



Review

Gamma electroencephalographic coherence and theory of mind in healthy subjects

Ferruccio Panzica^{a,*}, Elena Schiaffi^a, Elisa Visani^a, Silvana Franceschetti^a, Anna Rita Giovagnoli^b^a Unit of Neurophysiopathology, Department of Diagnostics and Applied Technology, Fondazione IRCCS Istituto Neurologico Carlo Besta, Via Celoria 11, 20133 Milano, Italy^b Unit of Neurology and Neuropathology, Department of Diagnostics and Technology, Fondazione IRCCS Istituto Neurologico Carlo Besta, Milano, Italy

ARTICLE INFO

Article history:

Received 31 December 2018

Revised 6 June 2019

Accepted 11 July 2019

Available online 17 August 2019

Keywords:

Theory of mind

Empathy

Brain connectivity

Electroencephalogram

Coherence

ABSTRACT

Purpose: Structural brain imaging has revealed that damage to different brain regions may impair theory of mind (ToM) while functional imaging has shown that distributed neural circuits are activated by ToM and empathy. However, the coherence of the electroencephalogram (EEG) frequencies in a definite time span may change during these processes, indicating different neurophysiological correlates. This study evaluated the changes of EEG coherence during ToM tasks in comparison with Empathy, Physical causality, and baseline conditions, aiming to determine the neurophysiological correlates of ToM.

Methods: Sixteen healthy adults underwent a visual activation paradigm using 30 comic strips concerning ToM, Empathy, or Physical causality during EEG recording. The interhemispheric coherence was estimated using a bivariate autoregressive (AR) parametric model. The coherence spectra were analyzed in the alpha, beta, and gamma frequency EEG bands.

Results: Coherence analysis taking all of the responses showed that in the gamma band, in comparison with the Empathy, Physical causality, and baseline conditions, ToM was associated with significantly higher peaks between the frontal and parietal areas in the right hemisphere and, in comparison with the Physical causality and baseline conditions, in the left hemisphere. Analysis taking the correct responses confirmed these results.

Conclusions: In healthy adults, ToM processes are associated with immediate specific changes of brain connectivity, as expressed by high cortical coherence within the right frontal and parietal areas. These previously unexplored aspects indicate an online involvement of the right hemisphere networks in normal ToM. In patients with epilepsy, the study of EEG coherence during specific tasks may help determine the neural dysfunctions associated with impaired ToM.

This article is part of the Special Issue "Epilepsy and social cognition across the lifespan".

© 2019 Elsevier Inc. All rights reserved.

1. Introduction

Theory of mind (ToM) refers to the ability to understand others' mental states, recognizing that others' thoughts and perspectives may be different from one's own beliefs and reality, therefore cooperating to the understanding of the interpersonal interactions [1].

Structural brain imaging has revealed that damage to different brain regions may impair ToM [2–5]. Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have also clarified the neural basis of ToM, showing an involvement of the temporoparietal junction, temporal poles, medial prefrontal cortex, precuneus, and posterior cingulate [6–8], but distributed neural circuits have been proved to support ToM and empathy [9–11]. While empathy is considered an

ability to appreciate and share others' feelings concerning their affective states, ToM or mentalizing is the capacity to recognize others' cognitive (beliefs, motivations, lies, metaphors, delusions, desires, etc.) or affective mental states. There is some overlapping of empathy and affective ToM, although empathy also includes the sharing of an affective state and, at the neuropsychological level, is assessed using tasks that are quite different in content and procedure from those used to evaluate ToM [12].

Previous studies based on the event-related potentials (ERP) have shown that ToM judgments elicit a late slow activity over the right frontal and posterior cortical areas [13–16]. Mismatch negativity exploring the response to ToM tests has been proved reliable to measure the clinical outcome in patients with schizophrenia in comparison with healthy controls [17].

Most cognitive processes have been associated with event-related electroencephalographic (EEG) oscillations, and there is an increasing evidence that these processes derive from the interaction between functionally specialized and widely distributed brain regions [18]. In human subjects, the studies combining EEG and magnetoencephalography

* Corresponding author at: Unit of Neurophysiopathology, Department of Diagnostics and Technology, Fondazione IRCCS Istituto Neurologico C. Besta, Via Celoria 11, 20133 Milano, Italy.

E-mail address: ferruccio.panzica@istituto-besta.it (F. Panzica).

(MEG), using advanced methods of time series analysis, have revealed that neural synchrony is associated with cognitive functions that require large-scale integration of multiple neural activities. Examples of these functions are attention-dependent stimulus selection, multimodal integration, working memory, and the selective conscious processing of external stimuli [19]. Moreover, there is evidence that the event-related oscillations are modified in many types of neurologic and psychiatric disorders, in particular in cognitive decline, and that the functional cooperation between two distant brain regions may be expressed by EEG connectivity measures, such as coherence [20]. Brain connectivity, as expressed by EEG frequencies in a definite time span, may differently change during the cognitive processes, indicating distinct neurophysiological correlates.

EEG coherence analysis is a simple and fast procedure that can be easily applied in the clinical setting in unconstrained conditions, implying fast postanalysis measures. This study evaluated the role played by synchrony and cooperation among brain regions during ToM processes and the changes of EEG coherence during ToM tasks in comparison with Empathy, Physical causality, and baseline conditions. Specifically, the EEG coherence spectra associated with ToM stimuli were compared with those elicited during Empathy and Physical conditions, using an experimental paradigm to register the stimulus-related EEG changes. We expected distinct changes of the EEG coherence during ToM processes, because of the involvement of the frontal areas in the time span preceding a subject's decision.

2. Methods

2.1. Subjects

Sixteen right-handed healthy subjects (4 males, mean age: 42.4 ± 13.3 years) were recruited among the hospital's visitors. None of the participants had current or past neurological or psychiatric illnesses or severe medical conditions. The local Ethical Committee approved the study, and all of the participants gave their informed consent. The subjects received no information about the features and meaning of the comic strips included in the paradigm or the differences between the stimuli categories (ToM, Empathy, Physical causality).

2.2. Task

A visual activation paradigm including a series of comic strips depicting very short stories was used. The stimuli were divided into blocks that comprehended a story category involving a specific condition: Physical causality, Empathy, or ToM [9]. Ten comic strips were used for each story category. The strips were shown to each subject for 3 s on the upper half of the screen. Afterwards, two pictures illustrating different story outcomes were displayed on the inferior half of the screen for 3 s; only one outcome represented a reasonable conclusion of the story. The subjects were required to make a choice between these two endings and to express their decision by extending the hand on the same side of the chosen picture.

2.3. Electroencephalogram recording and analysis

EEG was recorded by means of Ag/AgCl surface electrodes on the scalp using the 10–20 International System. Surface electromyography (EMG) signals were simultaneously recorded from electrode pairs placed bilaterally 2–3 cm apart over the wrist flexor and extensor muscles in order to detect the side of hand extension indicating the subject's choice and to accurately measure the time interval between the appearance of two pictures on the screen and the subject's choice as marked by the onset of EMG activity.

The EEG and EMG signals were acquired using a computerized Micromed Brain Quick system (Micromed SpA, Mogliano Veneto,

Treviso, Italy) at a sampling frequency of 256 Hz. All of the EEG signals were recorded using montages with a common reference electrode (placed at Fpz) that allowed offline mathematical data reformatting.

Before the analysis, EEG signals were digitally filtered in the 1.6–70 Hz, normalized by subtracting the mean value, and divided by the standard deviation.

The power spectra, interhemispheric coherence, and phase functions were estimated by means of a bivariate autoregressive (AR) parametric model [21]. This method can be applied to assess short EEG epochs, thus allowing to evaluate rapid dynamic changes.

The AR model sequence was established using the multichannel version of the Akaike criterion (AIC) [22]. We checked the adequacy and validity of the AR modeling by means of 'portmanteau' chi-square [13] and Anderson's tests [23].

The coherence function was defined as:

$$C_{xy}^2(f) = \frac{(S_{xy}(f))^2}{(S_{xx}(f))(S_{yy}(f))}$$

where $S_{xx}(f)$ and $S_{yy}(f)$ are the power spectral densities of the two EEG channels (x and y, respectively), and $S_{xy}(f)$ is the cross-spectral density. The coherence spectra were analyzed in the alpha (8–13 Hz), beta (13.2–30 Hz), and gamma (30.2–80 Hz) EEG frequency bands. The signals were preprocessed and analyzed using a custom-written toolbox in MATLAB.

In order to analyze the EEG coherence analysis, a 1000-ms time window starting from 500 after the appearance of two outcome pictures. The choice of this epoch was based on literature data indicating that the cognitive responses to ToM stimuli, as evaluated by ERP, occur in this time range. In order to verify the correctness of this choice, we evaluated the time of occurrence of EEG desynchronization and synchronization [Event-related desynchronization and synchronization (ERD/ERS)] occurring in the time window comprehended between the appearance of two pictures and the onset of EMG activity, according to Visani et al. [24].

2.4. Statistical analysis

Data were analyzed using IBM SPSS Statistics 20. Repeated measure ANOVA (RM-ANOVA) at a significance level of 5% assessed the effect of story category (condition) on the peak frequency and peak coherence values. The sphericity assumption was evaluated using Mauchly's test, and the Greenhouse–Geisser correction on the degrees of freedom was applied when appropriate.

For each EEG frequency band, RM-ANOVA was separately applied for peak frequency and coherence peak values using story category as the within-group factor. Separate analyses were done for the right and left hemispheres. When RM-ANOVA showed a significant main effect, contrast effects were evaluated with ToM as a reference using paired t-tests and setting significance at $p < 0.05$ according to Bonferroni correction for multiple comparisons. Paired t-tests were also used to evaluate differences between homologous EEG derivations on the right and left hemispheres.

3. Results

Preliminary analysis performed to confirm the occurrence of reactive EEG oscillations showed that, within the time window ranging from 500 to 2000 ms, desynchronization (blue areas) followed by synchronization (yellow area) occurred in the alpha and beta bands (Fig. 1). Before the occurrence of alpha and beta synchronization changes, a clear synchronization was observed in the low gamma band (30–40 Hz). All of these changes involved centroparietal areas.

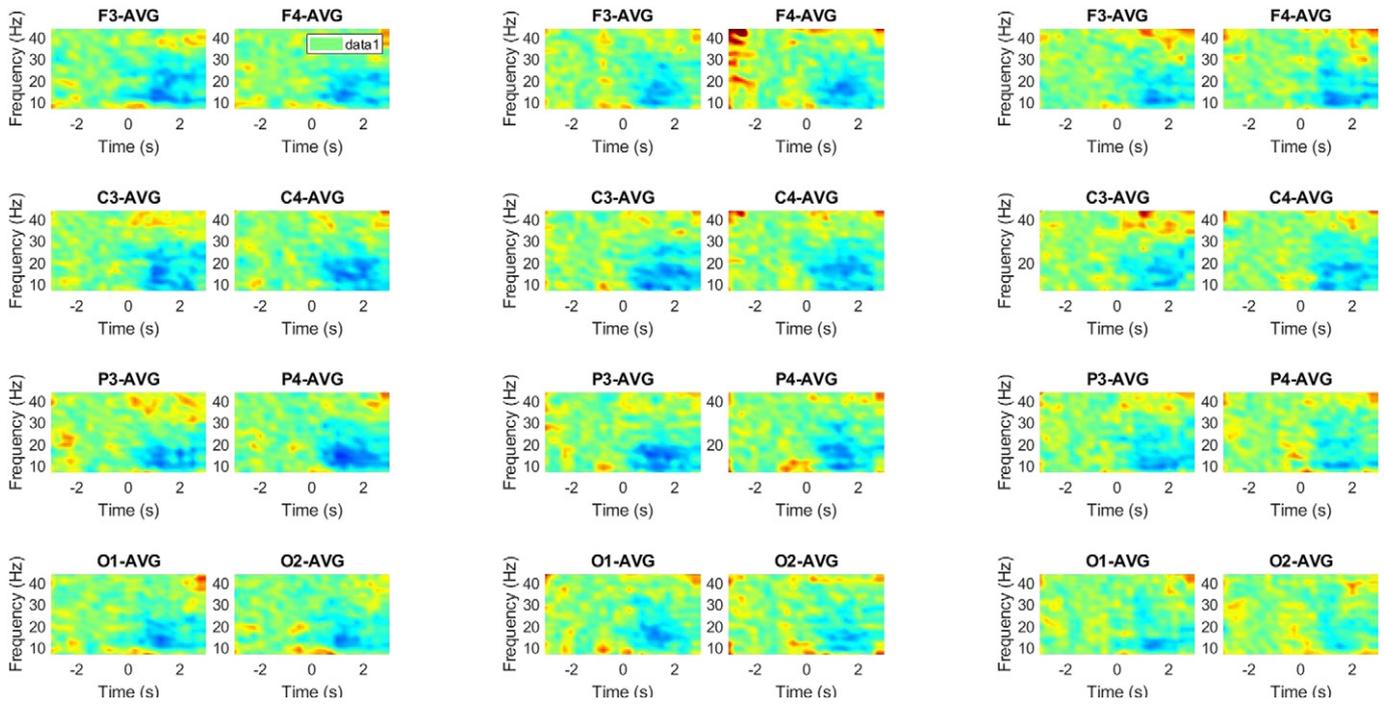


Fig. 1. Grand-average time-frequency maps of the ERD/ERS activity. The graph shows the grand-average time-frequency maps of the ERD/ERS activity. A clear desynchronization occurred in alpha band (blue areas) in a time window between 0.5 and 1.5–2.0 more obvious on the frontocentral–parietal regions of both hemispheres; in the same time window and in the same regions, a synchronization could be observed in the gamma band (30–40 Hz, yellow areas).

3.1. Coherence analysis

All of the participants completed the task for each conditions. Repeated measure ANOVA taking all of the responses did not reveal any difference in the response time (Physical causality: 2.40 ± 1.41 s; Empathy: 2.29 ± 1.47 s; ToM: 2.60 ± 1.41 s) and the number of correct responses (Physical causality: 8.7 ± 1.1 ; Empathy: 8.5 ± 1.1 ; ToM: 7.4 ± 1.6) between three stimulus conditions. Table 1 reports the mean coherence peak frequency and the values of peak coherence amplitude for each story category in different frequency bands, summarizing all of the correct and incorrect responses. See also Fig. 2 for a representative coherence spectra.

3.1.1. Peak frequency

In each condition, RM-ANOVA did not reveal any differences between the peak frequencies and the coherence values in the alpha and beta bands. Paired t-test revealed no significant differences between homologous derivations on the right and left hemispheres in any frequency.

3.1.2. Peak coherence amplitude

On the contrary, in the gamma band, RM-ANOVA revealed a significant effect of different conditions for peak coherence values between the frontal–parietal regions of the right and left hemispheres ($F(3,45) = 10.25, p < 0.001$ and $F(3,45) = 3.84, p = 0.015$) while no difference was observed between the peak frequencies (Fig. 2).

The contrasts using ToM as reference revealed on the left hemisphere a significant difference between coherence in gamma band between ToM and Empathy ($p < 0.001$), ToM and Physical causality ($p = 0.021$), and ToM and baseline ($p < 0.001$). On the right hemisphere, the contrasts revealed a significant difference between ToM and Physical causality ($p = 0.014$) and ToM and baseline ($p = 0.001$). By comparing all couples of different conditions using paired t-test, the only surviving significant differences occurred between ToM and baseline ($p = 0.003$) and ToM and Empathy ($p = 0.018$) on the right hemisphere, and ToM and baseline on the left one ($p = 0.012$).

We repeated the same analysis in the gamma band only including the EEG epochs associated with correct responses (Table 2). Repeated

Table 1
Peak coherence frequency and values in different electroencephalogram frequency bands.

Condition	Band	F4-C4 vs P4-O2 Mean frequency (Hz)	F4-C4 vs P4-O2 Mean coherence	F3-C3 vs P3-O1 Mean frequency (Hz)	F3-C3 vs P3-O1 Mean coherence
Baseline	Alpha	10.16 ± 1.42	0.18 ± 0.13	9.10 ± 2.43	0.23 ± 0.15
Physical causality		9.64 ± 2.26	0.25 ± 0.14	9.37 ± 2.75	0.16 ± 0.06
Empathy		10.26 ± 2.58	0.26 ± 0.22	9.42 ± 2.24	0.19 ± 0.07
ToM	Beta	10.5 ± 2.34	0.24 ± 0.15	9.74 ± 2.49	0.17 ± 0.06
Baseline		20.60 ± 3.15	0.15 ± 0.07	20.09 ± 3.34	0.17 ± 0.11
Physical causality		21.27 ± 3.56	0.13 ± 0.05	20.48 ± 3.90	0.18 ± 0.11
Empathy	Gamma	22.37 ± 3.30	0.15 ± 0.99	20.11 ± 3.69	0.17 ± 0.09
ToM		21.75 ± 2.34	0.14 ± 0.08	22.48 ± 4.77	0.18 ± 0.12
Baseline		39.00 ± 1.45	0.08 ± 0.03	37.81 ± 2.24	0.09 ± 0.06
Physical causality	38.90 ± 2.14	0.12 ± 0.05	38.16 ± 3.59	0.11 ± 0.04	
Empathy	39.30 ± 3.04	0.12 ± 0.06	38.81 ± 3.18	0.13 ± 0.07	
ToM	39.47 ± 2.14	0.18 ± 0.06	39.47 ± 2.14	0.16 ± 0.06	

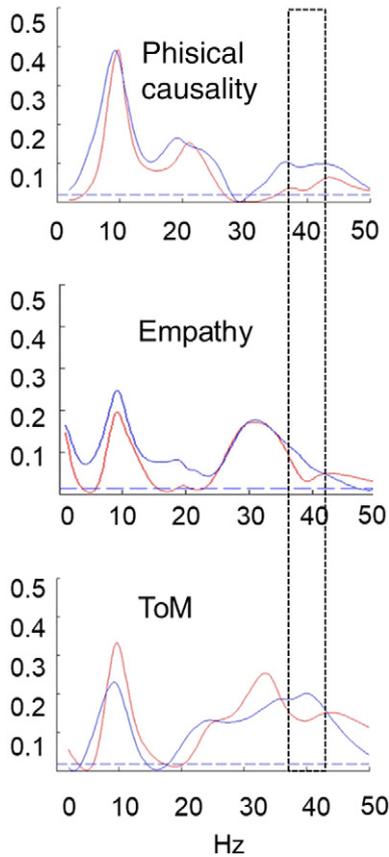


Fig. 2. Averaged coherence spectra obtained in a representative subject in different conditions; note the prominent coherence around 40 Hz in response to ToM stimulus. In blue, the coherence obtained on right hemisphere.

measure ANOVA did not show any differences between the number of correct responses given by different subjects or in different conditions.

Repeated measure ANOVA showed a significant effect of condition on the peak coherence values [right hemisphere: $F(3,45) = 6.62$, $p = 0.001$; left hemisphere: $F(3,45) = 0.021$]. For the right hemisphere, contrasts using ToM as a reference revealed a significant difference between ToM and all of the other conditions (baseline $p = 0.003$; Physical causality $p = 0.002$; Empathy $p = 0.004$). Paired t-test confirmed significant differences between ToM and other conditions (baseline $p = 0.004$; Physical causality $p = 0.009$; Empathy $p = 0.018$). No other differences were observed. For the left hemisphere, contrasts using ToM as reference only revealed a significant difference between ToM and baseline ($p = 0.021$).

4. Discussion

Brain connectivity is expected to vary during different mental activities [25]. This study analyzed the EEG coherence in response to visual activation paradigms aiming to clarify its changes during ToM processes in comparison with Physical causality, Empathy, and baseline

conditions. Results showed that, in the gamma band, EEG coherence was significantly greater during ToM processes in comparison with other conditions, with particular evidence on parietal and frontal lobe areas.

During ToM tasks, an increased peak coherence at frequencies of about 40 Hz (gamma band) only involved the frontal and parietal areas bilaterally, with a clear predominance on the right hemisphere. This suggests that ToM processes are specifically associated with gamma connectivity in the right cortical areas. The main role played by the right hemisphere in ToM was previously indicated by studies in healthy subjects [26–31] and patients with right hemisphere stroke [32], although either left or right temporal lobe epilepsy has been associated with impaired ToM [33,34].

A special involvement of the EEG gamma frequencies during various cognitive performances has been largely reported both in healthy subjects and patients affected by neurological or psychiatric disorders. An enhancement of the gamma oscillations around 40 Hz was early reported by Gray and Singer [35] and Singer [19] who investigated the role played by these oscillations in cat's primary visual cortex (V1) during stimulus-induced synchronization; these authors formulated the hypothesis of “binding-by-synchrony”, implying that synchronized oscillations represent a mechanism capable to coordinate distributed neuronal responses. After this experimental study, several evidences reported the association between oscillations at 40 Hz and cognitive and executive functions in humans, namely in the case of tests exploring working memory, attention, and access to consciousness or motor-planning [13,36–39].

Present findings of transitory synchronization changes activated by ToM suggest an online mechanism of functional coupling between neural assemblies in the frontal and parietal regions. Summerfield and Mangels [40], assessing the functional coupling between the frontal and parietal regions during a recognition memory task, found that the synchronization of the neuronal responses in the gamma band may be an important mechanism used by these regions to exchange information during the retrieval of past events. As well, in a group of healthy subjects, Bhattacharya et al. [41] found that synchronization between the frontal and right parietal cortex was significantly increased during mental rotation with respect to resting state. The frontoparietal connectivity is also known to play a crucial role in the thalamocortical network that regulates cortical states and behavior [42,43]. These studies analyzed the functional coupling of frontoparietal regions during long-term memorization of visuospatial contents (Hemispheric Encoding / Retrieval Asymmetry (HERA) model) by means of high-resolution EEG, showing a statistically significant coherence in the gamma band in the left hemisphere, during encoding, and, in the right hemisphere, during retrieval.

The transitory brain activation during ToM processes involves areas that are also implicated in empathy [9,44,45]. However, an association of different functions with the same brain areas does not necessarily counteract cognitive domain specificity. Indeed, the paradigm used in the present study differentiated the neurophysiological changes associated with ToM with respect to Empathy and Physical causality, suggesting that ToM has specific neural correlates. Especially, in comparison with Empathy, ToM involved more synchronous and powerful gamma oscillations that were detected in a restricted time window. Unlike functional neuroimaging, which detects brain activations a few seconds after

Table 2
Peak frequency and coherence values in electroencephalogram gamma band during correct responses.

Condition (correct responses)	F4-C4 vs P4-O2 Mean frequency (Hz)	F4-C4 vs P4-O2 Mean coherence	F3-C3 vs P3-O1 Mean frequency (Hz)	F3-C3 vs P3-O1 Mean coherence
Baseline	38.58 ± 2.29	0.13 ± 0.06	37.67 ± 2.45	0.09 ± 0.03
Physical causality (8.7 ± 1.1)	39.23 ± 2.27	0.14 ± 0.04	38.86 ± 2.62	0.12 ± 0.04
Empathy (8.5 ± 1.1)	38.59 ± 1.79	0.14 ± 0.05	38.83 ± 2.74	0.14 ± 0.05
ToM (7.4 ± 1.6)	39.04 ± 2.48	0.18 ± 0.05	38.82 ± 2.25	0.14 ± 0.06

stimulus presentation, EEG recording can register online functional changes, allowing to define precise temporal–spatial correlates and to distinguish the correlates of ToM and Empathy.

This paradigm may help clarify the EEG changes during ToM processes in patients with chronic epilepsy, also considering that brain functions and anatomy may be rearranged secondarily to seizures and focal lesions [33,46]. Functional dynamic alterations of the frontoparietal system have been found in patients with frontal lobe epilepsies by analyzing the functional network connectivity at fMRI [47]. The frontoparietal networks are possibly implied in the conscious state during “complex” partial seizures [48]. Moreover, using fMRI or EEG recording, a significant involvement of frontal, central, and parietal connectivity has been detected in adults [49] or children with idiopathic generalized epilepsy [50] and in children with idiopathic rolandic epilepsies [51,52].

Present findings have to take into account some limitations. The electrode array was restricted while high-resolution EEG array or MEG sensors may reach more accurate localization of the coherence peaks and topographical distribution. A larger sensor array would also allow the use of different EEG parameters characterizing the peak amplitude and improving spatial resolution.

To conclude, ToM processes may induce coherent oscillations in EEG gamma frequency band in the frontal, central, and parietal areas, reflecting online functional connectivity. Such activations appear specifically related to ToM in comparison with Empathy and Physical causality, and they prominently involve the right hemisphere. Further studies are needed to confirm the specificity of gamma oscillations during ToM tasks and to further define the cortical regions and timing of these changes. A combined EEG–neuropsychological paradigm in healthy subjects and patients with epilepsy may help determine the mechanisms implied in specific cognitive impairments or recovery.

Declaration of Competing Interest

The authors declare no conflicts of interests.

Acknowledgments

The authors thank all of the study participants.

Funding

This work received no financial supports.

References

- [1] Adolphs R. The neurobiology of social cognition. *Curr Opin Neurobiol* 2001;11: 231–9.
- [2] Rowe AD, Bullock PR, Polkey CE, Morris RG. “Theory of mind” impairments and their relationship to executive functioning following frontal lobe excisions. *Brain* 2001; 124:600–16.
- [3] Stone VE, Baron-Cohen S, Keane J, Young A. Acquired theory of mind impairments in individuals with bilateral amygdala lesions. *Neuropsychologia* 2003;41:209–20.
- [4] Bodden ME, Dodel R, Kalbe E. Theory of mind in Parkinson’s disease and related basal ganglia disorders: a systematic review. *Movement Dis* 2010;25:13–27.
- [5] Parente A, Manfredi V, Tarallo A, Salsano E, Erbetta A, Pareyson D, et al. Selective theory of mind impairment and cerebellar atrophy: a case report. *J Neurol* 2013;260: 2166–9.
- [6] Saxe R, Kanwisher N. People thinking about thinking people: the role of the temporo-parietal junction in “theory of mind”. *NeuroImage* 2005;19:1835–42.
- [7] Bzdok D, Schilbach L, Vogeley K, Schneider K, Laird AR, Langner R, et al. Parsing the neural correlates of moral cognition: ALE meta-analysis on morality, theory of mind, and empathy. *Brain Struct Funct* 2012;217:783–96.
- [8] Schurz M, Radua J, Aichhorn M, Richlan F, Perner J. Fractionating theory of mind: a meta-analysis of functional brain imaging studies. *Neurosci Biobehav Rev* 2014;42: 9–34.
- [9] Vollm BA, Taylor ANW, Richardson P, Corcoran R, Stirling J, McKie S. Neuronal correlates of theory of mind and empathy: a functional magnetic resonance imaging study in a nonverbal task. *Neuroimage* 2006;29:90–8.
- [10] Kanske P, Böckler A, Singer T. Models, mechanisms and moderators dissociating empathy and theory of mind. *Curr Top Behav Neurosci* 2017;30:193–206.
- [11] Stietz J, Jauk E, Krach S, Kanske P. Dissociating empathy from perspective-taking: evidence from intra- and inter-individual differences research. *Front Psych* 2019;10: 126.
- [12] Baron-Cohen S, Wheelwright S, Skinner R, Martin J, Clubley E. The autism-spectrum quotient (AQ): evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *J Autism Dev Dis* 2001;31:5–17.
- [13] Lopes da Silva FH, Nijl Mars. Parametric methods in EEG analysis. *Electroencephalography, basic principles, clinical application and related fields*. Amsterdam: Elsevier; 1987.
- [14] Sabbagh MA, Bowman LC, Evraire LE, Ito JMB. Neurodevelopmental correlates of theory of mind in preschool children. *Child Dev* 2009;80:1147–62.
- [15] Liu D, Sabbagh MA, Gehring WJ, Wellman HM. Neural correlates of children’s theory of mind development. *Child Dev* 2009;80:318–26.
- [16] McCleery JP, Surtees ADR, Graham KA, Richards JE, Apperly IA. The neural and cognitive time course of theory of mind. *J Neurosci* 2011;31:12849–54.
- [17] Lee SH, Sung K, Lee KS, Moon E, Kim CG. Mismatch negativity is a stronger indicator of functional outcomes than neurocognition or theory of mind in patients with schizophrenia. *Prog Neuropsychopharmacol Biol Psychiatry* 2014;48:213–9.
- [18] Siegel M, Donner TH, Engel AK. Spectral fingerprints of large-scale neuronal interactions. *Nat Rev Neurosci* 2012;13:121–34.
- [19] Singer W. Neuronal synchrony: a versatile code for the definition of relations? *Neuron* 1999;24:49–65.
- [20] Basar E. Brain oscillations in neuropsychiatric disease. *Dialogues Clin Neurosci* 2013; 15:291–300.
- [21] Panzica F, Franceschetti S, Binelli S, Canafoglia L, Granata T, Avanzini G. Spectral properties of EEG fast activity ictal discharges associated with infantile spasms. *Clin Neurophysiol* 1999;110:593–603.
- [22] Marple SL. Digital spectral analysis with applications. Englewood Cliff, NJ: Prentice Hall; 1987.
- [23] Box GEP, Jenkins GM. Time series analysis. San Francisco, CA: Holden-Day; 1970.
- [24] Visani E, Agazzi P, Canafoglia L, Panzica F, Ciano C, Scafoli V, et al. Movement-related desynchronization-synchronization (ERD/ERS) in patients with Unverricht–Lundborg disease. *Neuroimage* 2006;33:161–8.
- [25] Kucyi A, Tambini A, Sadaghiani S, Keilholz S, Cohen JR. Spontaneous cognitive processes and the behavioral validation of time-varying brain connectivity. *Netw Neurosci* 2018;2:397–417.
- [26] Saxe R, Wexler A. Making sense of another mind. *Neuropsychologia* 2005;43: 1391–9.
- [27] Surian L, Siegal M. Sources of performance on theory of mind tasks in right hemisphere-damaged patients. *Brain Lang* 2001;78:224–32. <https://doi.org/10.1006/brln.2001.2465>.
- [28] Brunet Gouet, Decety J. Social brain dysfunctions in schizophrenia: a review of neuroimaging studies. *Psychiatry Res* 2006;148(2–3):75–92.
- [29] Frith CD, Frith U. The neural basis of mentalizing. *Neuron* 2006;50:531–4.
- [30] Carrington SJ, Bailey AJ. Are there theory of mind regions in the brain? A review of the neuroimaging literature. *Hum Brain Mapp* 2009;30:2313–35.
- [31] Van Overwalle F. Social cognition and the brain: a meta-analysis. *Hum Brain Mapp* 2009;30:829–58.
- [32] Hamilton J, Radlak B, Morris PG, Phillips LH. Theory of mind and executive functioning following stroke. *Arch Clin Neuropsychology* 2017;32:507–18.
- [33] Shacher M, Winkler R, Grunwald T, Kraemer G, Kurthen M, Reed V, et al. Mesial temporal lobe epilepsy impairs advanced social cognition. *Epilepsia* 2006;47:2141–6.
- [34] Giovagnoli AR, Franceschetti S, Reati F, Parente A, Maccagnano C, Villani F, et al. Theory of mind in frontal and temporal lobe epilepsy: cognitive and neural aspects. *Epilepsia* 2011;52(11):1995–2002.
- [35] Gray CM, Singer W. Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. *Proc Natl Acad Sci U S A* 1989;86:1698–702.
- [36] Tallon-Baudry C, Bertrand O. Oscillatory gamma activity in humans and its role in object representation. *Trends Cogn Sci* 1999;3:151–62.
- [37] Herrmann CS, Munk MHJ, Engel AK. Cognitive functions of gamma-band activity: memory match and utilization. *Trends Cogn Sci* 2004;8:347–55.
- [38] Fries P. Neuronal gamma-band synchronization as a fundamental process in cortical computation. *Annu Rev Neurosci* 2009;32:209–24.
- [39] Uhlhaas PJ, Pipa G, Lima B, Melloni L, Neuschwander S, Nikolić D, et al. Neural synchrony in cortical networks: history, concept and current status. *Front Integr Neurosci* 2009;3(art 17):1–19.
- [40] Summerfield C, Mangels JA. Functional coupling between frontal and parietal lobes during recognition memory. *Neuroreport* 2005;16:117–22.
- [41] Bhattacharya J, Petsche H, Feldmann U, Rescher B. EEG gamma-band phase synchronization between posterior and frontal cortex during mental rotation in humans. *Neurosci Lett* 2001;311:29–32.
- [42] Tononi G, Koch C. The neural correlates of consciousness: an update. *Ann N Y Acad Sci* 2008;1124:239–61.
- [43] Babiloni C, Vecchio F, Cappa S, Pasqualetti P, Rossi S, Miniussi C, et al. Functional frontoparietal connectivity during encoding and retrieval processes follows HERA model. A high-resolution study. *Brain Res Bull* 2006;68:203–12.
- [44] McCabe K, Houser D, Ryan L, Smith V, Trouard T. A functional imaging study of cooperation in two-person reciprocal exchange. *Proc Natl Acad Sci U S A* 2001;98: 11832–5.
- [45] Gallagher HL, Happe F, Brunswick N, Fletcher PC, Frith U, Frith CD. Reading the mind in cartoons and stories: an fMRI study of “theory of mind” in verbal and nonverbal tasks. *Neuropsychologia* 2000;38:11–21.
- [46] Giovagnoli AR, Parente A, Didato G, Deleo F, Villani F. Expanding the spectrum of cognitive outcomes after temporal lobe epilepsy surgery: a prospective study of theory of mind. *Epilepsia* 2016;57:920–30.
- [47] Klugah-Brown B, Luo C, He H, Jiang S, Armah GK, Wu Y, et al. Altered dynamic functional network connectivity in frontal lobe epilepsy. *Brain Topogr* 2019;32:394–404.

- [48] Cavanna AE, Rickards H, Ali F. What makes a simple partial seizure complex? *Epilepsy Behav* 2011;22:651–8.
- [49] Wei HL, An J, Zeng LL, Shen H, Qiu SJ, Hu DW. Altered functional connectivity among default, attention, and control networks in idiopathic generalized epilepsy. *Epilepsy Behav* 2015;46:118–25.
- [50] Rotondi F, Franceschetti S, Avanzini G, Panzica F. Altered EEG resting-state effective connectivity in drug-naïve childhood absence epilepsy. *Clin Neurophysiol* 2016;127:1130–7.
- [51] Luo C, Yang F, Deng J, Zhang Y, Hou C, Huang Y, et al. Altered functional and effective connectivity in anticorrelated intrinsic networks in children with benign childhood epilepsy with centrotemporal spikes. *Medicine (Baltimore)* 2016;95:e3831.
- [52] Varotto G, Franceschetti S, Caputo D, Visani E, Canafoglia L, Freri E, et al. Network characteristics in benign epilepsy with centro-temporal spikes patients indicating defective connectivity during spindle sleep: a partial directed coherence study of EEG signals. *Clin Neurophysiol* 2018;129:2372–9.