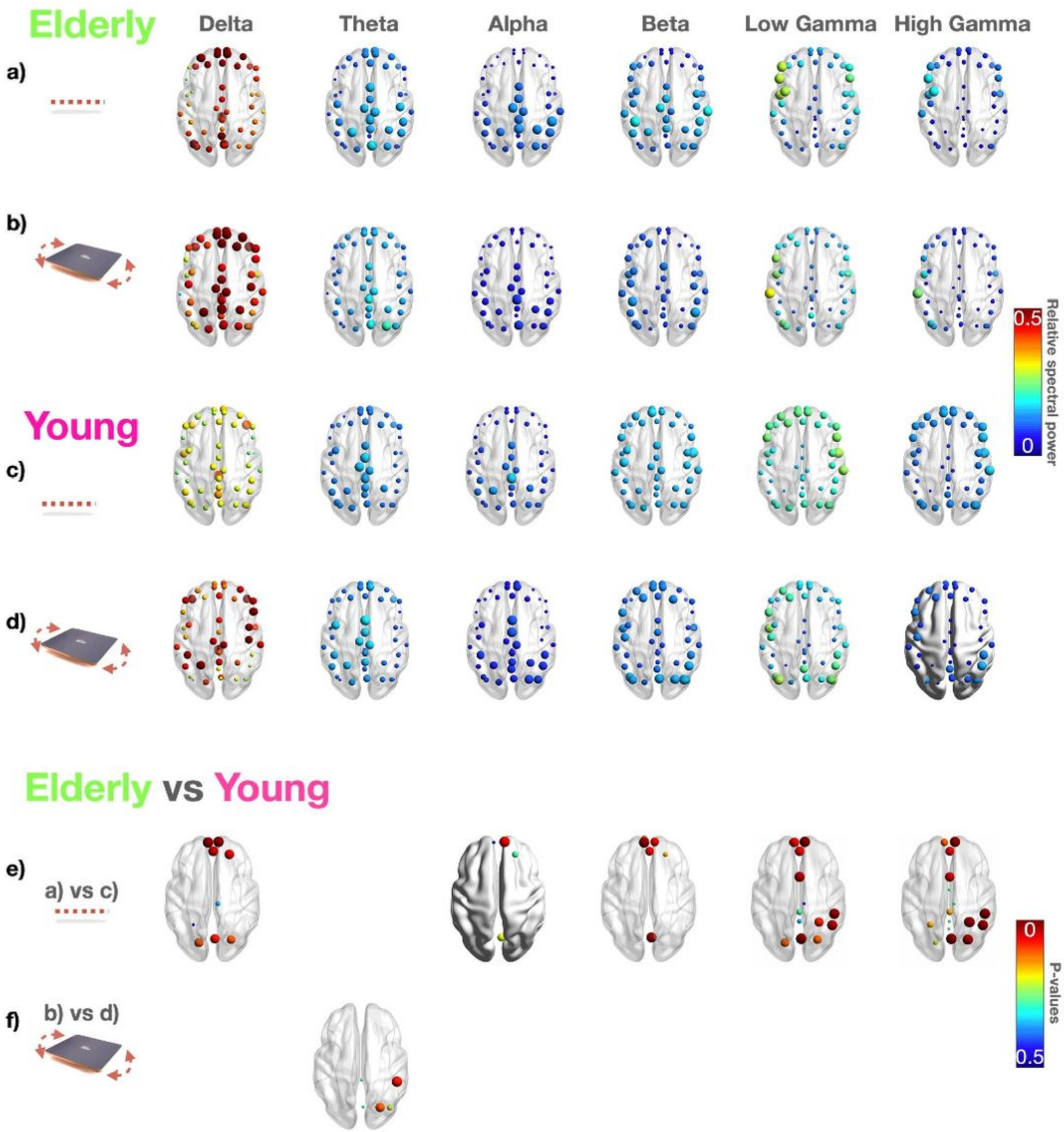

Figure 2

EEGpowerspectraduringstatic(0%)anddynamic(coreboard)balance. Median values computed among the elderly in a) and b) and among the younger adults in c) and d) for each ROI represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude. Such information is also coded through a color scale. In particular, we reported the power spectra values for each EEG frequency band (ordered per columns) during static balance (0%) in a) and c) and during dynamic balance on the core board in b) and d). The p-values of the statistical significant differences between the younger and the elderly group were reported in panel e) during static balance (0%) and f) during dynamic balance (core board). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

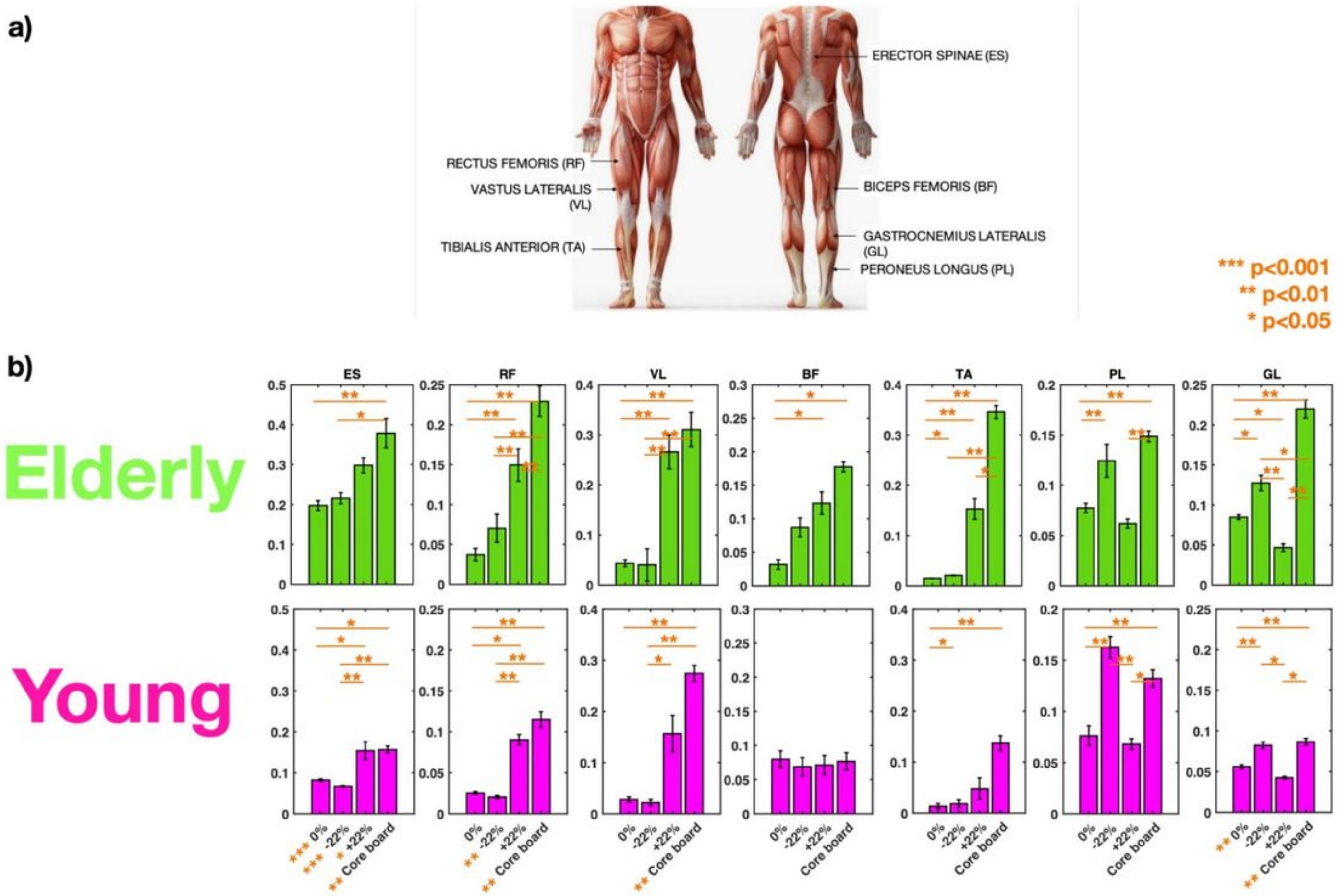

Figure 3

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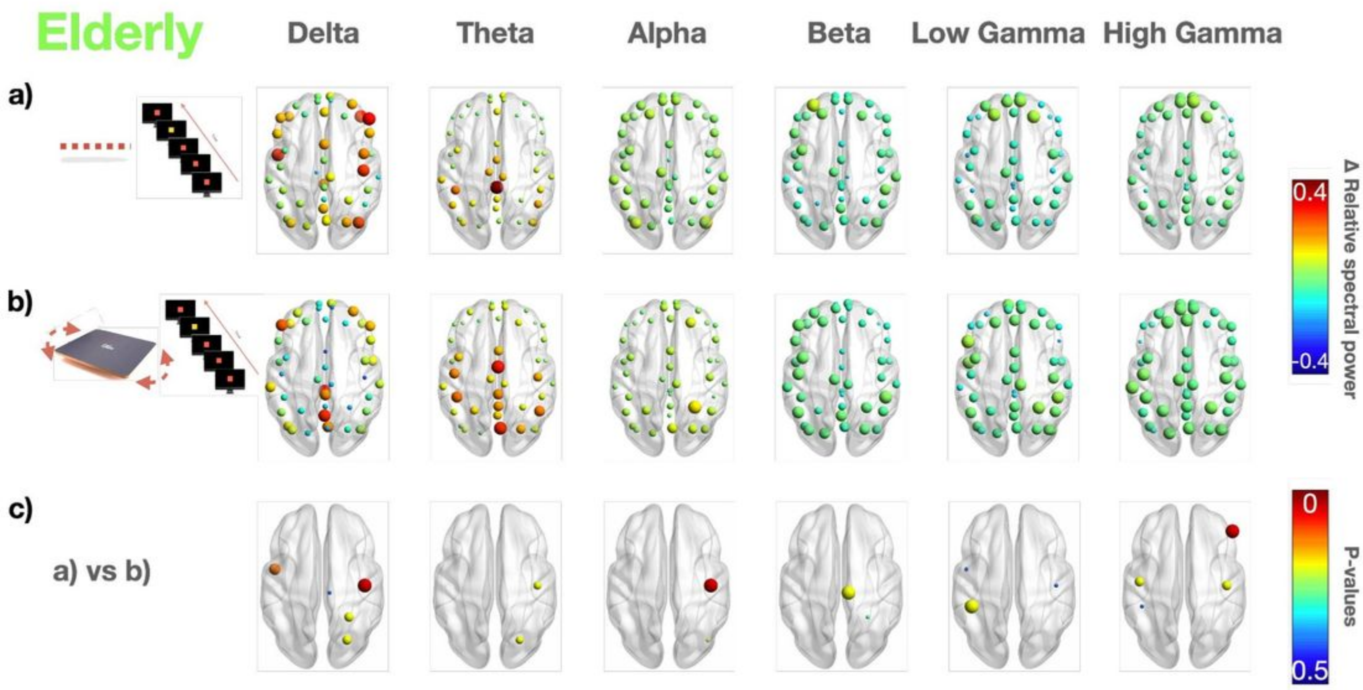

Figure 4

EEGpowerspectraduringdual-taskinginstatic(0%)anddynamic(coreboard)balanceintheelderly. Median values computed among elderly for each ROI represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude. Such information is also coded through a color scale. We reported the difference (Δ) of the power spectra between the 0.5 s-epoch post-odd stimulus and the 0.5 s-epoch pre-odd stimulus in the same postural conditions of Figure 2. The p-values of the statistical significant differences between a) and b) condition are reported in c). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

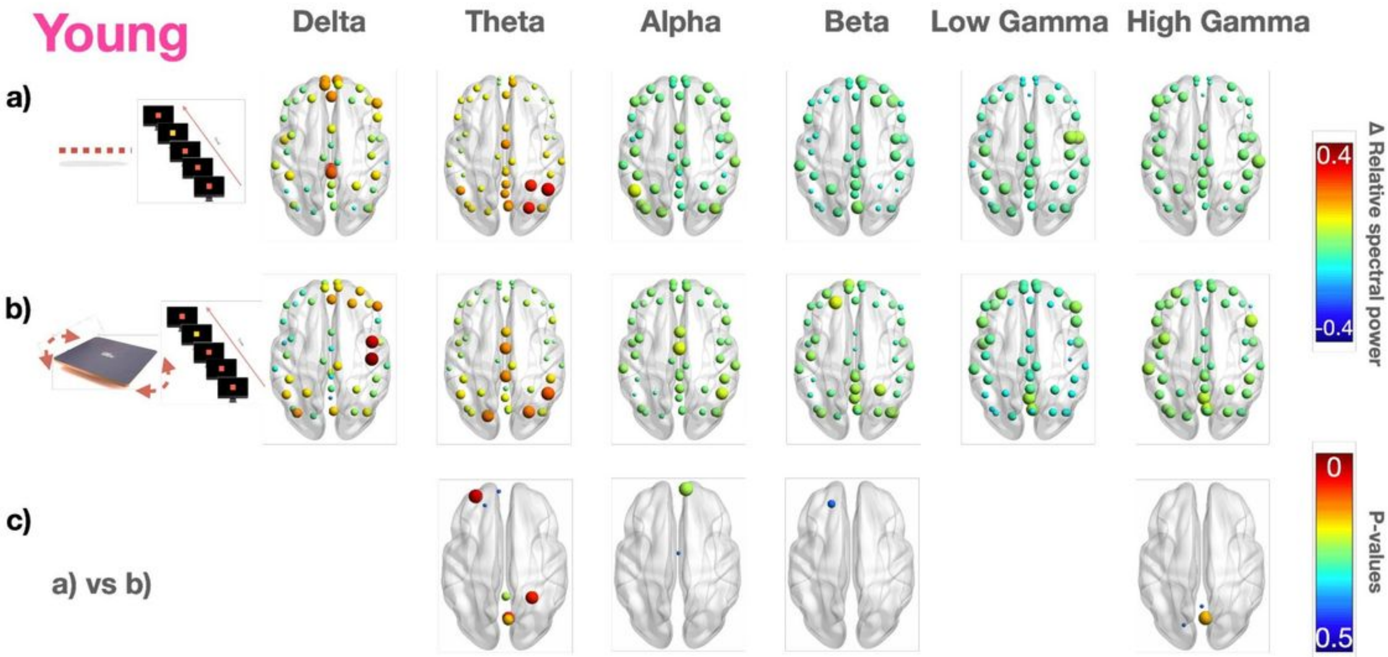

Figure 5

EEGpowerspectraduringdual-taskinginstatic(0%)anddynamic(coreboard)balanceintheyounger adults. Median values computed among younger adults for each ROI represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude. Such information is also coded through a color scale. We reported the difference (Δ) of the power spectra between the 0.5 s-epoch post-odd stimulus and the 0.5 s-epoch pre-odd stimulus in the same postural conditions of Figure 2. The p-values of the statistical significant differences between a) and b) condition are reported in c). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

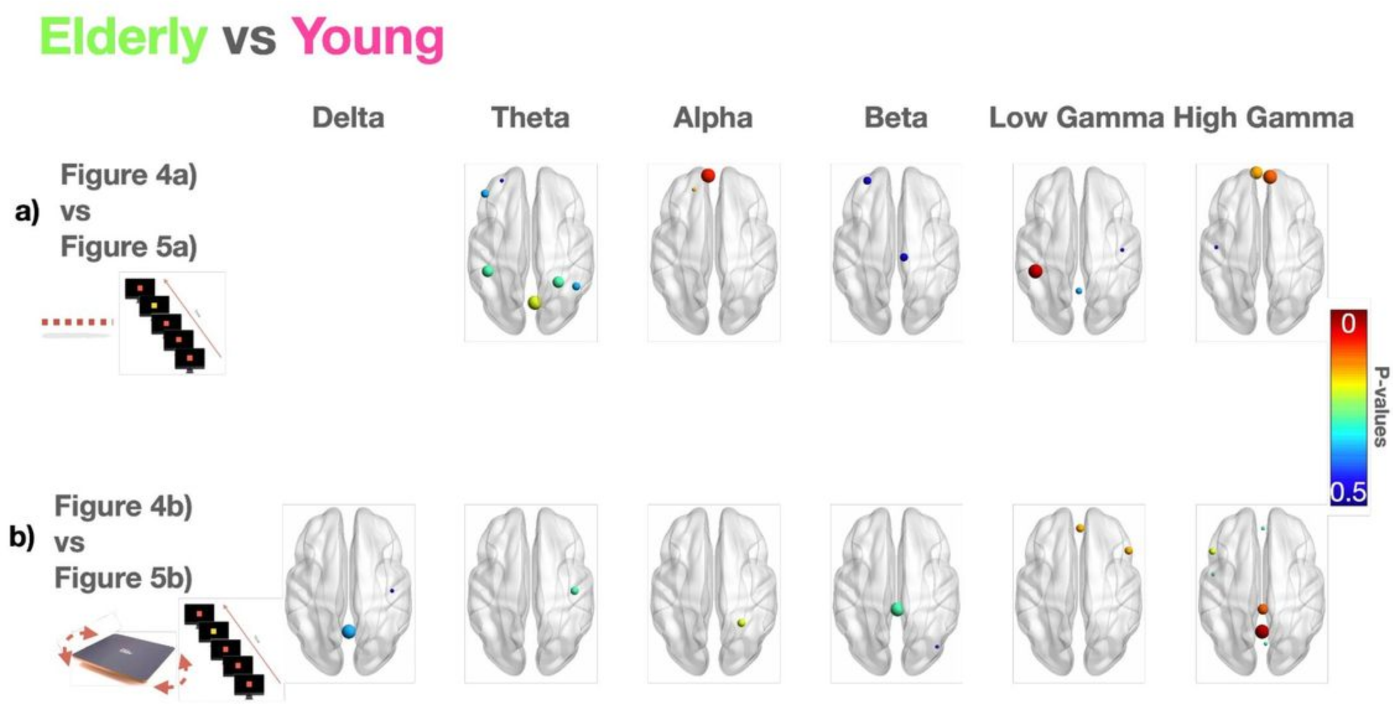

Figure 6

Statisticsinelderlyvsyoungeradultsduringoddstimuliinstatic(0%)anddynamic(coreboard)balance. Thep-valuesofthe statisticalsignificantdifferencesbetween theyoungerandthe elderlygroupduring a)visualoddstimuli and static balance (0%) and b) during visual odd stimuli and dynamic balance (core board). Each p-value < 0.05 is represented by a sphere centered on the cortical region, whose radius is linearly related to the magnitude, coded also through a color scale.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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