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Crochet increases attention through a requiring motor skill learning

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In this study, we compared the effects promoted by a brief single session of crochet in a group of skilled knitters (CRO) and a control group (CRT) on the Attentional Network Test (ANT) and the whole brain Functional Connectivity (FC) revealed by Magnetoencephalography (MEG). Data revealed that crochet determined a significant effect (before, T0, vs after, T1, the crochet session) on reaction times (for all cue and stimulus types), improving alertness and orienting networks (but not executive control) only in the CRO group. Data of FC are coherent with the behavioural ones. We observed that the Betweenness Centrality maximum (BCmax) index in the beta band significantly increased, and global FC in the alpha band significantly increased at T1 for the CRO group but not for the CTR group. Increased global BCmax in the beta band after the crochet activity correlated with better performance (reduced reaction times), suggesting that the brain has become more efficiently integrated, thus increasing the information exchange between different brain areas. Decreased global FC in the alpha band may reflect a transition from a quiet, global rest to a condition of increased alertness and readiness to stimuli. Finally, we discuss the hypothesis that these results could be the reinforcement of connections between motor and attentional networks promoted by learning the complex motor skills of crochet.

Several studies have shown that craft-handed activities (for example knitting, crochet and pottery) have psychological benefits, such as relaxation, relief from stress, and enhanced perceived sense of control and choice, probably because they represent a form of self-expression, giving to participants a sense of purpose and, in some case, a meaningful vehicle for social activities[1,2]. In this context, knitting and crocheting fans strongly believe in the several positive effects that their occupation may provide; they also perceive their passion as a means of being productive whilst engaging in passive activities, such as watching television or travelling, or during an unproductive time, such as queuing or waiting for appointments[2]. All these benefits for mental health and stress relief contributed to reviving an old-fashioned craft as a portable, "cool" hobby, potentially useful even for therapeutic purposes[3]. The creativity stimulated by the conception of an object and the repetitiveness of the actions has been advocated as the main reason to explain relaxation and a sense of accomplishment promoted by the textile-related arts[1,2]. Beyond these psychological benefits, previous studies revealed that crocheting and knitting have a deep impact in promoting attention, improving spatial awareness and facilitating Motor Skill Learning (MSL), related or even not-related to the textile-related arts[2,4].

In works focusing on MSL, the complex relationship between perceptual input and motor actions has been extensively studied using "simplified" experimental settings[5]. Taking into consideration this "compartmentalized" approach, it is not completely surprising that there has been little consideration of the cognitive impact on motor control and of the influences of a demanding MSL on the "cognitive" functions, such as memory and attention, especially in the complex environmental conditions as the ecological, real-world context is[6].

Some studies demonstrate how allocating attentional resources to a concurrent task could interfere with sequence learning, sensorimotor adaptation, and force-field learning[7,8]; however, these studies focused mainly on how divided attention negatively affects immediate motor performance, thus not considering how it affects motor memory formation and retrieval which depends on whether participants consistently perform the secondary task during MSL and later recall stages, independently of the total amount of available attentional resources[9]. Intriguingly, Song and Bédard[10] showed that a motor skill learned during a dual task was recalled only when a similar secondary task was present, while the performance reverted to untrained levels as if the motor task had not been learned when participants were tested without the secondary task. This counterintuitive

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result suggests that a requiring and faceted context (in this work the dual task) could act as a boost for MSL and motor memory. These results highlight that attention plays a crucial role during MSL in selecting sensory stimulation to integrate it with motor memory beyond merely providing resources for learning[10]. In turn, it is possible to speculate that intense exercises enhance the attentional components: requiring attentional states due to MSL could form an enduring internal context for visuomotor memory which is independent of the external environment without decreasing the attention capacity[11].

This challenging daily activity, acquired and continually improved through enduring and repetitive sessions, probably acted as a boost for the attentional networks and their effective allocation.

Hence, our study aimed to identify the effect of crocheting on the attentional brain networks, comparing the modifications of the cortical connectivity detected by Magnetoencephalography (MEG) with the behavioural scores obtained at the Attentional Network Test (ANT)[12], after a single session of crochet in a group of experienced crocheters (CRO), in comparison with a control group (CTR).

Results

Behavioural task

All volunteers adequately carried out the protocol, including ANT, which is a computerized test measuring the three main attentive networks, i.e. Alerting, Orienting and Executive Control.

One subject of the CRO group was excluded from all analyses due to technical problems during the acquisition, whereas three CRO subjects and one CTR subject were excluded from the analyses because they made too many errors in the behavioural task (error rate 11.5%, 12.8%, 10.8% and 12.8%, respectively). Therefore, 36 subjects from the CRO group and 11 from the CTR group were included in the analysis.

For the remaining subjects in the first test (T0) the mean error rate was 6.9% and 8.7% for CRO and CTR respectively, while in the second test (T1) was 3.0% and 4.8%.

For both groups, the accuracy increased between the first and second test (CTR: 96.86 ± 0.49% vs. 98.2 ± 0.69%; CRO: 96.91 ± 0.47% vs. 98.61 ± 0.28%). rmANOVA showed a significant main effect of TIME on accuracy and global RTs ($F(1,46) = 12.94$, $p < 0.001$, $\eta^2 = 0.22$ and $F(1,46) = 18.83$, $p < 0.001$, $\eta^2 = 0.29$ respectively). Post-hoc tests revealed that the accuracy significantly increased in both groups (CTR: $t(10) = -4.06$, $p = 0.002$, $d = -1.22$; CRO: $t(36) = -3.84$, $p < 0.001$, $d = -0.63$). The mean RTs significantly decreased in CRO group ($t(36) = 4.85$, $p < 0.001$, $d = 0.72$) and strongly reduced in CTR group ($t(10) = 2.17$, $p = 0.055$, $d = 0.63$). On average, in both groups, the RTs decreased in all conditions (Table 1).

For the different cue types, rmANOVA showed a significant effect of TIME ($F(1,46) = 19.02$, $p < 0.001$, $\eta^2 = 0.29$) and cue types ($F(1.5,69.48) = 48.63$, $p < 0.001$, $\eta^2 = 0.51$). Comparing separately the group between the first and second ANT test, RTs decreased in both groups, but significantly only in the CRO group (Table 1).

For the different stimulus types, rmANOVA showed a significant effect of TIME ($F(1,46) = 18.97$, $p < 0.001$, $\eta^2 = 29$), stimulus types ($F(1.25,57.31) = 95.06$, $p < 0.001$, $\eta^2 = 0.67$) and a significant interaction between them ($F(1.73,79.37) = 8.77$, $p < 0.001$, $\eta^2 = 0.16$). Comparing RTs between the first and second ANT test, post-hoc tests

		Center cue (ms)	No cue (ms)	Spatial cue (ms)	Mean RT (ms)	T0 vs T1
CRO group						
Congruent	T0	503.2 ± 12.3	517.8 ± 13.0	486.7 ± 11.2	**503.3 ± 11.7**	t(36) = 4.97, p < 0.001, d = 0.82
	T1	481.0 ± 11.4	481.9 ± 12.2	451.1 ± 10.4	**473.0 ± 10.8**	
Neutral	T0	509.5 ± 11.8	505.5 ± 11.0	476.5 ± 12.0	**495.8 ± 11.3**	t(36) = 3.56, p = 0.001, d = 0.59
	T1	477.6 ± 11.6	493.5 ± 11.6	457.1 ± 12.3	**474.5 ± 11.2**	
Incongruent	T0	552.2 ± 13.0	551.3 ± 10.9	516.8 ± 12.7	**540.5 ± 11.8**	t(36) = 5.33, p < 0.001, d = 0.88
	T1	521.7 ± 12.6	517.6 ± 11.4	476.6 ± 11.8	**506.2 ± 11.6**	
Mean	T0	**520.8 ± 12.0**	**524.6 ± 11.4**	**493.2 ± 11.6**	**513.1 ± 11.4**	
	T1	**493.4 ± 11.5**	**497.6 ± 11.4**	**461.1 ± 11.3**	**484.6 ± 11.1**	
	T0 vs T1	t(36) = 4.55, p < 0.001, d = 0.75	t(36) = 4.24, p < 0.001, d = 0.70	t(36) = 5.19, p < 0.001, d = 0.85	t(36) = 4.85, p < 0.001, d = 0.80	
CTR group						
Congruent	T0	520.2 ± 26.7	535.5 ± 23.5	493.9 ± 29.2	513.9 ± 24.7	t(10) = 2.07, p = 0.065, d = 0.62
	T1	496.2 ± 24.2	499.3 ± 24.2	462.7 ± 24.0	485.2 ± 22.5	
Neutral	T0	508.3 ± 26.3	513.2 ± 22.1	480.5 ± 24.0	499.8 ± 23.5	t(10) = 1.68, p = 0.123, d = 0.51
	T1	483.9 ± 22.4	496.9 ± 24.2	464.8 ± 24.0	481.0 ± 22.6	
Incongruent	T0	559.8 ± 25.1	561.4 ± 23.1	511.0 ± 26.0	*543.6 ± 24.5*	*t(10) = 2.60, p = 0.026, d = 0.78*
	T1	521.4 ± 23.2	526.8 ± 23.0	484.4 ± 26.8	*512.1 ± 22.9*	
Mean	T0	*528.5 ± 25.6*	536.6 ± 22.7	495.1 ± 25.9	518.9 ± 24.0	
	T1	*500.2 ± 23.5*	507.6 ± 22.3	470.7 ± 24.7	492.7 ± 22.4	
	T0 vs T1	*t(10) = 2.29, p = 0.045, d = 0.69*	t(10) = 2.03, p = 0.070, d = 0.61	t(10) = 2.06, p = 0.066, d = 0.62	t(10) = 2.17, p = 0.055, d = 0.66	

Table 1. Reaction time (RT) of the attentional test. Bold text indicates a significant difference between T0 (first test) and T1 (second test) after correction for multiple comparisons. Italic text indicates results not surviving the correction (trend).

revealed that RTs decreased to all stimulus types in both groups, but the differences were significant for the CRO group (Table 1), whereas they were not significant for the CTR group.

rmANOVA showed a significant effect of TIME for alertness and orienting networks (F(1,46) = 6.72, p = 0.013, $\eta^2 = 0.13$ and F(1,46) = 5.41, p = 0.024, $\eta^2 = 0.11$). Post-hoc tests revealed that the difference was significant for the CRO group (ART: t(36) = − 2.79, p = 0.004, d = − 0.46; ORT: t(36) = 2.97, p = 0.003, d = − 0.49), but not for the CTR group (ART: t(10) = − 1.59, p = 0.143, d = − 0.48; ORT: t(10) = 1.32, p = 0.218, d = 0.40, Table 2).

Functional connectivity

Briefly, for each participant of the CRO and CTR group, 45 non-overlapping epochs with a duration of 2 s each of MEG signal in the open-eye resting condition before and after crochet performance (CRO) or relaxing (CTR) were selected. From these epochs, different indices of Functional Connectivity (FC) were calculated in the classical EEG bands from 4 to 30 Hz. FC was calculated by means of weighted Phase Lag Index (wPLI); wPLI weights the cross-spectrum according to the magnitude of the imaginary component. This allows it to limit the influence of cross-spectrum elements around the real axes which are at risk of changing their “true” sign with small noise perturbations.

rmANOVA on global FC in the alpha band showed a significant main effect of TIME (F(1,46) = 5.06, p = 0.029, $\eta^2 = 0.10$) and a trend toward the significance of between groups difference (F(1,46) = 3.00, p = 0.090, $\eta^2 = 0.06$). Post-hoc tests revealed that the global FC was significantly higher at T1 with respect to T0 for the CRO group (t(36) = − 3.79, p = 0.003, d = − 0.52), but not for the CTR group (t(10) = − 0.917, p = 0.381, d = − 0.28). When comparing connectivity values at T1 between groups, a trend for higher values in the CRO than in the CRT group was found (t(46) = − 1.75, p = 0.087, d = − 0.60). The post-hoc power analysis revealed that the study has limited power (power = 0.53) to detect the observed effect size with the given sample size. No other differences were found.

rmANOVA on BC maximum values (BCmax) in the beta band showed a significant effect of TIME (F(1,46) = 4.91, p = 0.032, $\eta^2 = 0.10$). Post-hoc revealed that BCmax values increase at T1 with respect to T0 in the CRO (t(36) = − 2.40, p = 0.022, d = − 0.39) but not in the CRT group (t(10) = − 1.40, p = 0.191, d = − 0.42).

rmANOVA on Tree Hierarchy (TH) in alpha band measures showed a robust trend toward the significance of between-groups factor (F(1,46) = 3.85, p = 0.056, $\eta^2 = 0.08$). Post-hoc-test showed that the values increased almost significantly at T1 only in the CRO group (t(36) = − 1.77, p = 0.085, d = − 0.29) whereas they did not change in the CRT group (t(10) = 0.20, p = 0.845, d = − 0.06). The TH value at T1 was significantly higher in CRO with respect to CTR group (t(46) = − 1.99, p = 0.053, d = − 0.68). The post-hoc power analysis revealed that the study was slightly underpowered (power = 0.62) to detect the observed effect size with the given sample size, even in presence of a medium effect size.

Results of FC are shown and plotted in Table 3 and Fig. 1, respectively.

Correlation between FC and behavioral measures

The correlation analysis between changes in FC and behavioral measures gave no significant results for theta bands. In beta band a significant relationship was found between BCmax and RT changes (r(48) = − 0.34, p = 0.017), whereas in alpha band, a strong trend to significance was found between FC and RT changes (r(48) = 0.28, p = 0.056) (Fig. 2).

Discussion

In this study, we investigated for the first time the short-term effects of crochet on the performance in a well-known attentional test and on the global cortical functioning networks revealed by MEG, in a group of crocheters, compared with a sex and age-matched control group.

We studied the behavioural effects of crochet by submitting the enrolled volunteers to the ANT test before and after a short crochet session. The ANT and subsequent variants can evaluate all three attentional components (i.e., alerting, orienting and executive control[13,14]). ANT was previously used in healthy children[15], in younger[12,13] and older adults[15,16], proving its validity and reliability in studying the modifications of the attentional networks.

In our sample, we found that crochet improved alerting and orienting networks because a significant effect of time (T0 vs T1) on RTs (for all cue and stimulus types) and alertness and orienting networks (but not for executive control) was found for the CRO but not for the CRT group. As these scores usually remain constant after repeated sessions even in an older population[15,16], the improvements in alerting and orienting scores can be attributed to the crochet performance.

Data of FC are coherent with the behavioural ones: in resting condition, we observed a TH in the alpha band and BCmax in the beta band significantly higher at T1 with respect to T0 for the CRO group, but not

	CRO group		CTR group	
	T0	T1	T0	T1
Alertness (ms)	**− 14.58 ± 4.34**	**− 0.91 ± 4.16**	− 15.04 ± 10.62	− 3.09 ± 6.26
Orienting (ms)	**− 16.48 ± 4.92**	**− 29.94 ± 4.05**	− 26.3 ± 10.36	− 33.48 ± 6.56
Executive control (ms)	37.20 ± 3.88	33.22 ± 3.39	29.72 ± 7.26	26.85 ± 8.42

Table 2. Alertness, orienteering and executive control networks results. Bold indicates a significant difference between T0 (first test) and T1 (second test).

		CTR T0	CTR T1	CRO T0	CRO T1
Theta	wPLI	0.36 ± 0.00	0.36 ± 0.00	0.36 ± 0.00	0.36 ± 0.00
	BCmax	0.69 ± 0.02	0.69 ± 0.02	0.68 ± 0.01	0.70 ± 0.01
	Diameter	15.3 ± 0.82	16.6 ± 0.94	15.65 ± 0.50	15.35 ± 0.52
	Tree Hierarchy	0.37 ± 0.00	0.37 ± 0.01	0.38 ± 0.01	0.37 ± 0.01
Alpha	wPLI	0.27 ± 0.00	0.28 ± 0.00	**0.28 ± 0.00**	**0.29 ± 0.01**
	BCmax	0.71 ± 0.02	0.75 ± 0.03	0.71 ± 0.01	0.69 ± 0.01
	Diameter	14.3 ± 0.91	12.4 ± 0.75	13.38 ± 0.57	13.40 ± 0.46
	Tree Hierarchy	0.39 ± 0.01	0.39 ± 0.01	**0.40 ± 0.01**	**0.42 ± 0.01**
Beta	wPLI	0.15 ± 0.00	0.16 ± 0.00	0.16 ± 0.00	0.16 ± 0.00
	BCmax	0.69 ± 0.01	0.72 ± 0.03	**0.68 ± 0.00**	**0.72 ± 0.01**
	Diameter	14.10 ± 1.10	14.8 ± 0.91	14.70 ± 0.58	15.03 ± 0.53
	Tree Hierarchy	0.39 ± 0.02	0.37 ± 0.02	0.40 ± 0.01	0.38 ± 0.01

Table 3. Comparison of minimum spanning tree measures during the resting condition. Bold indicates a significant difference between T0 (first recording) and T1 (second recording). *wPLI* weighted Phase Lag Index, *BCmax* Betweenness Centrality maximal value.

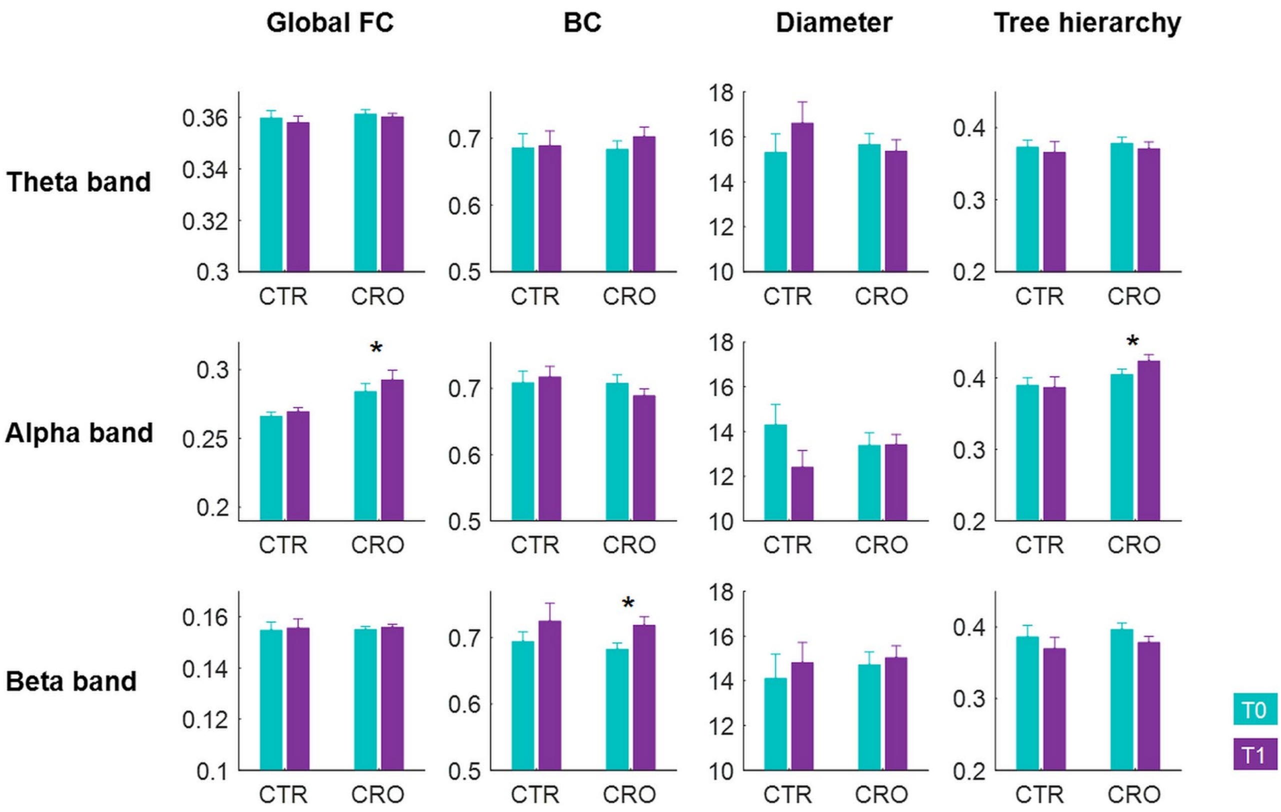

Fig. 1. Boxplots of the global connectivity measures for theta, alpha and beta bands at T0 (cyan) and T1 (purple). Statistically significances at $p < 0.05$ are indicated with an asterisk (*).

for the CTR group. TH measures the optimal topology of brain network organization, where information is transferred between different cortical areas in the fewest possible steps (and therefore in the shortest possible time) while preventing information overload of central brain regions[17,18]. Again, BCmax indicates the number of shortest paths passing through a definite node and it is related to the central network as expressed in terms of the importance of the most pivotal among them[17,18]. Since increased TH and BCmax values usually tend to correspond to an increased network integration, our results showed that a single session of crochet could promote the alerting and orienting network functioning probably increasing the information exchange between different brain areas. Moreover, we observed a quasi-significant higher global alpha FC in the CRO group than in the CRT group at T1 (not at T0). The increased connectivity could reflect the brain's effort to efficiently process information and coordinate activity across different brain regions. Indeed, crocheting demands more cognitive

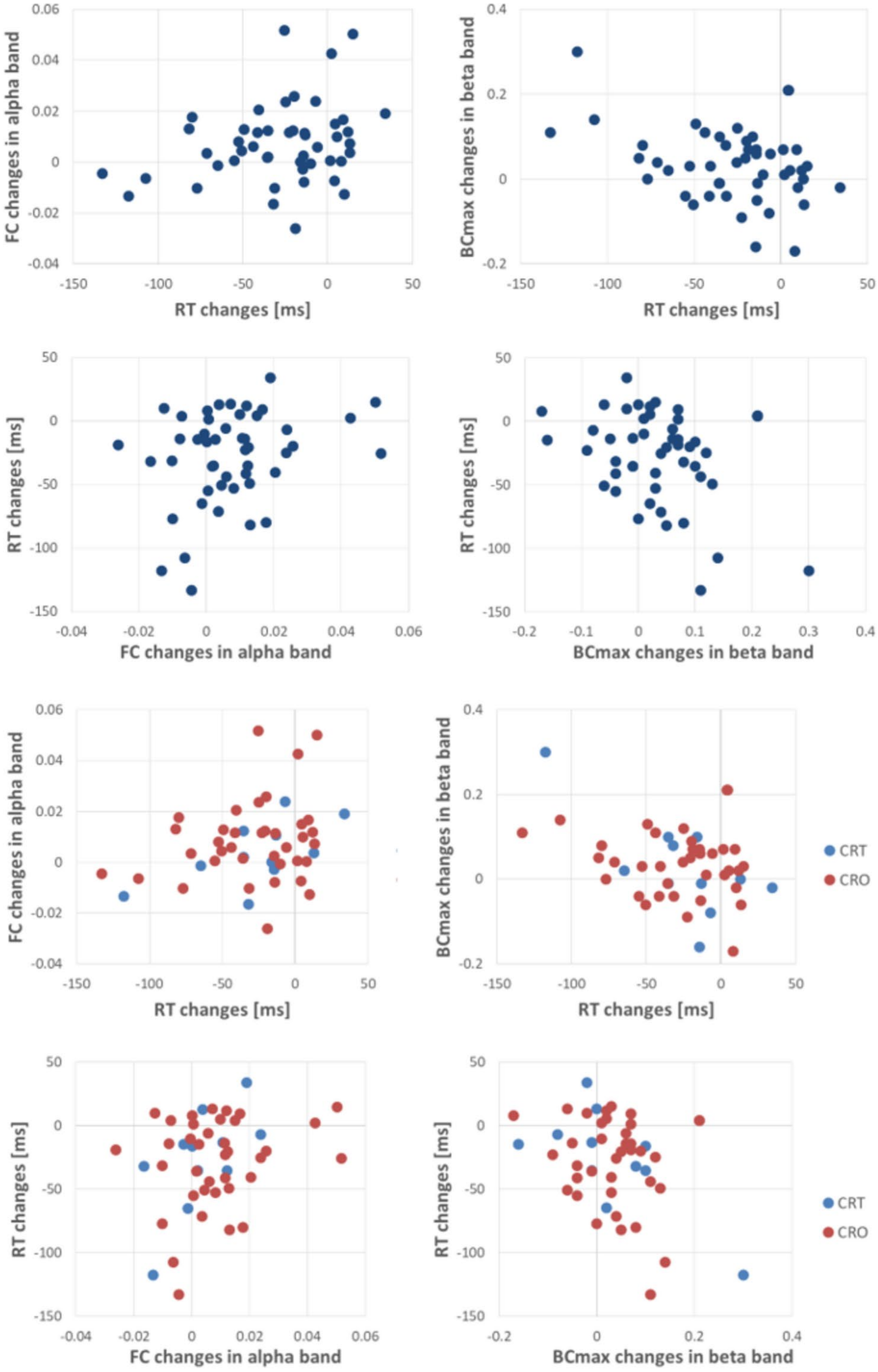

Fig. 2. Significant correlation between FC and behavioral measures.

resources and higher neural engagement. However, it is unexpected that a global FC and TH increase was found even after the end of the activity in the CRO group. While the current study was underpowered (power = 0.53), the observed effect size suggests a medium effect. Hence, this observed effect may have practical significance, though not statistically significant in this study; future research with a larger sample size is necessary to confirm these findings and provide more substantial evidence.

Surprisingly, we found that crocheting improved global RT, alerting, and orienting networks, but not executive control. Attention is composed of three separate anatomical and functional systems, i.e., alerting, orienting and executive control (conflict) networks, which, albeit independent, cooperate and influence each other to produce an adaptive and performing behavior[12,14,19,20]. Alerting is the ability to enhance and maintain readiness in preparation for an impending and imminent stimulus, orienting selectively allocates attentional resources to specific information among multiple ones, while the executive control network is active in complex situations involving planning, detecting errors, taking decisions, or giving different responses from the usual behavior[14,19,20]. In an ecological context, probably alerting and orienting networks cooperate in influencing the speed of reacting to environmental events; in a laboratory setting, there is further evidence that the global activation provided by the alerting network can make faster the orienting process to the salient stimulus/stimuli[13]; thus, we can speculate that crochet improves alerting and orienting brain networks, because it involves coordinated and asymmetric movement of fingers and wrists, further complicated by the need for continuous and prompt changes of the attentional focus from the general plot to the manual gesture, to carry out the original project[2].

Since the ability of crocheting consists of complex manual skills, which require extensive, constant practice and repetition of the gestures, they probably promote the MSL, i.e., the process by which a sequence of finalized movements comes to be performed effortlessly through repetitive exercises and interactions with the different environmental contexts[4].

At the different stages of MSL, changes in brain activation patterns involve several cortical areas, the cerebellar cortex with the dentate nucleus, the striatum and other basal ganglia[21–24]. Attention is a critical component of the first stages of MSL since it enables an individual to focus on specific aspects of the motor task they are trying to learn. As motor skills become more automatic through practice, attentional demands can often decrease, freeing up cognitive resources for other tasks. This process is known as “attentional capacity” and is thought to enable individuals to process information more quickly and accurately[5]. Conversely, MSL promotes the reinforcement of the connections between motor and cognitive areas of the brain[25,26]. These connections facilitate the transfer of information between brain regions, allowing for more efficient and effective processing of complex movements. These new connections are also thought to enhance attentional networks in the brain[21,25]. In our work, we demonstrated increased global FC (i.e., increased TH and BCmax values) after the crochet session, corresponding to better network integration and information exchanges between different brain areas: this could be interpreted as the neurophysiological counterpart of the reinforcement of connections between motor and attentional networks. Increased global BCmax in the beta band after the crochet activity correlated with better performance (reduced reaction times), suggesting that the brain has become more efficiently integrated, thus reflecting the brain’s adaptive response to the task, potentially enhancing its ability to integrate and distribute information, manage cognitive resources more effectively, and process task-relevant information more efficiently. At the same time, we found a decrease in global FC in the alpha band correlating with better performance. Despite recent evidence suggesting its functional significance in the modulation of attentive processes[27], cortical alpha activity served an inhibitory role or is related to resting condition; hence, this result is expected for a task promoting attention and motor skills. We believe that in the attentional boosting promoted by crochet, some brain regions may acquire centrality in the network (higher BCmax), to the detriment of global FC, even considering that global FC and BCmax represent different facets of brain network activity (temporal coordination and topological importance).

Our results provided for the first time that crochet is associated with an increase in the attentional networks, namely in alerting and orienting networks, paving the way for the use of textile-related arts in neurorehabilitation. We could speculate that it is possible to obtain the same effect also with other hobbies/activities in which the attention must quickly switch from a practical manual activity to a theoretical scheme and to the comparison with the obtained result, such as drawing, painting, knitting, crafting an object, doing decoupage. We are planning another study comparing crocheting with another activity that requires complex manual skills, which require extensive, constant practice and repetition of the gestures.

Limitations

Some limitations of this study must be underlined.

First, we want to explain that we preferred to compare crocheting with the resting state, which seemed to us the most neutral among the many possible options. The participants had to remain inside the magnetic shielded room between the two tests to favour as much as possible the maintenance of an excellent signal-to-noise ratio and limit the artefacts, so it was impossible to comparing crocheting with any other usual activity/hobby with electronic devices or object with ferromagnetic part in the period between T0 and T1 (for example, it was impossible playing on the smartphone). The CRT group served us mainly to eliminate the confounding factor due to training and the performance improvement expected (and obtained) in the second trial by both CRO and CRT groups. Again, we know that the CRT and CRO groups are not comparable in size. However, it is not easy to find such a large group in the corresponding age range without neurological, psychiatric and internal medicine pathologies, also considering the imbalance of the CRO group between males and females, with an evident prevalence of females. Furthermore, we must consider that our Institute is a hospital and allocate most of the resources to space for diagnosing and treating neurological diseases. Therefore, studies without patients have limited space due to daily diagnostic and research activity.

Then, we used an anatomical atlas to reduce the number of regions and create a network for the group study[28]. However, we know that brain activations do not necessarily respect these boundaries, and we generally could miss information, failing to capture individual differences[29,30]. The data-driven selection of the ROIs, primarily used in functional Magnetic Resonance Imaging (fMRI) studies[31–33], is less applied to MEG studies[34] as the variability is higher due to the additional step of inversion of the sources which can be affected by the type of the algorithm used[35,36]. More recent studies exploring functional subnetworks with fMRI use connectome atlases[37]. Alternatively, as in fMRI data, atlas-free vertex-wise analysis can also be applied[38]. These methods are based on estimating the connectivity of many regions in conjunction with less conservative statistics and inference on a network level[39,40]. Our work was based on a limited number of anatomical ROIs and future studies should improve the comprehension of the complex relationship between networks, increasing the sensitivity with atlas free, high dimensional analysis.

Finally, we did not investigate the modification of the attentional networks during the phases of learning and consolidation of the motor memory of crochet. Crochet takes a very long time to acquire a good mastery of making the craftwork. Therefore, evaluating such a dynamic over time would have been very challenging for both our working group and the volunteers. Future studies based on the comparison of novices and expert practitioners in the field of textile-related arts could bridge this gap, revealing the effect of crochet on attention at different MSL stages. Future studies based on the comparison of novices and expert practitioners in the field of textile-related arts could bridge this gap, revealing the effect of crochet on attention at different MSL stages.

Methods

Study population

Forty-one people experts in crochet (crocheters group, CRO, 40 females, ages ranging from 33 to 65, mean = 52.2 ± 7.6 years) and twelve subjects with no experience in crochet and/or knitting (control group, CTR, 12 females, age ranging from 32 to 73, mean: 49.3 ± 11.3 years) were enrolled, from January 2021 to December 2022, to perform a behavioural-MEG study. All participants were adults (> 18 years), right-handed, and had a normal or corrected-to-normal vision.

All the volunteers of the CRO group usually perform crochet and knitting; we included in the study only people who crocheted at least 1 h/day for at least 5 days/week during the last two months before the study initiation. For both groups, the exclusion criteria were the presence of concomitant neurological disease and the current use of drugs affecting the central nervous system.

This study was carried out following the ethical standards of the Declaration of Helsinki and its later amendments, and it was approved by the Ethical Committee of Fondazione-IRCCS-Istituto Neurologico “Carlo Besta” of Milan, Italy (approval number: 76/2020; date of approval: October 7th, 2020). Participants gave their written informed consent before their inclusion in the study.

Protocol and experimental design

The protocol included five phases: MEG acquisition in resting condition (a), execution of ANT task (b), 20 min of awake resting (CTR group) or crocheting (CRO group) (c), MEG acquisition in resting condition (d), execution of ANT task (e). In the following parts of the manuscript, reference will be made to T0 for (a) and (b) and to T1 for (d) and (e) phases, respectively. The experimental design is shown in Fig. 3A.

The whole protocol took place inside the shielded room of the MEG for a total duration of about one hour.

Acquisition in resting condition

The acquisition in resting condition consisted of 3 min with eyes open and 3 min with eyes closed. Participants were asked to remain still as much as possible and avoid blinking and falling asleep. The acquisition in resting condition was repeated twice, before (T0) and after (T1) the crochet work or rest.

Behavioural task

The ANT task primarily described by Fan[12] was used, implementing the stimuli on Stim2 software (Compumedics-Neuroscan; Compumedics Limited, Abbotsford, Victoria, Australia; Neuroscan, Charlotte, NC, USA). Responses were detected through two button devices (Current Designs Inc., Philadelphia, PA, USA), one in each hand.

During the ANT task, cues (asterisks) and stimuli (arrows) were presented on a screen positioned in front of the subject. The task requires participants to determine whether a central arrow (target) points left or right. Each trial started with a fixation cross displayed for a time randomly ranging from 400 to 1200 ms. A cue was then presented for 100 ms and followed by a fixation cross with a duration of 400 ms. The cue can be one of the following types: no cue, centre cue, double cue (one at the top and one at the bottom of the screen) and spatial (one at the top or the bottom of the screen). Subsequently, the stimulus was presented for 1700 ms. The stimuli were associated with three conditions: neutral, congruent and incongruent. The target was flanked by two lines on both sides in the neutral condition or by two arrows in the other two conditions. The arrows pointed toward the same direction as the target arrow in the congruent condition or the opposing direction in the incongruent condition. The target always appeared at the location of the asterisk in the spatial-cue condition, and the target positions varied (above or below) randomly in other conditions. After participants made a response, the stimulus disappeared immediately and a fixation cross was set again (Fig. 3B).

The ANT was repeated twice, before (T0) and after (T1) the crochet; the two blocks of ANT were randomized: each of them included 288 trials and lasted about 17 min. A practice block of 20 trials was conducted before the experiment to allow participants to become familiar with the task and the recording environment.

For all the participants, the reaction time (RT) of each stimulus was determined as the time length between the onset of the target stimulus and the response detected by pressing the button device. The alertness network RT was calculated by subtracting the cue from the no-cue RT. The orienting network RT was calculated as the difference between centre cue and spatial cue RT. The executive control network RT was calculated by subtracting the congruent from the incongruent RT. Data deriving from individuals who made more than 10% of errors of the total in the behavioural test were excluded from the subsequent analysis.

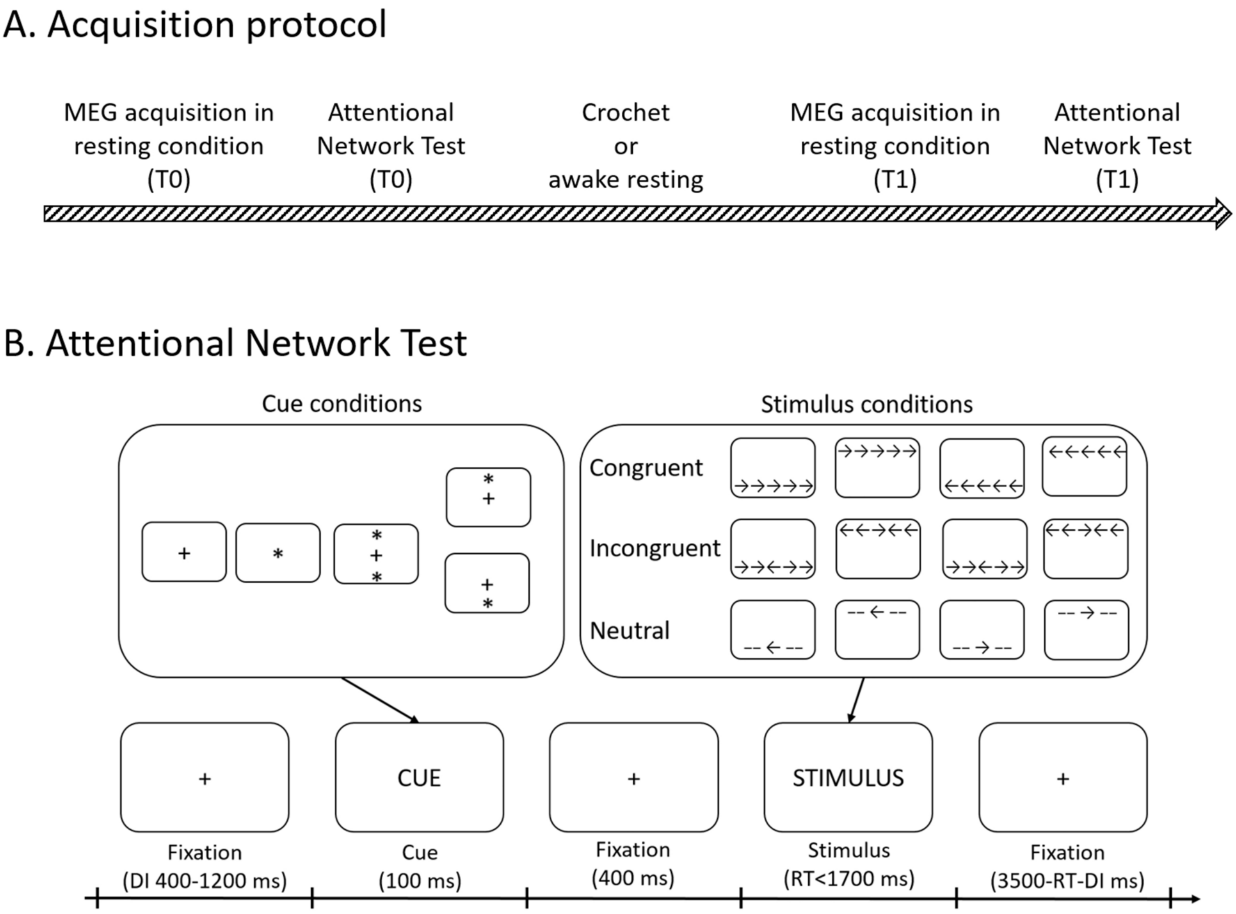

Fig. 3. Experimental design (**A**) and the behavioural test (**B**).

Crochet and rest-activity

After the first execution of the first ANT, all the CRO participants performed a crochet activity which consisted of reproducing a simple pattern (granny square) to complete a hexagonal tile of about 10 cm diagonal, for a total duration of about 20 min. Participants were asked to work in the usual manner and speed. All the equipment for crochet included the wool balls, and the wooden, MEG-compatible hooks were provided by the no-profit organization Gomitolorosa ONLUS.

The subjects of the CTR group were asked to stay in a relaxed and quiet resting condition for a total duration of 20 min. To ensure that the subject did not fall asleep, the subject's MEG trace was monitored also during this phase, and in case of signs of drowsiness, the subject was prompted via intercom.

MEG

MEG data acquisition and pre-processing MEG signals were acquired using a 306-channel whole-head MEG system (Triux, Elekta Oy, Helsinki, Finland) with a sampling frequency of 1 kHz. Bipolar electro-oculographic (EOG) and electrocardiographic signals (ECG) were also acquired. The participant's head position inside the MEG helmet was continuously monitored by five Head Position Identification (HPI) coils located on the scalp. The locations of HPI, together with three anatomical landmarks (nasion, right and left preauricular), and additional scalp points were digitized before the recording through a 3D digitizer (FASTRAK, Polhemus, Colchester, VT, USA).

The raw MEG data were pre-processed off-line using the spatiotemporal signal space separation method[41] implemented in the Maxfilter 2.2 (Elekta Neuromag Oy, Helsinki, Finland) to subtract external interference and correct for head movements using HPI signals. Physiological artefacts were removed through the use of Signal-Space Projectors[42] using EOG and ECG signals to mark eye movements or blinks and heartbeat, respectively. Finally, data were band-pass filtered at 1–100 Hz. To characterize instrument and environmental noise for source modelling, the noise covariance matrix was estimated using 2 min of empty-room recordings collected just before each session.

Individual MEG data were co-registered with a template MRI[43] (MNI/ICBM152) using digitized scalp points. Then, MEG forward model was calculated using the overlapping-spheres approach. Based on the Desikan-Killiany atlas, regions of interest (ROIs) were defined in the subject's co-registered MRI. The time series of neuronal activity were reconstructed by projecting sensor signals to source space using the dynamic Statistical

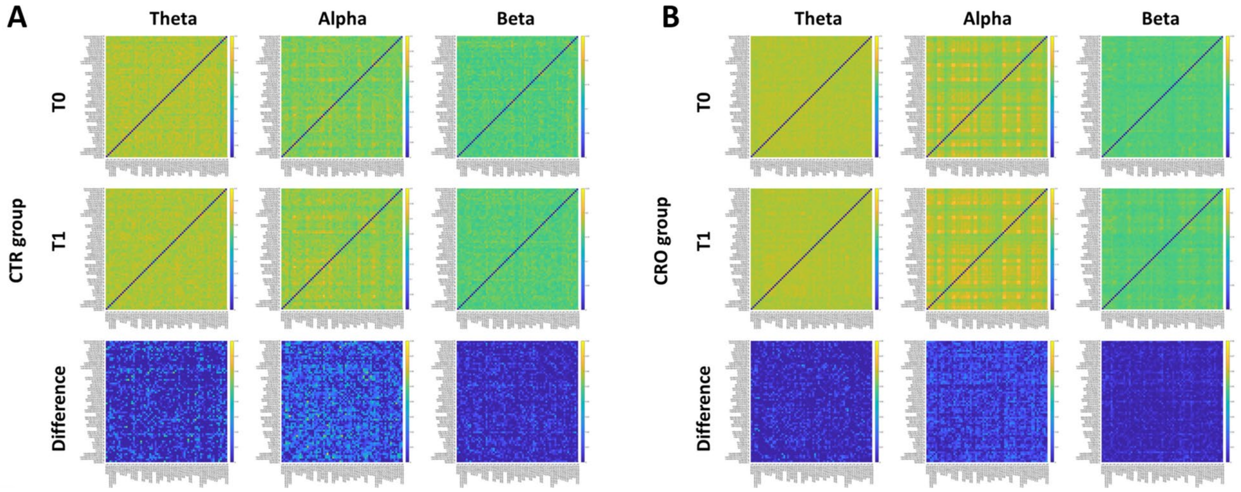

Fig. 4. The adjacency matrix for theta, alpha and beta bands calculated at T0, T1 and their differences for the CTR (**A**) and the CRO (**B**) groups, respectively.

Parametric Mapping (dSPM) method[44]. To obtain a single time series per ROI, a mean of all vertices of each ROI was calculated after correcting for an opposite sign source direction. The analysis was performed using Brainstorm software[45].

Functional connectivity analysis For each participant of the CRO and CTR group, 90 consecutive seconds of MEG signal in the open-eye resting condition before and after crochet performance (CRO) or relaxing (CTR) were selected and then segmented into 45 non-overlapping epochs with a duration of 2 s each. From these epochs, different indices of FC were calculated in the classical theta (4–8 Hz), alpha (8–13 Hz) and beta (13–30 Hz) frequency bands, while frequencies < 4 Hz and > 30 Hz were excluded from the analysis.

wPLI[46] was estimated for each frequency band in each cortical ROI and then as mean overall ROIs (global FC). The results were averaged over the epochs for each subject, thus obtaining an FC matrix for each frequency band. We calculated the individual difference matrix by subtracting the adjacency matrix at T0 from that at T1, we averaged over the nodes and then compared the two groups (Fig. 4).

Network topology was examined using Minimum Spanning Tree (MST) graphs derived from the functional connectivity matrices[47]. The MST graph is a sub-network derived from a weighted network including the highest weights possible without forming any loop. Consequently, the resulting graph has the same number of links, allowing comparison across groups or conditions without running the risk of bias due to differences in edge density. MST is proposed to reflect the functional core of the network[48].

To study the network integration, the following global connectivity measures were extracted from MST graph: BCmax, Diameter, and TH. BCmax measures the central network organization in terms of the importance of the most central node. High values of diameter indicate a decreased global efficiency. TH characterize the hypothesized optimal topology of brain network organization. A schematic depiction of the MSTs calculation pipeline is shown in Fig. 5.

Analyses were performed using custom Matlab (MATLAB 2021a, MathWorks, Inc., Natick, MA, USA) based on Fieldtrip[49] and BCT[50] toolboxes; for MST we used the toolbox developed for the data-driven topological filtering based on orthogonal MST[51], again, for BCmax we normalized the data with the formula $BC_{norm} = BC/(N - 1)(N - 2)/2$, as specified by a previous article[52].

Statistical analysis

Accuracy and RTs were compared using repeated measures ANOVA (rmANOVA) with GROUP (CRO and CTR) as between factor and TIME (T0 and T1) as within factor. rmANOVA was applied also to compare cue type (centre, spatial and no cue) and stimulus type (congruent, incongruent, neutral) as within factor. The same analysis was applied for network scores global FC and connectivity indexes for each band separately.

The sphericity assumption was evaluated using Mauchley's test and the Greenhouse–Geisser degree of freedom correction was applied when appropriate. Post-hoc tests were performed using paired or independent t-tests with Bonferroni correction for multiple comparisons. Statistical significance was set at $p < 0.05$. Values are expressed as mean ± standard error of the mean. All statistical analyses were performed with SPSS (IBM Statistic, version 28.0).

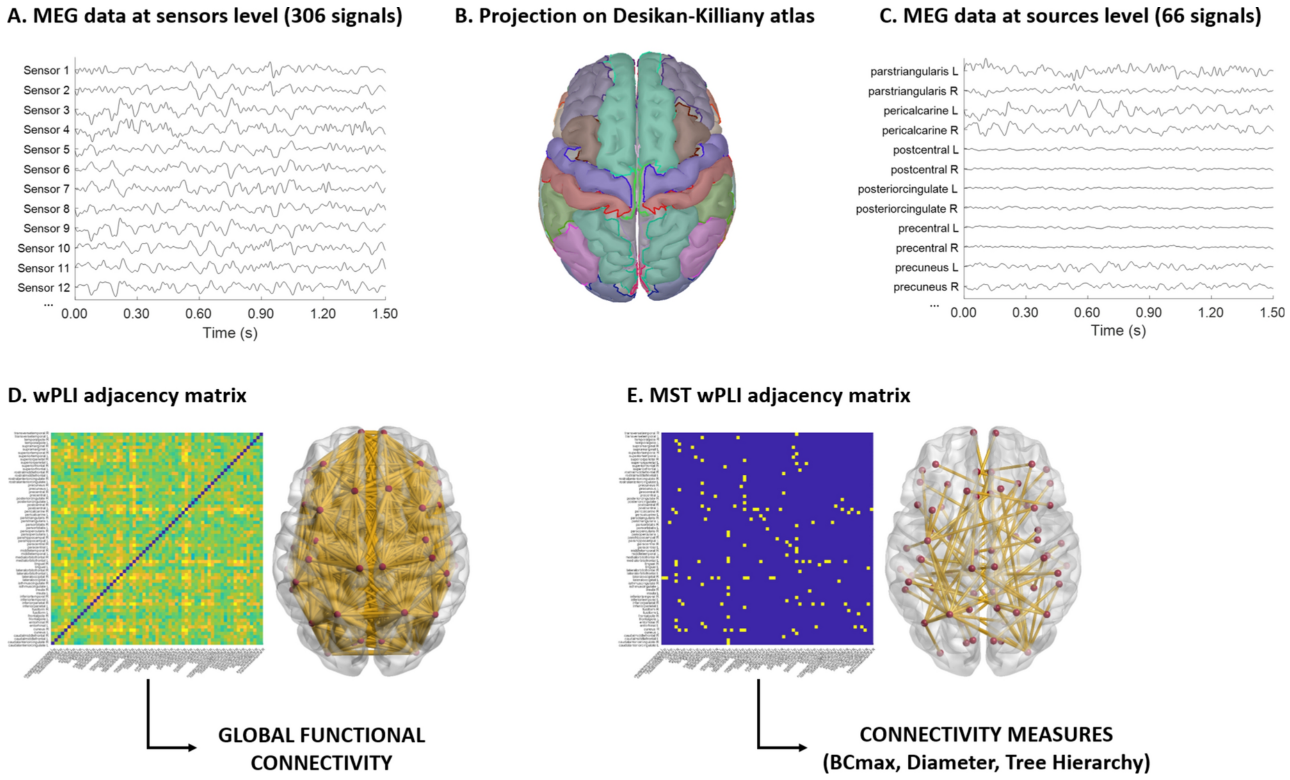

Fig. 5. Schematic depiction of the Minimum Spanning Trees calculation pipeline. (**A**) MEG signals at sensors level. (**B**) Desikan-Killany atlas parcellation. (**C**) time series reconstructed per ROI. (**D**) wPLI adjacency matrix from which global functional connectivity was calculated. (**E**) Minimum spanning tree (MST) graphs derived from the functional connectivity matrices and from which connectivity indices (BCmax, Diameter and TH) were calculated.

Data availability

The datasets generated and/or analysed during the current study will be available in the ZENODO repository, www.zenodo.org

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Author contributions

D.R.S.: conceptualization (lead), supervision, writing-original draft; C.M.: conceptualization (supporting); project administration; D.D.: formal analysis (supporting), software (equal); D.B.: data-curation (equal); S.D.: data-curation (equal); P.A.: data-curation (equal); E.P.: writing-review & editing; P.T.: resource, funding acquisition; E. V.: formal analysis (lead), software (equal), visualization. All authors reviewed the final version of the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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