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Modeling the connections of brain regions in children with autism using cellular neural networks and electroencephalography analysis

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ABSTRACT

The brain connections in the different regions demonstrate the characteristics of brain activities. In addition, in various conditions and with neuropsychological disorders, the brain has special patterns in different regions. This paper presents a model to show and compare the connection patterns in different brain regions of children with autism (53 boys and 36 girls) and control children (61 boys and 33 girls). The model is designed by cellular neural networks and it uses the proper features of electroencephalography. The results show that there are significant differences and abnormalities in the left hemisphere, ($p < 0.05$) at the electrodes AF3, F3, P7, T7, and O1 in the children with autism compared with the control group. Also, the evaluation of the obtained connections values between brain regions demonstrated that there are more abnormalities in the connectivity of frontal and parietal lobes and the relations of the neighboring regions in children with autism. It is observed that the proposed model is able to distinguish the autistic children from the control subjects with an accuracy rate of 95.1% based on the obtained values of CNN using the SVM method.

1. Introduction

Autism spectrum disorder (ASD) is a neurological disorder with psychological symptoms, which is usually appears in the first three years of the life. The term "autism" was introduced by Leo Kanner in 1943 [1]. Autism is a disorder that directly affects the human brain's functions and connections [2]. It is associated with some disturbances in social communications, personal perceptions, and emotions. Based on the statistics, the annual prevalence of this disorder is 6 per 1000 people, reaching almost 2% in some countries like US [3].

A large number of studies have been conducted on the individuals' brain connections, suggested certain connections in various regions of the brain in different human conditions and also showed the abnormalities in the brain patterns and connections of individuals with neuropsychological disorders [4,5]. Johansen-Berg and Rushworth [6] and Sporns et al. [7] claimed that brain connection can be examined by considering the physical connections between regions, known as structural connection, or by looking at the similarity of temporal characteristics of the brain activity in the regions, called functional connection [6,7]. In addition, Johansen-Berg, Sporns and Buckner et al. [8] found that the brain regions indicate the temporal correlations of activation patterns during some active processes like perception, cognitive processing, and rest [7]. Task-related functional connection provides evidence by which the networks of the brain regions are recruited in order to process and integrate information, and respond to task demands appropriately [9]. Assaf et al. [10] and Weng et al. [11] focused on resting-state functional connection without external stimulation. People were typically trained to close their eyes and thought about nothing for about 5–10 min. Based on the results, a decrease occurred in the functional connection between the precuneus and medial prefrontal cortex, default mode of network core areas, and other default mode of sub-networks areas [9,10].

Electroencephalography (EEG) is a test which detects electrical brain activities and reports abnormal brain activities. EEG indicates that there is an underlying structural disorder in patients with autism [12]. EEG is used for diagnostic purposes and the results are obtained from the power of the signal or the shape of the signal in a certain frequency-band. In addition, EEG is used to localize neural activity

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[13]. Many researchers have studied the EEGs and analyzed signals of autistic subjects. Grossi et al. [14] presented an artificial adaptive system to extract interesting features in computerized EEG and then they distinguished ASD children from control children. Sheikhani et al. [15] investigated the use of EEG signals based on the Lempel-Ziv frequency methods (LZ) and Short-Time Fourier Transform (STFT). After evaluating the results, they distinguished two groups of control and autistic subjects with 81% accuracy [15]. In another study, ICA was analyzed and the possibility of extracting independent resources from the EEG signals, as well as the correlation between different brain autistic regions was considered [16]. Their results indicated that the correlation in the left hemisphere, including F3, C3 and P3 channels, for autistic children was lower than the same regions for children in the control group [16,17]. According to Von Stein [18] and Sheikhani [3], the average of the gamma frequency band in some components of the left hemisphere for autistic children was higher than of the control children while it was lower for the theta band [17]. Further, Sheikhani [3] used EEG spectrogram analysis for autistic and control children and concluded that the best classification of autistic children from control subjects was observed in the relaxed eye-opened condition and the alpha band [9]. Wang et al. [19] investigated resting-state EEG in ASD by focusing on spectral power, coherence and hemispheric asymmetry aspects. They provided a summary of recent findings in ASD resting-state EEG studies and discussed the limitations of this area. Based on the results, ASD resting-state EEG studies would suggest a U-shaped profile of electrophysiological power alterations, with excessive power in high-frequency and low-frequency bands, abnormal functional connection and enhanced power in the left hemisphere of the brain [19]. Orekhova [20] evaluated the high frequencies of the power spectrum of autism groups in the 3–8 age range and concluded that the high gamma-band activity relies on the spatial distance of the electrodes, which occurred due to the sources generating muscle artifacts. Dumas et al. [21] examined the whole brain and the hypothesis of functional dissociation of mu and alpha responses to observing human actions in ASD based on the bandwidths. Source reconstructions showed that this impact was related to a joint mu-suppression deficit over the occipital-parietal regions, as well as an increase in the frontal regions [21]. Duffy et al. [22], in their study, determined the spectral coherence factors for discriminating the autistic and control groups using discriminant function analysis (DFA). In addition, they used principal components analysis (PCA) to identify the EEG spectral coherence factors with the corresponding loading patterns and described the ASD-specific coherence differences by loading patterns on the DFA-selected coherence factors by compared to the controls.

Based on the results, significant differences were observed for the 40 factors among the 2–12 aged subjects [22]. In another study, Duffy et al. [23] investigated the relationship between Asperger's syndrome (ASP) and autism using EEG coherence study. At first, they derived the coherence data and then reduced the frequencies using PCA and concluded that these factors could significantly differentiate neurotypical ASD from the control group by DFA. Based on DFA rules, this approach classified subjects as control or ASD with accuracy rate of 96.2%, and identified ASP subjects from the ASD population using new DFA rules with accuracy rate of 92.3% [23].

Adam Just et al. [24] and Vissers et al. [9], in their studies, discussed the abnormalities in brain connections in children with autism. In the lack of connection theory, that has been mentioned by Adam Just et al., the intra-cellular connections of anterior and posterior cortical and the problem of the reduced interaction between the anterior regions and parietal lobe in people with autism were studied using fMRI (functional Magnetic Resonance Imaging) [24]. They found that many of the previous models were neural network or connectionist models which have carefully examined the possibility that autism was characterized by abnormalities at the level of individual connectionist units and weights in a neural network [24]. For example, Cohen [25] indicated that poor generalization in autism caused by inadequate numbers of hidden units. In some other studies, McClelland et al. [26], Gustafsson et al. [27], and O'Laughlin [28] asserted that excessive conjunction coding and excessive inhibition were explained as underaroused depression in the amygdala, hypervigilant learning in the temporal and prefrontal cortices, and the failure of adaptive timing in the hippocampal and cerebellar regions. Brock et al. [29] attributed weak central coherence to an impairment of temporal binding between local networks while, temporal binding within local networks was supposed to be intact or even enhanced possibly.

Considering the aforementioned studies, a few models have focused on specific experimental data [24]. For example, Bjorne et al. [30] described attention-switching deficits as an exception. Grossberg et al. [31] proposed the most complex connectionist model of autism [31]. This model presents an imbalance of parameters among three component subsystems. Only one previous computational model of autism has provided an explanation about the brain connection, at least at a general level [24]. Noriega et al. [32,33] used the SOM (Self-Organized Map) neural network to demonstrate the perceptual abnormalities in autistics' brains. They maintained that the main causes of the problems in autistic people were related to weak central coherence to disrupt the key regions of the brain and imbalance in excitatory-inhibitory networks of these individuals [32,33]. Papageorgiou et al. [34] proposed a model to identify the autism based on the FCMs (Fuzzy Cognitive Map). FCMs were trained by Nonlinear Hebbian Learning algorithm (NHL). Their results demonstrated that their proposed FCM ensemble algorithm works better than the NHL based approach [34].

In all studies, significant differences between the EEG signals and the regions connections of autistic people, and the control group were confirmed. In the aforementioned methods, only the statistical methods were used to separate two groups by EEG signals without presenting a unique model of the brain function. While, the presented model by a unique model based on the Cellular Neural Network (CNN) can represent the connection patterns of various brain regions as well as brain functions and can also distinguish autistic children from control children. Regarding the volume conduction like the human brain in which all regions connect with their adjacent and non-adjacent regions, this model can present the complex intra- and inter-connections in each region. Finding the proper features of the EEG helps the model to display the brain connections among different regions of the brain. This paper is organized into three basic sections: 1) recording EEG signals, 2) signal analysis and modeling of the brain structure, and 3) validating model and separating subjects into two groups. Section 2 describes how to record the EEG signals. Section 2 presents the feature extraction, signal analysis and modeling the brain connection. The results and discussion are provided in Section 3. Finally, the conclusion is presented in Section 4.

2. Materials and method

The present study includes three basic sections of signal recording, signal analysis, and modeling the brain. Fig. 1 illustrates the pictorial algorithm used in this study to calculate the inter- and intra- regional connections.

2.1. Participants

The participants initially included 100 children with autism and 100 control children. The ASD diagnosis was performed by two expert child and adolescent psychiatrists based on the DSM-IV-TR (Diagnostic and statistical manual of mental disorder, American psychiatric association [35]). The control group was selected from two primary healthy schools in Tehran based on psychiatric interview. Prior to initiation of the study, Institutional Review Board (IRB) approval was obtained through the Tehran University of Medical Sciences IRB, and parents who agreed to their child's participation in the study gave informed consent. In this regard, 11 ASD children were excluded due to some difficulties in