Brain Research Bulletin 167 (2021) 33–36

Contents lists available at ScienceDirect

Brain Research Bulletin

journal homepage: www.elsevier.com/locate/brainresbull

Assessing the dependence of the number of EEG channels in the brain networks' modulations

Francesca Miraglia [a,*], Carlo Tomino [b], Fabrizio Vecchio [a], Francesca Alù [a], Alessandro Orticoni [a], Elda Judica [c], Maria Cotelli [d], Paolo Maria Rossini [a]

[a] Brain Connectivity Laboratory, Department of Neuroscience and Neurorehabilitation, IRCCS San Raffaele Pisana, Rome, Italy
[b] Scientific Directorate, IRCCS San Raffaele Pisana, Rome, Italy
[c] Department of Neurorehabilitation Sciences, Casa Cura Policlinico, Milano, Italy
[d] Neuropsychology Unit, IRCCS Istituto Centro San Giovanni di Dio Fatebenefratelli, Brescia, Italy

ARTICLE INFO

Keywords:
EEG
Brain networks
Resting state

ABSTRACT

Aim of the study was to evaluate the influence of the EEG channels number on the brain networks' analysis, to establish whether and how much higher density EEG actually contributes to add supplementary information to brain networks analyses. 59 electrodes EEGs were recorded in 20 healthy subjects in eyes open and closed condition. For each condition, we analyzed the recording dataset of 59 channels, and three sub-datasets obtained by the selection of 44, 30, 19 channels from the 59 ones. Then we computed the EEG sources of current density and evaluated the SW index in the four EEGs data montages. Results showed that in the eyes open condition the number of recording channels influences more the SW index modulation respect that in the eyes closed condition. Conversely, in the eyes closed condition the brain activity is less affected by specific brain regions' activations and the signal's generators produced not significant variations on EEG data and consequently the small world network measure is not affected by the recording channels number. We can conclude that in the eyes closed condition, the 19 EEG channels is an acceptable montage to study brain networks' modulations, to both detect the higher and the lower brain waves' frequencies.

1. Introduction

Electroencephalography (EEG) is a low cost, largely diffused and non invasive technique that allows a cost-effective large population screening both for research and clinical applications.

The first standard montage of EEG was the 10–20 system developed by Jasper and colleagues (Jasper, 1958). Later, the 10–20 system was extended from the 10 % till to the 5% electrode positions, resulting in systems with up to 345 electrode arrays (Oostenveld and Praamstra, 2001).

Recently, with the spreading of the EEG source imaging techniques, it has emerged the interest to increase the number of EEG channels' recording in order to better reconstruct the brain rhythm generators. Nowadays, the currently available systems allow EEG recordings from up to 256 locations on the scalp. Accordingly, in the last years the high density EEGs (HD-EEG) -which refers to the use of 60-to–256 electrodes- have taken place an increasing use in clinical and research's evaluations (Liu et al., 2017, 2018).

However, especially in the clinical practice it is well known that the patients' compliance increases if the exam's procedures are fleeter than possible. In the case of EEG recording, the exam's duration is influenced by the operation of reducing the skin-electrodes' impedances: therefore, lower is the number of EEG channels, lower will be the procedure duration.

In this study, we aimed to evaluate the influence of the number of EEG channels on the brain sources reconstruction and on the relative networks' analysis, in order to establish whether and how much a progressively higher density of EEG configuration actually contributes to add supplementary information to brain networks analyses.

2. Methods

2.1. Participants

20 healthy adult volunteers (10 females and 10 males; mean age = 26.1 years, SE = 0.7) were enrolled. All of them were right-handed at

* Corresponding author at: Brain Connectivity Laboratory, IRCCS San Raffaele Pisana, Via Val Cannuta, 247, 00166, Rome, Italy.
E-mail address: francesca.miraglia@sanraffaele.it (F. Miraglia).

https://doi.org/10.1016/j.brainresbull.2020.11.014
Received 16 July 2020; Received in revised form 4 November 2020; Accepted 19 November 2020
Available online 23 November 2020
0361-9230/

Handedness Questionnaire (Salmaso and Longoni, 1985) and had no previous psychiatric or neurological disease history. Informed consent was obtained from each participant. Experimental procedures were conformed to the Declaration of Helsinki and national guidelines and approved by local Ethics Committee.

2.2. EEG recordings

The experimental procedure was conducted in a low-light quiet room while the participants were relaxed and seated. EEG recordings of 5 min duration were obtained from each subject in both eyes closed (EC) and eyes open (EO) resting state conditions.

According to the 10–20 International system, 59 scalp electrodes (Fp1,Fp2,F3,F4,C3,C4,P3,P4,O1,O2,F7,F8,T7,T8,P7,P8,Fz,Cz,Pz,FC1, FC2,CP1,CP2,FC5,FC6,CP5,CP6,F1,F2,C1,C2,P1,P2,AF3,AF4,FC3,FC4, CP3,CP4,PO3,PO4,F5,F6,C5,C6,P5,P6,AF7,AF8,FT7,FT8,TP7,TP8,PO7, PO8,Fpz,CPz,POz,Oz) were positioned with two additional electrooculogram channels for monitoring eyes movements. During the EEG recordings, the skin/electrode impedances were maintained below of 5 KΩ, and the sampling rate system acquisition was fixed at 512 Hz.

2.3. EEG data analysis

Data were analyzed with Matlab software and using scripts based on EEGLAB toolbox. In order to remove the low and high frequency artifacts (i.e., line artifacts), the EEG signals recorded were filtered from 0.1 to 47 Hz with a Finite Impulse Response (FIR) filter as implemented in Matlab (MathWorks,Natick, MA). Then, the EEG data were re-referenced to the common average. To eliminate the residual artifacts (i.e. cardiac activity, eye movements, contractions of scalp muscles), for each subject's condition 2 s epochs were extracted and concatenated from continuous data, visually inspected and processed with Infomax ICA algorithm with EEGLAB solution (EEGLAB software). ICA is a blind source decomposition algorithm that enables the separation of statistically independent sources from multichannel data and it has validated as a powerful method in the artifact cancellation with respect to classical segment-rejection approach (Barbati et al., 2004; Porcaro et al., 2015). An expert EEGer analyzed components' properties and labeled components for rejection (i.e. identifying components to subtract from the data). Not more than the 20 % of the independent components were discarded, in order to preserve the recorded brain signal contribution. In detail, the percentage of components we have deleted was: 16.135 % ± 4.83 (%mean ± standard deviation) in the eyes open condition, 13.573 % ± 3.64 in the eyes closed condition.

For each subject and in both resting state conditions, after the ICs' removal, we analyzed three datasets with different EEG montages: the first dataset were composed by the recording data with 59 electrodes; the second dataset were obtained by the selection of 44 electrodes uniformly taken from the 59 recording channels (Fp1,Fp2,F3,F4,C3,C4, P3,P4,O1,O2,F7,F8,T7,T8,P7,P8,Fz,Cz,Pz,FC1,FC2,CP1,CP2,AF3,AF4, FC3,FC4,CP3,CP4,PO3,PO4,F5,F6,C5,C6,P5,P6,FT7,FT8,TP7,TP8,CPz, POz,Oz); the third were obtained with 30 of the 44 selected channels (Fp1,Fp2,F3,F4,C3,C4,P3,P4, O1,O2,F7,F8,T7,T8,P7,P8,Fz,Cz,Pz,FC3, FC4,CP3,CP4,FT7,FT8,TP7,TP8,CPz,POz,Oz); the last were composed by 19 of the 30 channels (Fp1,Fp2,F3,F4,C3,C4,P3,P4,O1,O2,F7,F8,T3, T4,T5,T6,Fz,Cz,Pz) (Fig. 1).

2.4. Functional connectivity and network analyses

For each subject-dataset, starting from the 19, 30, 44 and 59 EEG scalp electrodes, the electric neuronal activity distributions (current density vector field) were estimated on the cortex with eLORETA (exact low resolution brain electromagnetic tomography) software provided by Pascual-Marqui (Pascual-Marqui, 2002).

eLORETA is a low resolution brain electromagnetic tomography and it was chosen because it is a good method for sources reconstruction in the presence of both biological and measurement noise.

The intracerebral volume is partitioned in 6239 voxels at 5 mm spatial resolution. Thus, eLORETA images represent the electric activity at each voxel in neuroanatomic Montreal Neurological Institute (MNI) space as the magnitude of the estimated current density. Anatomical labels as Brodmann Areas (BAs) are also reported using MNI space, with correction to Talairach space. For each subject-dataset, brain connectivity was obtained by intracortical lagged linear connectivity (Pascual-Marqui, 2007) on 84 regions of interest (ROIs), which correspond to 42 Brodmann areas (BAs) for the left and 42 BAs for the right hemisphere, as available in eLORETA software.

Lagged linear connectivity was computed as measure of functional coupling between BAs:

$$LagR^2_{xyw} = \frac{[ImCov(x,y)]^2}{Var(x) * Var(y) - [ReCov(x,y)]^2}$$

Where x and y are the time series of two BAs, *Im* and *Re* are the imaginary and real part, *Var* and *Cov* are variances and covariance of the signals.

Basing on BAs and Lagged Linear Connectivity values, weighted and undirected brain networks were built with Brain Connectivity Toolbox (Rubinov and Sporns, 2010). The networks' nodes were the estimated cortical sources in the BAs, the networks' edges were weighted by the lagged linear value within each pair of vertices (Miraglia et al., 2020; Tecchio et al., 2016; Vecchio et al., 2017).

The Small World (SW) index was computed as it represents an index of brain network organization: it measures the balance between local connectedness and global integration of a network. Higher values of SW are representative of networks more random (associated with a short overall path length but a low level of local clustering); lower values of SW index are associated to more regular networks (with a high level of clustering but a high overall path length) (Miraglia et al., 2020; Vecchio et al., 2018).

The SW is defined as the ratio between the normalized clustering coefficient (C) and the normalized characteristic path length (L), in each EEG frequency band delta (2–4 Hz), theta (4–8 Hz), alpha 1 (8–10.5 Hz), alpha 2 (10.5–13 Hz), beta 1 (13–20 Hz), beta 2 (20–30 Hz) and gamma (30–45 Hz).

For each subject, the normalization was performed by dividing C and

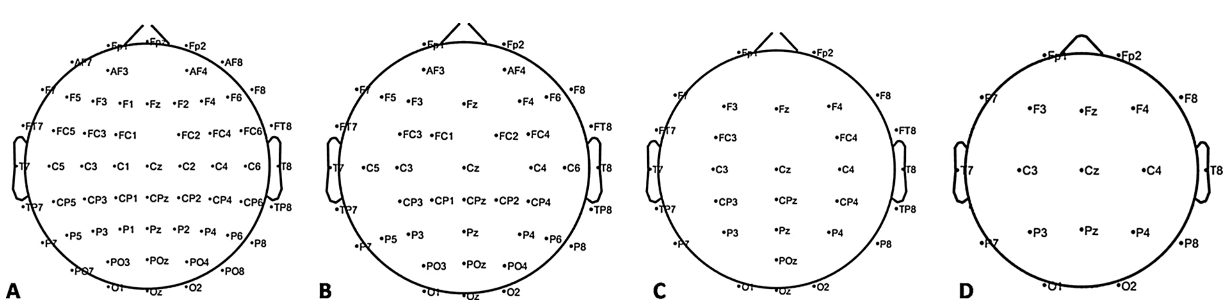

Fig. 1. EEG channels' locations: 59 electrodes (Panel A), 44 electrodes (Panel B), 30 electrodes (Panel C), 19 electrodes' montages (Panel D).

L respectively with the average values of C and L computed for all the frequency bands. This kind of normalization makes the data no longer dependent on the number of subjects nor on the number of nodes, diminishing the bias due to differences in network structure.

2.5. Statistical evaluation

Statistical analyses were performed with Statistica (StatSoft Inc., www.statsoft.com) by set up the significance level at $p < 0.05$.

The analyses consisted in two two-way ANOVAs in order to compare SW index separately in eyes open and in eyes closed condition, among the factors Montage (19, 30, 44 and 59 channels) and EEG Band (delta, theta, alpha 1, alpha 2, beta 1, beta 2, and gamma).

ANOVA was chosen as it is known to be robust with respect to the departure of normality and homoscedasticity of data being related. Greenhouse and Geisser correction was used for protection against the violation of sphericity assumption in the repeated measure ANOVA. Furthermore, it was performed posthoc analysis with Duncan's test (significance level at 0.05).

3. Results

The ANOVA for the evaluation of SW index in EO condition showed significant interaction ($F(18.324) = 2.4553$; $p = 0.0009$) among the factors Montage (19 channels, 30 channels, 44 channels, 59 channels) and EEG Band (delta, theta, alpha 1, alpha 2, beta 1, beta 2, and gamma) (on the left of Fig. 2). Duncan posthoc testing showed that: in delta band, the SW index was lower in the 59 channels montage respect to both the 19 ($F(18.324) = 2.4553$; $p = 0.0162$) and 30 ($F(18.324) = 2.4553$; $p = 0.0240$) channels montage; in gamma band, the SW index was higher in the 59 channels respect to the 19 channels montage ($F(18.324) = 2.4553$; $p = 0.0001$) and respect to the 30 channels montage ($F(18.324) = 2.4553$; $p = 0.0031$). Furthermore, in gamma band the SW index was higher in the 59 channels montage respect to the 44 channels montage ($F(18.324) = 2.4553$; $p = 0.05$).

The ANOVA for the evaluation of SW index in EC condition showed significant interaction ($F(18.324) = 1.8429$; $p = 0.0199$) among the factors Montage (19 channels, 30 channels, 44 channels, 59 channels) and EEG Band (delta, theta, alpha 1, alpha 2, beta 1, beta 2, and gamma) (on the right of Fig. 2): in particular, observing the significant bands of the EO, the gamma SW index was higher in the 59 channels montage respect the 19 $F(18.324) = 2.4553$; $p = 0.0436$) channels montage and respect to the 30 channels montage ($F(18.324) = 2.4553$; $p = 0.0016$).

4. Discussion

In the current study, we have evaluated the influence of the number of EEG channels on the brain sources reconstruction and on the related networks' analysis, in order to establish if an higher density EEG configuration actually contributes supplementary information to brain networks analyses.

To reach this aim, we recorded EEG data from 59 electrodes in healthy subjects during eyes open and eyes closed condition. For each condition, we have analyzed the recording dataset of 59 channels, and of three further sub-datasets obtained by the selection of 44, 30 and 19 channels from the 59 ones.

Then, we have extracted the current density of EEG sources and evaluated the SW index in the four different EEGs data montages in the eyes open and eyes closed conditions.

Results have shown significant differences in the eyes open condition in the low EEG frequency band – delta band- between 59 and 19 channels' montages, and between 59 and 30 channels' montages. In the high EEG frequency band -gamma band- significant interactions have been found between: 59 and 19 channels, 59 and 44 channels, 59 and 30 channels and between 44 and 19 channels' montage. In the eyes closed condition, significant interactions have been seen only in gamma band between 59 and 19 channels and between 59 and 30 channels' montage.

Thus, our findings suggested that the lower and the higher frequency bands are more sensitive to the number of EEG scalp electrodes. In particular, higher the number of electrodes, lower the delta and higher

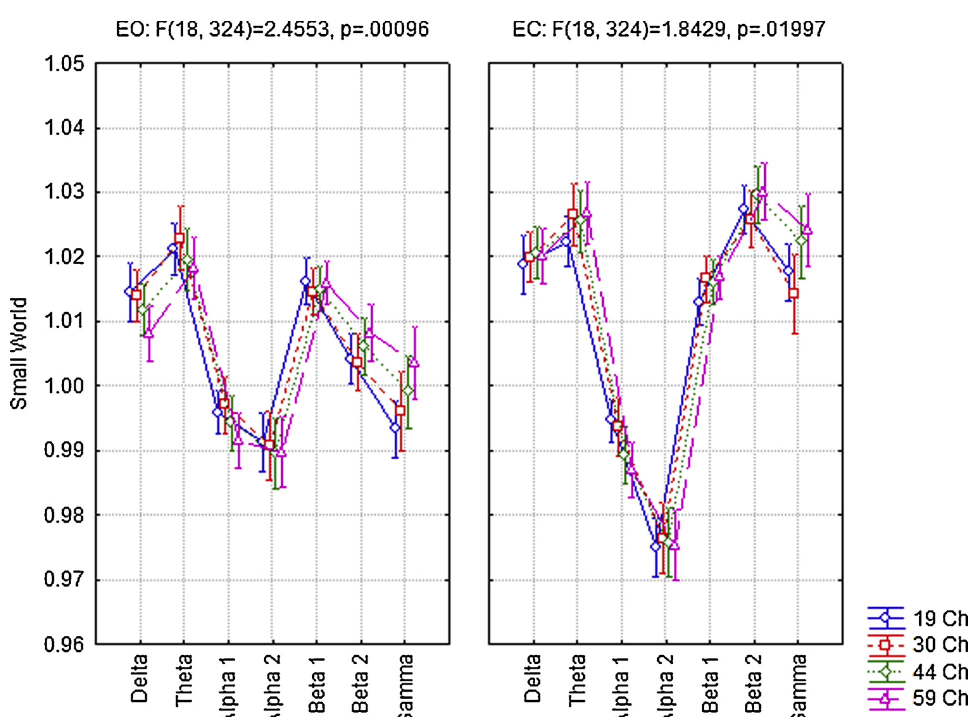

Fig. 2. SW index in Eyes Open (EO; left panel) and Eyes Closed (EC; right panel) in EEG bands (delta, theta, alpha 1, alpha 2, beta 1, beta 2, and gamma). In blue the 19 channels (19 Ch) EEG montage, in red the 30 channels (30 Ch) EEG montage, in green the 44 channels (44 Ch) EEG montage, in pink the 59 channels (59 Ch) EEG montage.

the gamma SW index.

From a physic point of view, brain neurons and EEG electrodes behave like two different antennas. An antenna in telecommunications is an electrical device capable of transmitting and/or receiving electromagnetic waves. The antennas behave as receiver when they return an electrical signal proportional to the electromagnetic field in which they are immersed, vice versa they behave as transmitter when radiate, in the form of an electromagnetic field, the signal electrically supplied by the transmitter. Accordingly, the brain neurons can be assimilated to brain electromagnetic signal transmitters and the EEG electrodes can be considered as the receivers of brain waves.

The reception of the signal by an antenna with receiver behavior depends on the frequency response of the antenna itself and in particular on the bandwidth. With the same signal to be detected, the lower the bandwidth, the more easily the waves will pass with a greater frequency, i.e. the slower ones. Moreover, the more receivers there will be, the easier it will be to intercept even the higher frequency waves. Accordingly, increasing the number of EEG electrodes, enhances the possibility to intercept the brain signals at the higher frequency bands, such as gamma band. For this reason, the major differences between the number of channels have been found in the gamma band.

Besides, our results have shown that in the eyes open condition the number of recording channels influences more the SW index modulation respect that in the eyes closed condition. The explanation of these results can be found in the resting state conditions. In fact, in eyes open condition participants are exposed to low visual and auditory stimuli. The reactivity to the environmental changes, even in resting conditions, may be accompanied by processing-specific focal EEG changes marking regional brain activity (e.g., delta with visual processing; gamma relating to higher-order processing and integration of the visual input) more prominent and reflecting the widespread communication of cortical and thalamo-cortical interactions (Grillon and Buchsbaum, 1986).

These results further suggest that visual input not only arouses the entire cortex, but also activates specific structures in the brain that are involved in visual processing (Barry et al., 2007). Consequently, as each brain region contributes in different way to the generation of the EEG signal, the greater the number of electrodes, the greater availability to evaluate the changes of the SW index intercepted by the source analysis.

Conversely, in the eyes closed condition the brain activity is less affected by specific brain regions' activations and the signal's generators produced not significant variations on EEG data and consequently the small world network measure is not affected by the number of recording channels.

Concluding, we can state that in the eyes closed resting state condition, the 19 EEG channels is an acceptable montage to study brain networks' modulations, to both detect the higher and the lower brain waves' frequencies. The current finding provides interesting avenue in the study of brain activity in particularly in patients requiring more complex management, in which their compliance to the EEG recordings is influenced by the exam duration and accordingly by the number of EEG electrodes used.

CRediT authorship contribution statement

Francesca Miraglia: Conceptualization, Methodology, Data curation, Writing - original draft. **Carlo Tomino:** Methodology, Writing - review & editing. **Fabrizio Vecchio:** Conceptualization, Methodology, Software, Writing - review & editing. **Francesca Alù:** Supervision, Writing - review & editing. **Alessandro Orticoni:** Software, Validation. **Elda Judica:** Writing - review & editing. **Maria Cotelli:** Writing - review & editing. **Paolo Maria Rossini:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

This work was partially supported by the Italian Ministry of Health for Institutional Research (Ricerca corrente).

References

Barbati, G., Porcaro, C., Zappasodi, F., Rossini, P.M., Tecchio, F., 2004. Optimization of an independent component analysis approach for artifact identification and removal in magnetoencephalographic signals. Clin. Neurophysiol. 115, 1220–1232.
Barry, R.J., Clarke, A.R., Johnstone, S.J., Magee, C.A., Rushby, J.A., 2007. EEG differences between eyes-closed and eyes-open resting conditions. Clin. Neurophysiol. 118, 2765–2773.
Grillon, C., Buchsbaum, M.S., 1986. Computed EEG topography of response to visual and auditory stimuli. Electroencephalogr. Clin. Neurophysiol. 63, 42–53.
Jasper, H.H., 1958. The ten-twenty electrode system of the International Federation. Electroencephalogr. Clin. Neurophysiol. 10, 371–375.
Liu, Q., Farahibozorg, S., Porcaro, C., Wenderoth, N., Mantini, D., 2017. Detecting large-scale networks in the human brain using high-density electroencephalography. Hum. Brain Mapp. 38, 4631–4643.
Liu, Q., Ganzetti, M., Wenderoth, N., Mantini, D., 2018. Detecting large-scale brain networks using EEG: impact of electrode density, head modeling and source localization. Front. Neuroinform. 12, 4.
Miraglia, F., Vecchio, F., Marra, C., Quaranta, D., Alù, F., Peroni, B., Granata, G., Judica, E., Cotelli, M., Rossini, P.M., 2020. Small world index in default mode network predicts progression from mild cognitive impairment to dementia. Int. J. Neural Syst., 2050004
Oostenveld, R., Praamstra, P., 2001. The five percent electrode system for high-resolution EEG and ERP measurements. Clin. Neurophysiol. 112, 713–719.
Pascual-Marqui, R.D., 2002. Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. Methods Find. Exp. Clin. Pharmacol. 24 (Suppl D), 5–12.
Pascual-Marqui, R.D., 2007. Instantaneous and lagged measurements of linear and nonlinear dependence between groups of multivariate time series: frequency decomposition. eprint arXiv:07111455, arXiv:0711.1455.
Porcaro, C., Medaglia, M.T., Krott, A., 2015. Removing speech artifacts from electroencephalographic recordings during overt picture naming. Neuroimage 105, 171–180.
Rubinov, M., Sporns, O., 2010. Complex network measures of brain connectivity: uses and interpretations. Neuroimage 52, 1059–1069.
Salmaso, D., Longoni, A.M., 1985. Problems in the assessment of hand preference. Cortex 21, 533–549.
Tecchio, F., Vecchio, F., Ventriglia, M., Porcaro, C., Miraglia, F., Siotto, M., Rossini, P.M., Rongioletti, M., Squitti, R., 2016. Non-ceruloplasmin copper distinguishes a distinct subtype of Alzheimer's disease: a study of EEG-Derived brain activity. Curr. Alzheimer Res. 13, 1374–1384.
Vecchio, F., Miraglia, F., Porcaro, C., Cottone, C., Cancelli, A., Rossini, P.M., Tecchio, F., 2017. Electroencephalography-derived sensory and motor network topology in multiple sclerosis fatigue. Neurorehabil. Neural Repair 31, 56–64.
Vecchio, F., Miraglia, F., Iberite, F., Lacidogna, G., Guglielmi, V., Marra, C., Pasqualetti, P., Tiziano, F.D., Rossini, P.M., 2018. Sustainable method for Alzheimer dementia prediction in mild cognitive impairment: electroencephalographic connectivity and graph theory combined with apolipoprotein E. Ann. Neurol. 84, 302–314.