The cognitive triad network - oscillation - behaviour links individual differences in EEG theta frequency with task performance and effective connectivity

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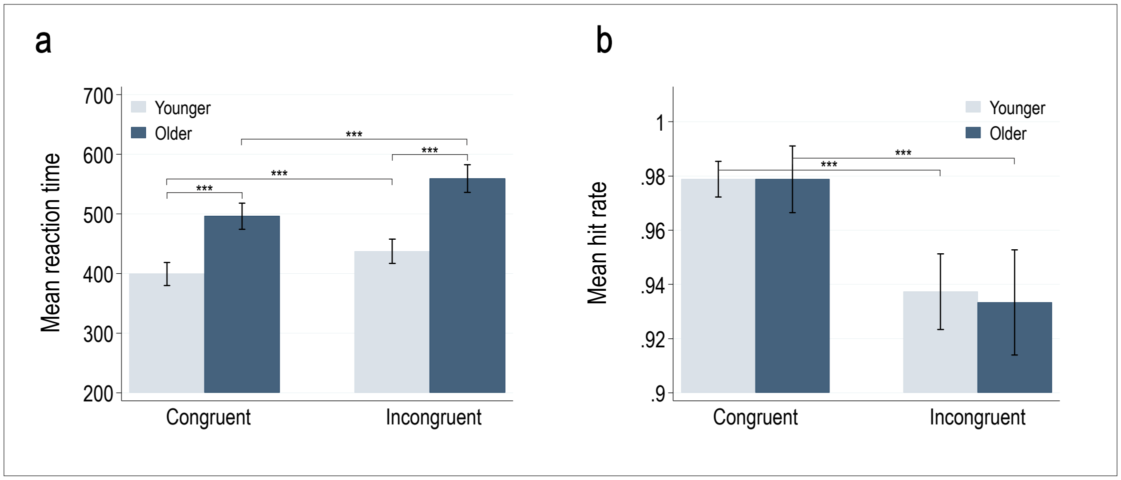
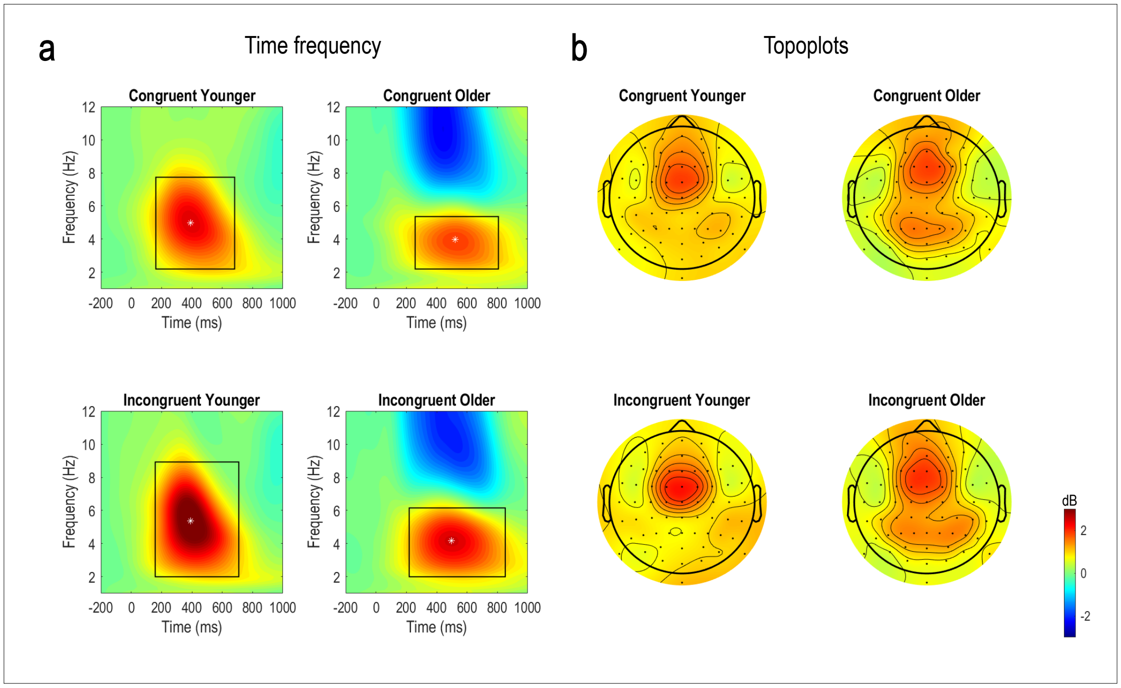
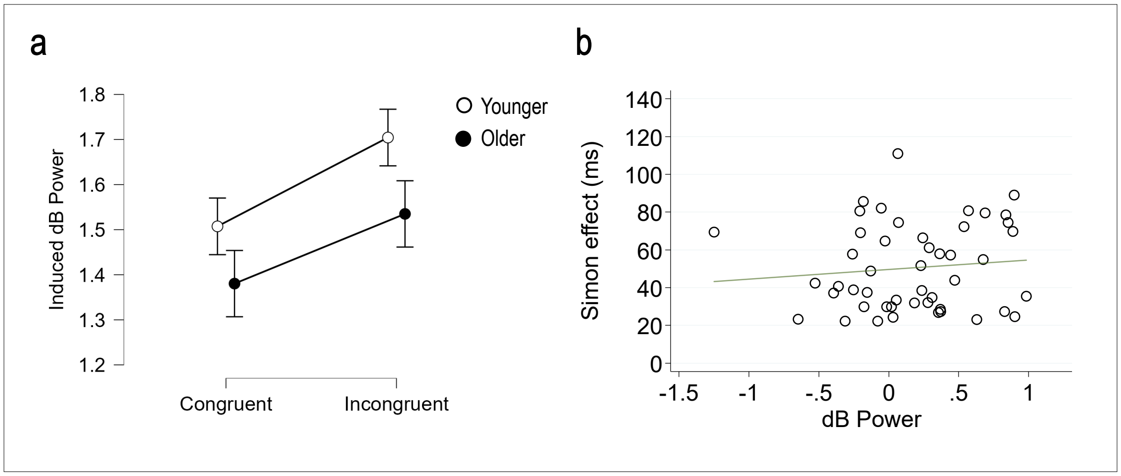
Supplementary information



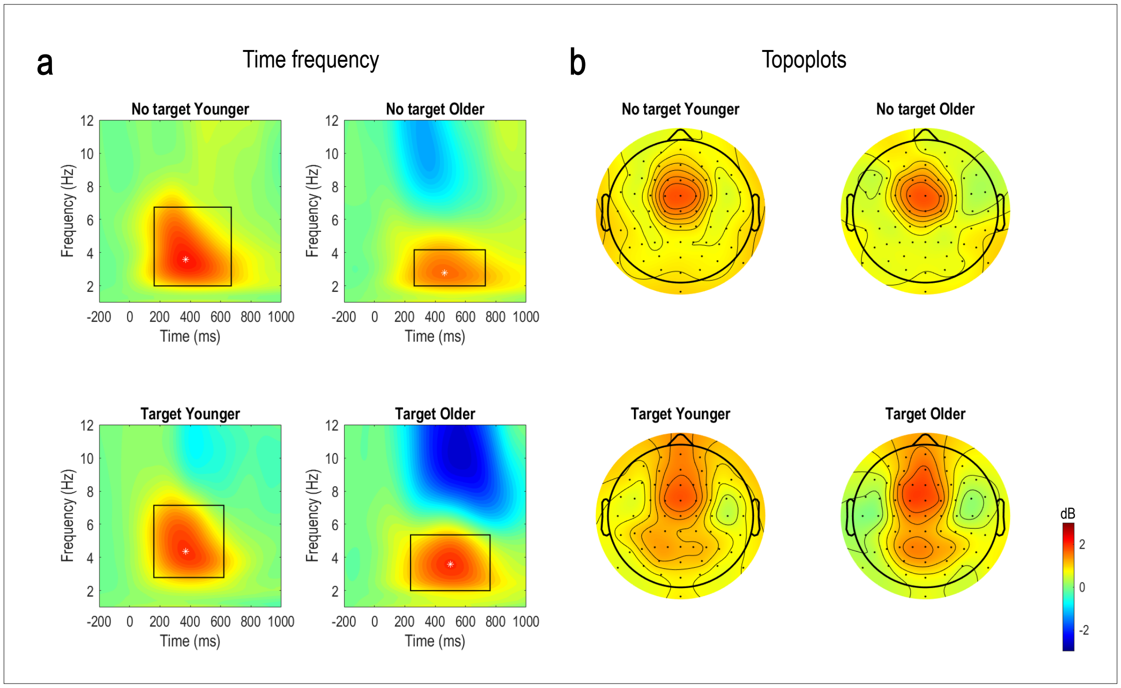
Supplementary Figure S1. Detailed Simon task analysis. Two-way mixed ANOVAs were performed on the mean reaction time (RT) and hit rate (HR). (**a**) The RT analysis revealed significant main effects of Condition [$F(1,46) = 333.64$, $p < .001$, $\eta_p^2 = 0.88$] and Age group [$F(1,46) = 59.06$, $p < .001$, $\eta_p^2 = 0.56$]. Additionally, a significant interaction between Condition and Age group in terms of RT was observed [$F(1,46) = 20.57$, $p < .001$, $\eta_p^2 = 0.309$]. Specifically, RTs in the incongruent condition (M = 498.36 ± 80.1) were significantly higher than in the congruent condition (M = 447.89 ± 68.96). Moreover, older adults exhibited higher RTs (M = 527.92 ± 53.31) than younger participants (M = 418.32 ± 47.11). Regarding the interaction between Condition and Age group, the difference in RTs between the congruent and incongruent conditions in the young group (Mean difference = -37.94, p<.001) was smaller than the difference observed in the older group (Mean difference = -63, p < .001). The results indicated that when presented with spatially conflicting stimuli, e.g., the word 'left' in the right ear, older adults were slower to press the button with the left hand, suggesting lower inhibitory control, as consistent with the ageing literature[1-3] leading to a larger Simon effect, as presented in Fig. 1 of the main text. (**b**) For HR, there was a significant main effect of Condition [$F(1,46) = 100.41$, $p < .001$, $\eta_p^2 = 0.69$]. Specifically, HRs in the incongruent condition (M = 498.36 ± 80.1) were significantly lower than in the congruent condition (M = 447.89 ± 68.96). No significant main effect of Age group [$F(1,46) = 0.06$, $p = 0.815$, $\eta_p^2 = 0.001$], and no interaction between Condition and Age group [$F(1,46) = 0.21$, $p = 0.65$, $\eta_p^2 = 0.005$] were found. The results show that participants responded more accurately to the Congruent stimulus, but there were no performance differences between the older and younger participants. In summary, older adults were slower to perform the task but did so as accurately as the younger adults.



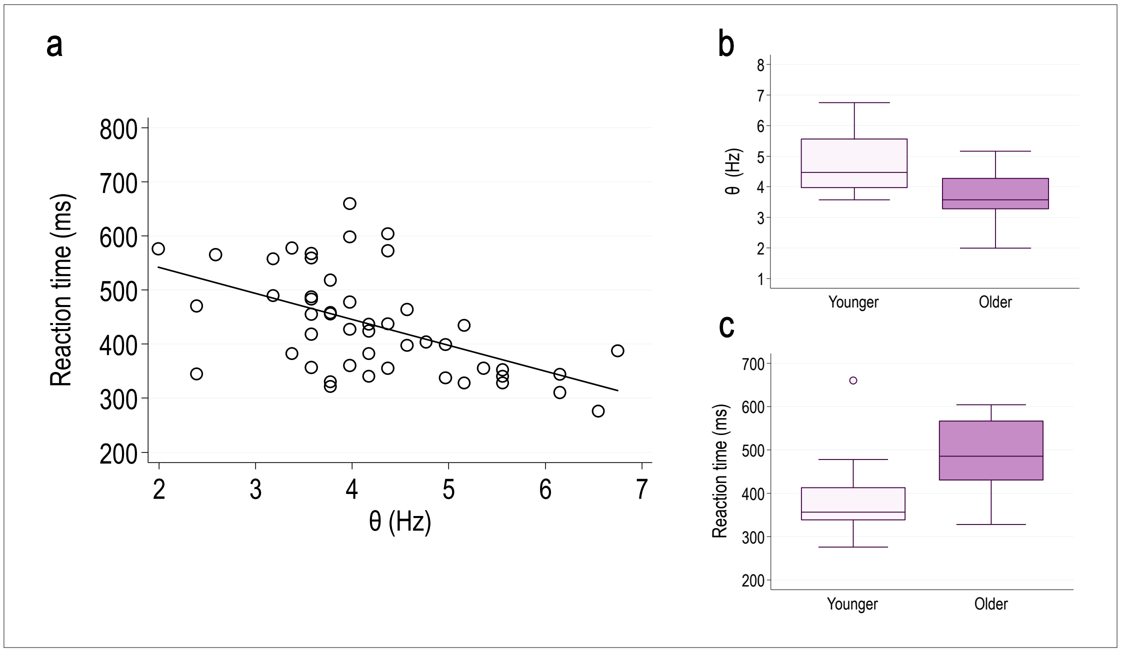
Supplementary Figure S2. Induced frontal theta oscillations during the Simon task. Induced power is calculated after removing the time-locked evoked activity. (**a**) The Time-Frequency graphs by condition and age groups in a pool of mid-frontal EEG electrodes comprising (FC3, FC1, FCz, FC2 and FC4). The white * indicates the peak f_θ at the group level for each condition/group. Higher theta power is observed in the Incongruent condition, as reported by multiple studies[4-8].The boxes mark the time-frequency window to extract the individual peak of f_θ. The younger adults had a significantly higher frontal f_θ. (**b**) Scalp topography by condition and age groups over the time and frequency range indicated by black boxes, corresponding to the time-frequency area with greater activity in the theta band. Note the broader scalp distribution of activity in older adults, indicating a more expansive network[9,10].



Supplementary Figure S3. Induced power analysis. Two-way mixed ANOVA was conducted on the mean of induced power for each subject across the Simon task conditions (congruent/incongruent) and age groups (older/younger adults), using data from the regions of interest highlighted in Figure S2. (**a**) The analysis revealed a significant main effect of condition on induced power [$F(1,46) = 6.61$, $p = .013$, $\eta_p^2 = 0.13$]. Induced power was significantly higher in the incongruent condition ($M = 1.62 \pm 1$) than in the congruent condition ($M = 1.44 \pm 0.87$). No significant difference in induced power was observed between age groups [$F(1,46) = 0.32$, $p = .57$, $\eta_p^2 = .007$]. Furthermore, there was no statistically significant effect of the interaction between condition and age group on induced power [$F(1, 46) = 0.1$, $p = .76$, $\eta_p^2 = 0.002$]. (**b**) Considering the difference in the power of the Simon effect (incongruent power - congruent power), no significant differences were found between the younger ($M = 0.2 \pm 0.44$) and older ($M = 0.16 \pm 0.51$) groups ($t(46) = 0.31$, $p = 0.76$, $d = 0.09$). Furthermore, no significant correlation was found between the power of the Simon effect and behavioural performance ($r(46) = .1$, $p = .48$).

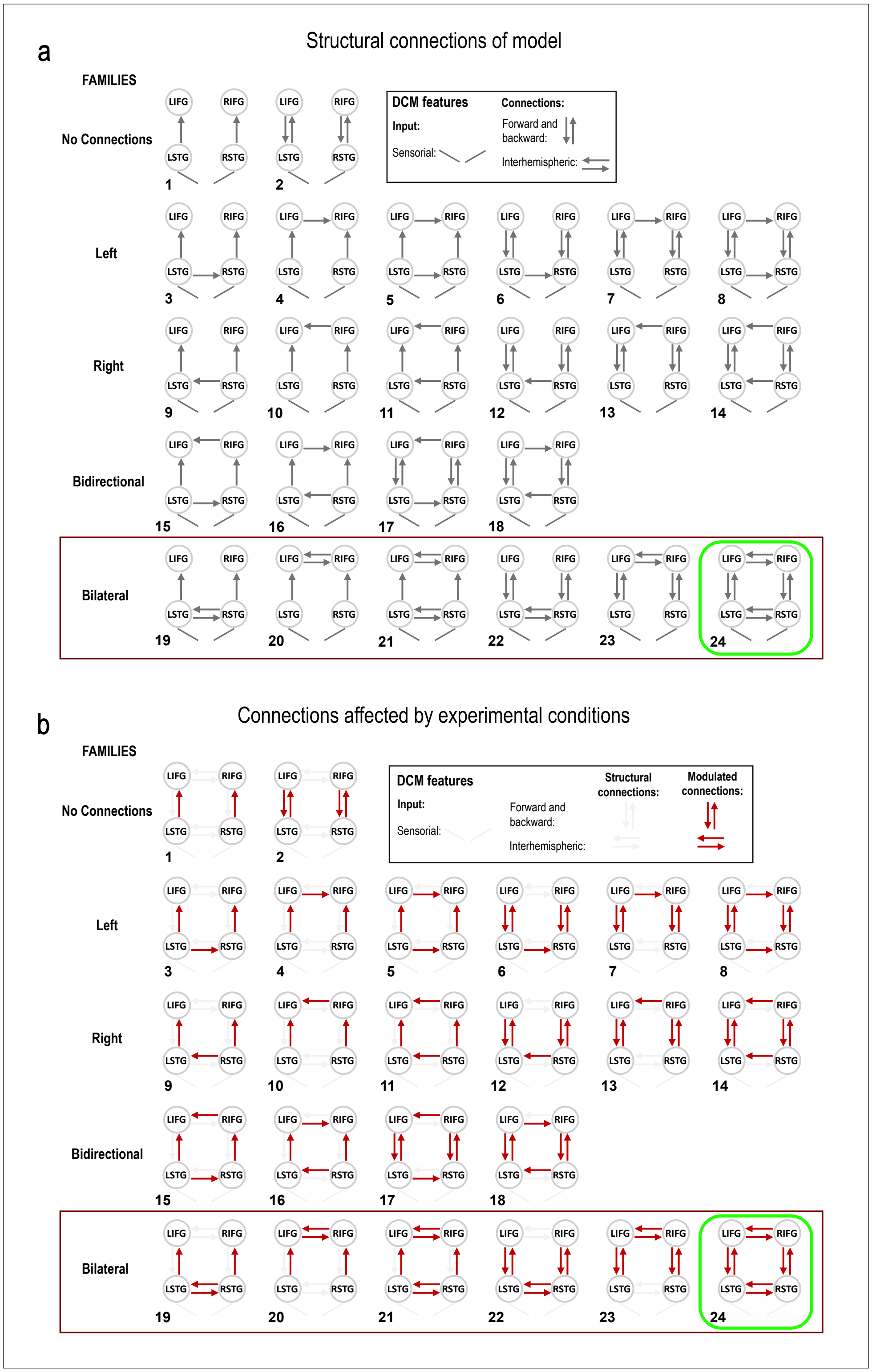


Supplementary Figure S4. Induced frontal theta oscillations during the auditory recognition task. Induced power is calculated after removing the time-locked evoked activity. (**a**) The Time-Frequency graphs by condition and age groups in a pool of mid-frontal EEG electrodes comprising (FC3, FC1, FCz, FC2 and FC4). The white * indicates the peak of f_θ at the group level for each condition/group. The black boxes mark the time-frequency window to extract the individual peak of f_θ. (**b**) Scalp topography by condition and age groups over the time and frequency range indicated by black boxes, corresponding to the time-frequency area with greater activity in the theta band.

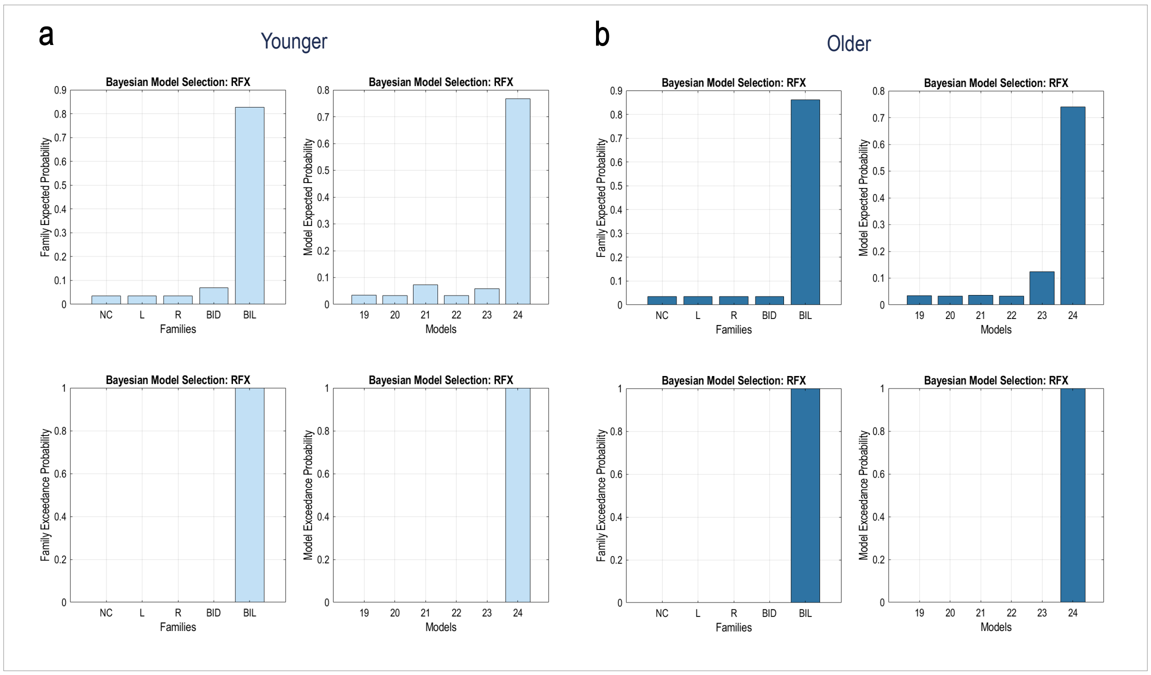


Supplementary Figure S5. Individual frontal theta frequency and Recognition task behavioural performance. In the recognition task, participants press the button on the higher or lower pitched sounds, counterbalanced between participants. (**a**) The reaction time of the target condition correlated with the individual induced peak, such that higher frequencies were associated with faster reaction times, f_θ $r(46) = -.53$, $p < .001$). (**b**) The individual induced peak of f_θ was significantly lower in the older adults compared to younger adults (U = 461, p < 0.001, r = .6, Mdn older = 3.58, Mdn young = 4.47) . (**c**) Older adults were significantly slower (M = 488.61, SD = 16.61) than the young adults (M = 382.74, SD = 77.67), (t(46) = -4.61, p < .001, d = -.1.33). However, there was no difference in HR (t(46) = .81, p=.43, d = .23). In summary, older adults were slower but performed as well as younger adults.

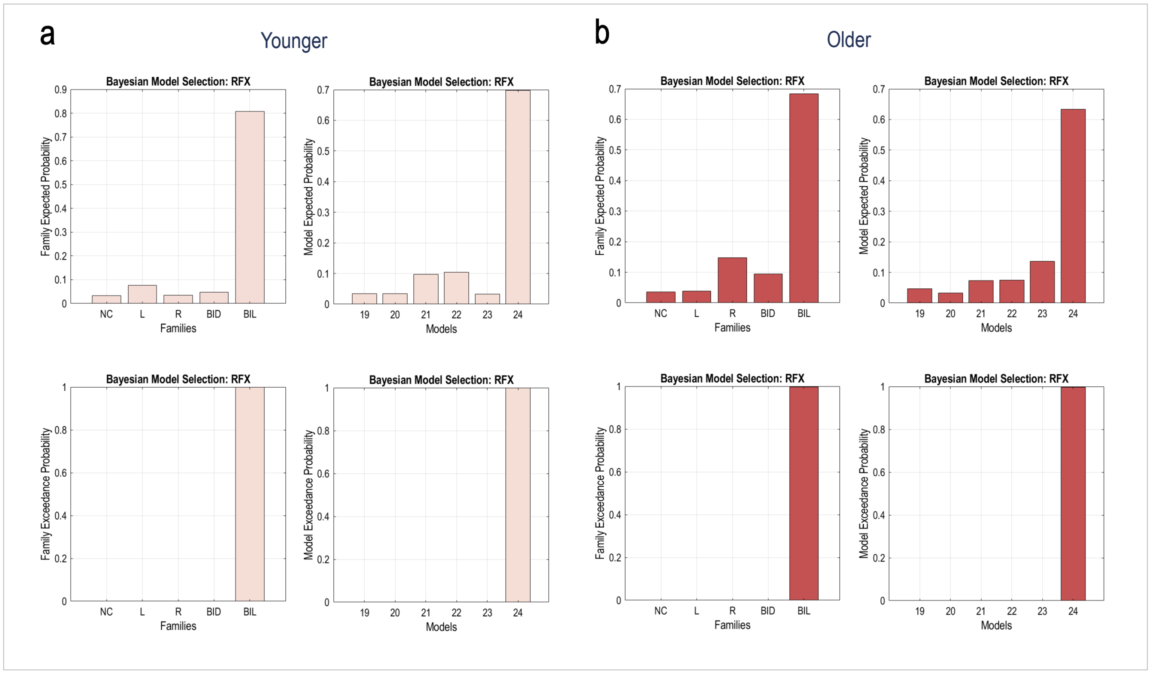
To compare the peak f_θ induced by the Simon task and the Auditory recognition task, we collapsed the conditions of both tasks and assessed for significant differences. The analysis revealed a significant difference (t(95) = 6.03, p < .001, d = 0.62), with the Simon task showing a higher peak f_θ (M = 4.63 Hz ± 1.3) in contrast to the Auditory Recognition task (M = 3.87 Hz ± 1.08).



Supplementary Figure S6. DCM model space for Simon task. The process of selecting the model employed to establish a relationship with theta frequency in the Simon task was conducted in two main stages, considering the left and right superior temporal gyrus (STG) and the left and right inferior frontal gyrus (IFG). (**a**) The initial stage was undertaken to establish structural connectivity, in which five families were considered according to their interhemispheric connectivity. Sensory input was always established in LSTG and RSTG. The best family was the Bilateral (red rectangle), and the winning model was the 24 (green square). (**b**) Based on the winning structural model (the most complex), a model space consisting of 24 models with the same families of the first stage was utilised to compare networks with different connections modulated by the effects of the congruent versus incongruent conditions. The best family was the Bilateral (red rectangle), and the winning model was the 24 (green square).

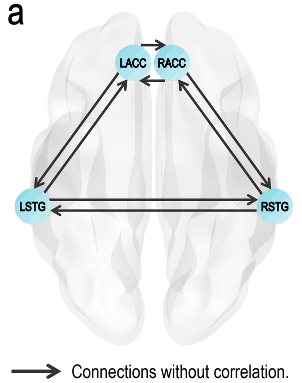


Supplementary Figure S7. Bayesian model selection testing structural models for the Simon task. (**a**) and (**b**) show the expected probability (top) and the exceedance probability (bottom) for each family (left) and models of the winning families (right) for younger and older adults, respectively. BMS favours model family BIL with bilateral interhemispheric connections between LSTG - RSTG and LIFG - RIFG in both groups [exceedance probability > 0.99]. Of all models of the winning family (BIL) for both groups, BMS favours model 24, with forward and backward connections between LSTG - LIFG, RSTG - RIFG, and bilateral interhemispheric connections between LSTG - RSTG and LIFG - RIFG (exceedance probability > 0.99).



Supplementary Figure S8. Bayesian model selection testing models with connections modulated by effects of congruent vs incongruent conditions of the Simon task. **(a)** and **(b)** show the expected probability (top) and the exceedance probability (bottom) for each family (left) and models of the winning families (right) for younger and older adults, respectively. BMS favours model family BIL with modulated bilateral interhemispheric connections between LSTG - RSTG and LIFG - RIFG in both groups (exceedance probability > 0.99). Of all models of the winning family (BIL) for both groups, BMS favours model 24, with modulated forward and backward connections between LSTG - LIFG, RSTG - RIFG, and bilateral interhemispheric connections between LSTG-RSTG and LIFG-RIFG (exceedance probability > 0.99).

a

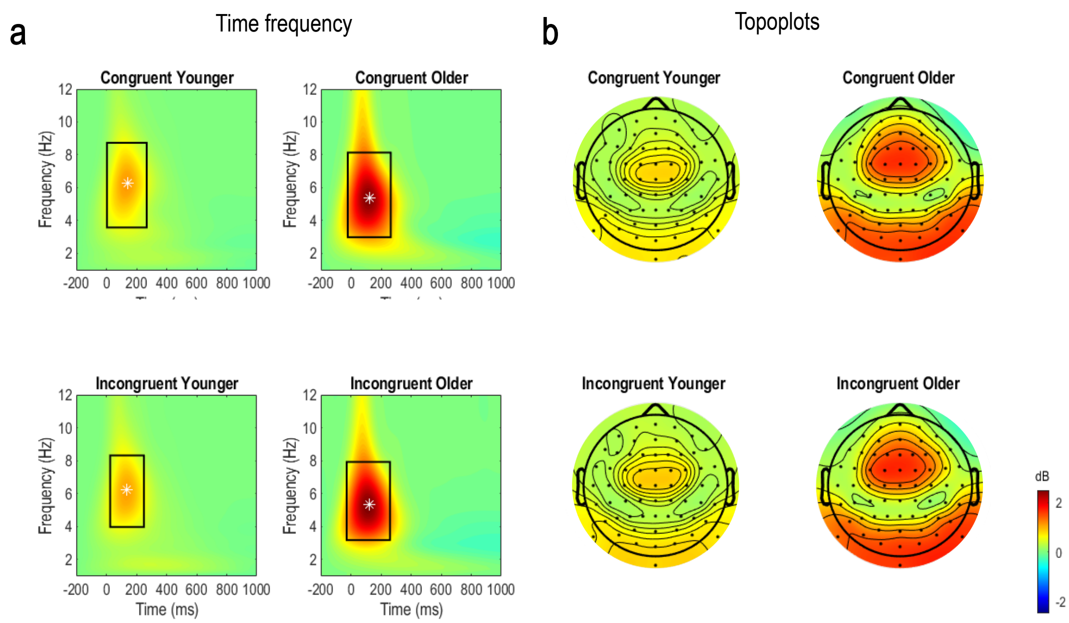


b

Correlation analysis

			Pearson		Spearman	
			r	p	rho	p
fθ	-	LSTG--RSTG	−0.128	0.386	0.015	0.917
fθ	-	LSTG--LACC	−0.222	0.129	−0.201	0.171
fθ	-	RSTG--LSTG	0.191	0.192	0.171	0.246
fθ	-	RSTG--RACC	0.133	0.366	0.041	0.780
fθ	-	LACC--LSTG	−0.099	0.504	−0.121	0.414
fθ	-	LACC--RACC	0.046	0.759	−0.007	0.965
fθ	-	RACC-RSTG	−0.019	0.899	−0.091	0.538
fθ	-	RACC--LACC	0.117	0.427	0.118	0.423

Supplementary Figure S9. Frontal theta frequency without correlation with the network connections of an alternative model in the Simon task. (**a**) Winning model in BMS considering the prefrontal sources LACC and RACC under the same methodology exposed in Supplementary Fig. S6. (**b**) Analysis without significant correlation between the connections of the winning model and the frontal theta frequency of each participant in the Simon task.



c

Independent Samples T-Test

	Test	Statistic	df	p	Cohen's d
Evoked fθ	Welch	3.17	35.46	0.003	0.915
Evoked power	Welch	-4.605	35.609	< .001	-1.329

d

Correlation analysis

				Coefficient	p
Evoked fθ	-	Simon effect	Spearman	-0.23	0.120
Evoked power	-	Simon effect	Spearman	0.25	0.092

Supplementary Figure S10. Phase locked theta activity during the Simon task. Phase-locked power is calculated by subtracting the induced activity from total power. (**a**) The Time-Frequency graphs by condition and age groups in a pool of mid-frontal EEG electrodes comprising (FC3, FC1, FCz, FC2 and FC4). The white * indicates the peak of evoked f_θ at the group level for each condition/group. The boxes mark the time-frequency window to extract the individual peak of evoked f_θ. (**b**) Scalp topography by condition and age groups over the time and frequency range indicated by black boxes, corresponding to the time-frequency area with greater activity in the theta band. (**c**) The younger adults had a significantly higher evoked f_θ and lower evoked power compared with the older group. (**d**) No significant correlations were found between phase-locked theta activity variables (evoked f_θ and evoked power) and the Simon effect.

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