ORIGINAL ARTICLE

Current source density and functional connectivity of frontal midline theta rhythm during craft activities: EEG-LORETA study

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Abstract

Frontal midline theta rhythm (Fmθ) has been shown to help connect distributed neural systems into brain functional networks for task execution. In this study, we investigated the current sources and functional connectivity of Fmθ that appeared during manual arts and crafts activities using the low resolution brain electromagnetic tomography (LORETA) method. Current sources of Fmθ are located in the anterior cingulate cortex and frontal lobe, and there are many functional connections in the delta, theta, alpha, beta, and gamma bands. These brain activities are suggested to reflect instantaneous increase in cognitive control associated with craft activities.

Key words: *craft activities, frontal midline theta rhythm, autonomic nervous system*

INTRODUCTION

Frontal midline theta rhythm (Fmθ) is a 4-8 Hz electroencephalography (EEG) activity that appears in the frontal midline during a wide range of cognitive tasks that require intense concentration. Fmθ is a distinct sinusoidal wave that lasts more than 1 sec (Ishihara, 1972). The source of Fmθ has been confirmed to be in the anterior cingulate cortex (ACC) (Ishii, 1999; Ishii, 2014). The ACC is now widely accepted to contribute to cognitive control and decision making and to play a role in motivating task execution (Bush, 2009; Mars, 2011; Holroyd, 2012). Fmθ appears to occur in tasks that require attention, such as breathing tasks in meditation (Kubota, 2001), rifle shooting (Doppelmayr, 2008), and mental arithmetic tasks (Ishii, 2014). During the appearance of Fmθ, more attention is allocated to the work task and less to the environment, thoughts, and passage of time outside of the task, making it more difficult to interrupt concentration on the task (Cavanagh, 2014).

Although Fmθ research initially focused on the strong theta component, which lasts more than 1 sec (Ishihara, 1972), most recent studies have focused on theta components of event-related potentials (ERP). ERP theta activity is also well-known to be related to attentional function, but the methods of analysis for both are essentially different. ERP analysis usually calculates power values for specific frequencies by averaging the stimulus-triggered waves. Fmθ was defined as a rhythmic sinusoidal wave, lasting at least 1 sec, with an amplitude that is clearly higher than the background activity (Ishihara, 1972). To interpret changes in averaged power as evidence of theta rhythmic changes, it is therefore necessary to confirm whether the individual raw waveforms show rhythmic sinusoidal waves, although this has not been done in most previous studies on ERP theta activity. Further, few studies have focused on Fmθ, an apparent theta activity that lasts longer than 1 sec, and some obscurity remains. Meanwhile, neurofeedback training utilizing Fmθ as a biomarker has been shown to improve memory control processes (Kathrin, 2020), and research on improving cognitive function by training and enhancing Fmθ appearance has received increasing attention in recent years (Reis, 2016; Rozengurt, 2016). This indicates the possibility of having Fmθ reconstruct various neural networks.

We previously reported that Fmθ was observed to occur during craft activities (Shiraiwa, 2020). Craft activities involve controlled movement of the body, especially manipulating tools with the hands to work on objects, and they are thought to use various neural networks in the brain, including cognitive, motor, perceptual, memory, thinking, learning, attention, and volition. Craft activities require closely intertwined multipurpose cognition and embodied processing (Huotilainen, 2018). Theta waves as sinusoidal components lasting longer than 1 sec not only represent a strong state of concentration, they can also represent a state of relaxation (Kubota, 2001). When Fmθ appeared for more than 1 sec during craft activities, parasympathetic activity was activated and a state of relaxation was achieved compared to the resting state (Shiraiwa, 2020). Fmθ therefore not only affects cognitive function, but also autonomic activity, and it may reflect diverse mechanisms. Strict distinction should be made between ERP theta activity and the Fmθ that lasts longer than 1 sec. Furthermore, Fmθ appearing for more than 1 sec has been associated with gamma waves in the right dorsolateral frontal lobe (Ishii, 2014; Griesmayr, 2010). Synchronization of Fmθ appearing with craft activities has not yet been reported.

The aim of this study is, first, to use the LORETA method to estimate the current source density of Fmθ over 1 sec that emerges during craft activities. Secondly, it aims to evaluate the functional connectivity of other frequency components that are synchronized during the appearance of Fmθ.

METHODS

Participants

Eight healthy volunteers, who were university students (four men and four women aged 21–22 years), participated in this study and provided written informed consent. The study was performed in accordance with the Declaration of Helsinki, and approved by the Osaka Kawasaki Rehabilitation University Ethics Committee.

Tasks

The craft activity was to knit three strands of embroidery thread. The embroidery threads were 20 cm long and were knitted with the ends secured to the table. Before the experiment, samples of the crafts were presented and participants practiced making them while the procedure was explained to them. The experiment was then conducted after participants fully understood the preparation procedure, with confirmation that there were no unclear steps. Participants had a 1-min rest (staring at an image of a landscape) followed by a 5-min crafting task, and this was repeated twice. The conditions under which Fmθ was observed during the crafting task were selected for EEG analysis.

EEG recordings and data acquisition

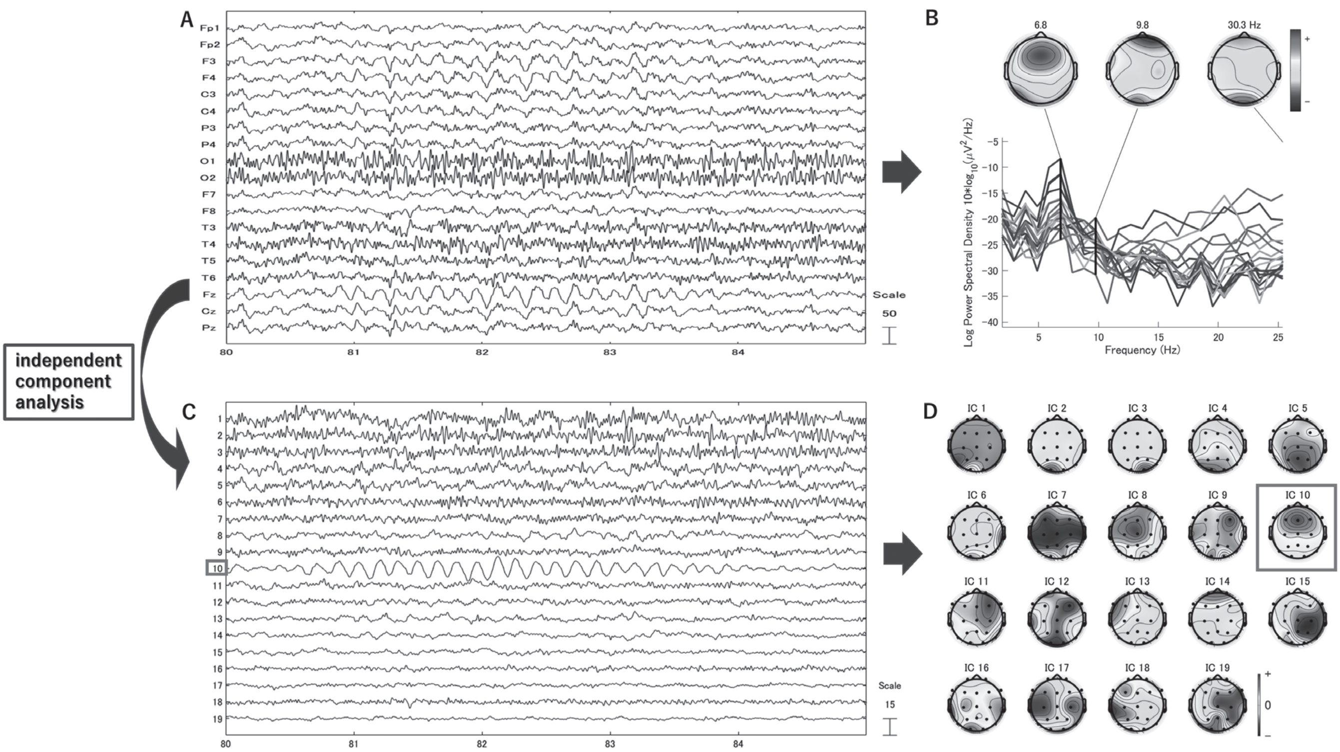
Polymate Pro MP6100 (Miyuki Giken Inc., Tokyo, Japan) was used for EEG recordings. EEG recordings were done with 19 electrodes using the International 10–20 System at the Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz, Pz positions. EEG data were acquired with a linked ears reference, sampled at 1000 Hz, and filtered offline between 1.5 Hz and 60 Hz. The impedance of each electrode was kept below 10 kΩ. All channels were referenced to FCz during recording. Data were processed using EEGLAB 2022.0 (Delorme, 2004) running in MATLAB 2022a (Mathworks). EEG recordings were filtered with low-pass (60 Hz) and high-pass filters (1.5 Hz). Artifact rejection (eye movement, blinking, muscle activity) was performed visually by placing markers at the start and end points of the artifact signal on the raw waveform, and the interval where an artifact appeared was removed.

EEG analysis

The criterion for Fmθ was a rhythmic sinusoidal wave observed at a frequency of 4-8 Hz with a local distribution with maximum near the frontal midline and lasting at least 1 sec. A two-way procedure was used to identify Fmθ. First, Fmθ was identified from raw data by inspection. Next, independent component analysis (ICA) was performed to extract components that were clearly sinusoidal θ waves and had a focal distribution with a maximum near the frontal midline. An example of Fmθ extracted by ICA is shown in Figures 1A,B,C,D. ICA was used as 'runica' algorithm implemented in EEGLAB (Makeig, 1997). Fmθ was identified by the above procedure, and then only Fmθ-appearing segments were extracted. Eight participants performed the task twice, resulting in the appearance of Fmθ in nine sessions of six participants. Artifact rejection by ICA was not chosen in this study because of its effect on the low-frequency component.

EEG source localization

eLORETA (Pascual-Marqui, 2011) was used to analyze the current source density distribution in the cortex. The eLORETA head model and electrode coordinates were based on the Montreal Neurological Institute's mean MRI brain map (MNI152) (Mazziotta, 2001), and the solution space contained 6239 voxels with 5 mm^3 spatial resolution. The eLORETA method has been validated in several previous studies using fMRI (Mulert, 2004; Vitacco, 2002), structural MRI (Worrell, 2000), and PET (Dierks, 2000) and its validity have been ensured.



Figures 1A,B,C,D. Fmθ identification. Mapping of waveforms and Fast Fourier transform and identification of Fmθ by independent component analysis. In this example, IC10 is Fmθ.

Table 1. Twenty-four cerebral regions of interest (ROIs) decided by eLORETA.

Anatomical regions	Brodmann area	ROI centroid MNI coordinates		
		x	y	z
Left middle temporal area (lMT)	37	-50	-70	-5
Right middle temporal area (rMT)	37	45	-70	-5
Left frontal eye fields (lFEF)	6	-25	-10	50
Right frontal eye fields (rFEF)	6	25	-10	50
Left superior parietal lobule (lSPL)	7	-25	-50	55
Right superior parietal lobule (rSPL)	7	25	-50	55
Left anterior prefrontal cortex (laPFC)	10	-35	55	5
Right anterior prefrontal cortex (raPFC)	10	35	55	5
Left dorsolateral prefrontal cortex (ldlPFC)	9	-50	15	40
Right dorsolateral prefrontal cortex (rdlPFC)	9	50	15	40
Anterior cingulate cortex (aCC)	32	5	30	25
Left anterior inferior parietal lobule (laIPL)	40	-50	-50	45
Right anterior inferior parietal lobule (raIPL)	40	50	-50	45
Left anterior insula (laINS)	47	-30	20	-5
Right anterior insula (raINS)	47	30	20	-5
Left hippocampal formation (lHF)	28	-20	-20	-20
Right hippocampal formation (rHF)	28	20	-20	-20
Ventromedial prefrontal cortex (vmPFC)	10	-5	50	-5
Posterior cingulate cortex (pCC)	23	0	-55	15
Left posterior inferior parietal lobule (lpIPL)	39	-50	-70	30
Right posterior inferior parietal lobule (rpIPL)	39	50	-70	30
Visual fields (Vis)	18	0	-90	-5
Left auditory fields (lAud)	41	-55	-25	10
Right auditory fields (rAud)	41	55	-25	10

The current source density of the eLORETA cortical functioning image was calculated for six frequency bands: delta (2–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta1 (13–20 Hz), beta2 (20–30 Hz), and gamma (30–60 Hz). The EEG data were divided into epochs of every 2 sec for each task using LORETA software, and averaged files were created for each task. The appearing Fmθ-only data was similarly divided into epochs of every 2 sec and averaged into a file.

Functional connectivity analysis

To analyze functional connectivity, a method of determining cortical regions of interest (ROIs) for each voxel was employed, and 24 cortical ROIs were defined (Table 1). The lagged phase synchronization was used to analyze functional connectivity between all pairs of ROIs. This lagged phase synchronization represents the degree of coupling between the two signals after the instantaneous zero-lag component is removed, and thus is expected to accurately correct for volume conduction effects and physical artifacts.

Statistical Analysis

By comparing averaged data for the entire task with Fmθ-only data, we determined that Fmθ activity is captured in terms of current source density and functional connectivity. The eLORETA applies the statistical nonparametric mapping method (SnPM) for statistical analysis of current source density (Holmes, 1996). Group differences in cortical source localization in each frequency band were evaluated by independent F-ratio-tests for each voxel based on log-transformed current source density power in eLORETA. Significantly different cortical voxels were identified in the three-dimensional statistical mapping by a nonparametric permutation/randomization procedure, and the average signal source power of each voxel and its distribution in the permuted values were compared. eLORETA performed 5000 data randomizations and corrected for multiple comparisons at all voxels and frequencies, without resorting to Gaussianity, to determine a threshold for the critical probability of the actual observed log F-ratio values.

To estimate group differences in lagged phase synchrony between pairs of 24 ROIs in each frequency band, eLORETA applied an independent-samples t-test to generate t-statistics for brain connectivity. Functional coupling analysis examined all couplings (276 couplings) between 24 ROIs in six frequency bands (276 × 6 = 1656) with 1656 tests using eLORETA. In addition, the eLORETA nonparametric randomization method based on the 'maximal statistic' (Holmes, 1996; Nichols, 2002) was also applied, to correct for multiple comparisons.

RESULTS

Source localization

Fmθ appearance data showed significantly higher current source density in the theta component in the anterior cingulate gyrus and frontal lobes compared with the task-averaged data (Log F-ratio = 0.552, $p < 0.01$) (Figure 2). No significant differences were found at other frequency bands.

Functional connectivity

Functional connectivity of Fmθ appearance data, compared with task-averaged data, showed significantly increased six frequency bands lagged phase synchronization in the ROI (Figure 3 and Table 2)($t = 3.672$, $p < 0.05$).

DISCUSSION

The LORETA method was used in this study to identify the current source density and functional connectivity of Fmθ that appeared during craft activities and lasted for more than 1 sec. Although Fmθ

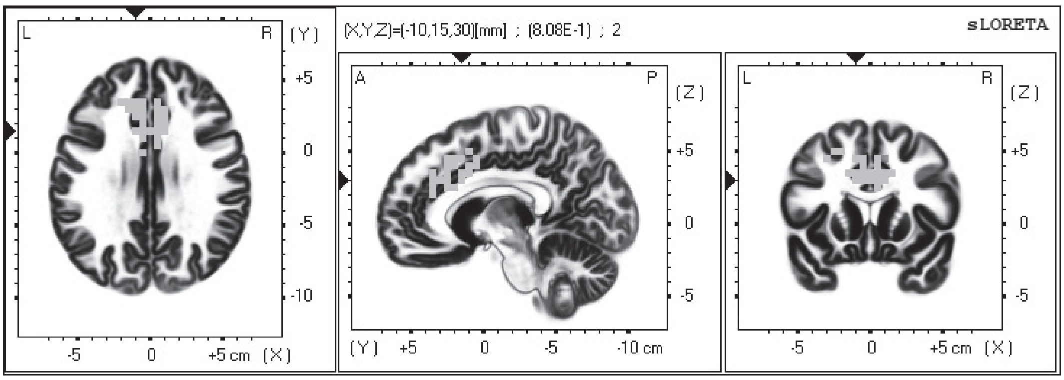


Figure 2. The Fmθ appearance data showed significantly higher current source density in the theta component in the anterior cingulate gyrus and frontal lobes compared to the task-averaged data ($p < 0.01$)

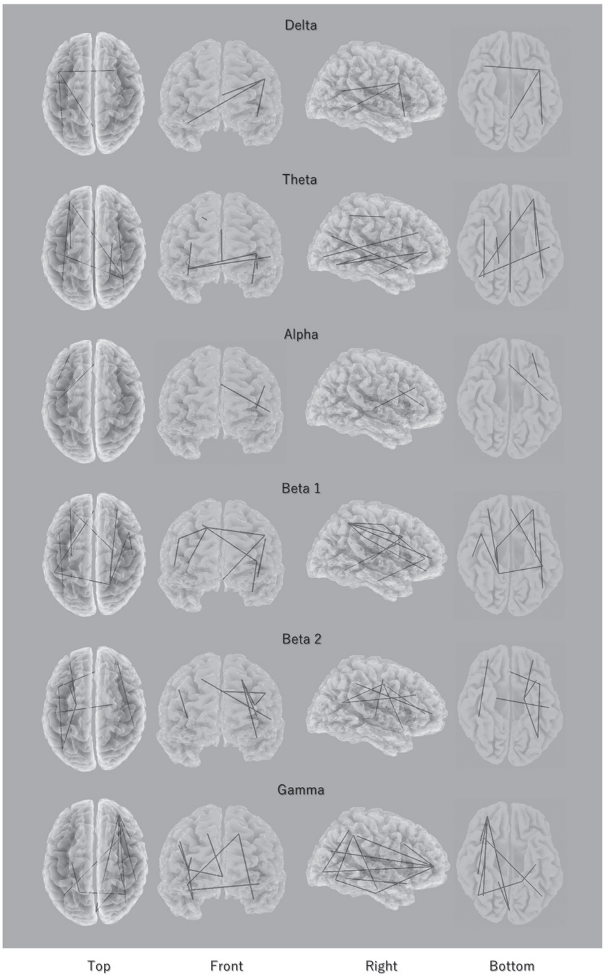


Figure 3. Changes in ‘lagged phase synchronization (LPS)’ in Fmθ phase compared with average phase in all frequency bands. Lines indicate significantly increased lagged phase synchronization ($p < 0.05$).

Table 2. Changes in ‘lagged phase synchronization (LPS)’ in Fmθ phase compared with average phase in all frequency bands and the involved anatomical regions.

Frequency bands	Areas of significance (Brodmann area)
Delta	**Increased** LPS between:
	- ldlPFC(9) and lMT(37); raINS(47); pCC(23)
Theta	**Increased** LPS between:
	- rSPL(7) and rFEF(6)
	- laPFC (10)and lMT(37); rMT(37); lHF(28)
	- aCC(32) and Vis(18)
	- raINS(47) and rpIPL(39)
	- lAud(41) and rMT(41)
Alpha	**Increased** LPS between:
	- laPFC(10) and ldlPFC(9)
	- aCC(32) and lAud(41)
Beta 1	**Increased** LPS between:
	-lMT(37) and ldlPFC(9)
	-laPFC(10) and rFEF(6); lHF(28)
	-rSPL(7) and rFEF(6); raPFC(10); rdlPFC(9); laIPL(40)
	-rAud(41) and rdlPFC(9)
	-vmPFC(10) and laIPL(40)
Beta 2	**Increased** LPS between:
	-lFEF(6) and laPFC(10); laINS(47); lpIPL(39)
	-rFEF(6) and lAud(41)
	-raPFC(10) and raIPL(40)
	-ldlPFC(9) and aCC(32); lpIPL(39)
gamma	**Increased** LPS between:
	-lMT(37) and raINS(47)
	-rMT(37) and lSPL(7); rHF(28)
	-lSPL(7) and lHF(28)
	-rSPL(7) and Vis(18)
	-raPFC(10) and rdlPFC(9); raIPL(40); rHF(28); rpIPL(40); Vis(18)

has been the subject of research for several decades, its functional linkages and relationships with other components have not yet been fully elucidated. In the present study, the appearance of Fmθ resulted in an increase in functional connectivity of other frequencies, such as beta and gamma.

The Fmθ generated during the craft activity in this study showed the highest neural activity in the frontal lobe, mainly in the ACC, as a result of eLORETA current source density. This result is consistent with many previous studies (Ishii, 1999; Onton, 2005; Sauseng, 2007). The ACC is reportedly connected to many different brain regions and is involved in cognitive and emotional functions, such as motivation, decision making, information processing, and attention (Devinsky, 1995; Wang, 2005). Furthermore, the ACC and several other prefrontal areas have been proposed to be part of a neuronal network representing central executive function (Baddeley, 1996) during working memory demands. Fmθ was thus suggested to reflect the activity of the executive system based on ACC. However, central executive function cannot be limited to the ACC and other prefrontal brain structures alone because a wide variety of executive processes exist in the prefrontal brain (Smith, 1999). Our mental resources are limited, even when we consciously try to focus our attention. Considering the capacity allocation model, the amount of attention capacity allocated during Fmθ emergence is likely to be allocated more to the task of performing a given task than to the environment. In other words, Fmθ helps to combine distributed neural systems into a functional network for task execution (Anderson, 2010; Daitch, 2013; Sauseng, 2007). The generation of Fmθ is therefore considered to be a top-down signal, which couples with the diverse executive system network.

The present functional connectivity analysis confirmed that there is diverse connectivity at each frequency during the appearance of Fmθ. In delta waves, functional connectivity was increased in ldlPFC and lMT; raINS; pCC. In theta waves, many long-range theta connections were increased in frontal, parietal and occipital lobes. Long-range theta connections between prefrontal and parietal regions probably reflect integrative processes mediated by the central executive system. This is consistent with the idea that lower frequencies such as theta and delta waves are associated with integrative brain function (Von Stein, 2000). In particular, our results confirm long-range coupling of theta waves to the frontal and parietal lobes. The integration of visual and sensorimotor information is represented by long-range connections between the frontal and parietal lobes (Classen, 1998; Hummel, 2005). The strength of occipital theta coupling in the present study may therefore represent the integration of visual information with motor responses.

In addition, theta connectivity in the frontal and occipital lobes has been reported to reflect top-down control in mental arithmetic (Mizuhara, 2007), task switching (Sauseng, 2006), and execution-intensive working memory tasks (Sauseng, 2005). This theta connectivity has been proposed to be the integration and coordination of the sub-networks involved in a particular working memory process (Sauseng, 2010), suggesting that theta connectivity is a strong candidate for executive function.

Craft activities characteristically have a working memory process that puts the memorized knitting method into action because the visual information is coupled with the necessary motor responses. Both processes are thought to be represented in long-range theta connections in the frontal and occipital lobes. In alpha and beta waves, many functional linkages increased in the frontal and parietal lobes. Specifically, they were concentrated in the superior parietal lobule and in the prefrontal cortex, which are considered to be sensory and motor functions. From PET and fMRI studies it is known that motor imagery activates various cerebral structures including, at the cortical level, the supplementary motor area, the premotor areas, and the primary sensorimotor areas (Decety, 1994; Porro, 1996; Roth, 1996). The beta activity of the primary motor cortex is fundamental to motor control (Engel, 2010). In light of these previous studies, it is likely that this beta activity reflects the hand movements associated with craft activities.

The gamma waves showed long-range connections from the frontal to temporal and occipital lobes on the right side. Gamma waves are generated in the right dorsolateral prefrontal cortex during Fmθ generation (Ishii, 2014). The appearance of gamma activity in the right prefrontal cortex associated with this Fmθ appearance was described as a mechanism to interrupt neural activity that interferes with ongoing cognitive tasks. Moreover, some studies suggest that theta and gamma coupling underlies the working memory process (Engel, 2001; Canolty, 2010). Fmθ, a central component in working memory tasks, was shown to be linked to gamma activity during stimulus manipulation (Griesmayr, 2009). This activity was concluded to reflect the integration and coordination of different cognitive processes, such as executive top-down control and the reorganization of memory and time. In light of the above points, the theta - gamma connectivity in our study may represent top-down control and reorganization of memory items associated with manual arts and crafts activities.

Fast Fourier transform analysis reveals prominent frequencies within the EEG segment, so it cannot accurately capture Fmθ as originally defined by Ishihara (1972), and cannot account for the temporal component of the EEG in detail. Similarly, ERP analysis cannot capture a rhythmic sine wave. Given the limitations of these analytical methods, we identified Fmθ using raw waveform inspection and clustering by ICA. Fmθ over 1 sec originates near the ACC, it was associated with diverse functional connectivity, and was associated with an instantaneous increase in cognitive control. Fmθ and related functional connectivity may therefore reflect a neural network of craft activities that require diverse cognitive functions.

Study limitation

The small sample size and limited age range (20-22 years) of our participants limits the generalizability of our findings, but this age range was selected because Fmθ tends to appear in younger age groups. As a further limitation, the LORETA method was used to identify current source density and functional connectivity, but this method has spatial limitations. Furthermore, the measurements were made at 19 electrodes, so the results should be interpreted with caution.

Summary

Fmθ over 1 sec occurring during craft activities increased functional connectivity in delta, theta, alpha, beta, and gamma activity. An instantaneous increase in cognitive control is suggested to be associated with craft activities.

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