

1 **Machine learning Classification of Dyslexic Children based**  
2 **on EEG Local Network Features**

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15

## 16 **Abstract**

17 Machine learning can be used to find meaningful patterns characterizing individual  
18 differences. Deploying a machine learning classifier fed by local features derived from graph  
19 analysis of electroencephalographic (EEG) data, we aimed at designing a neurobiologically-  
20 based classifier to differentiate two groups of children, one group with and the other group  
21 without dyslexia, in a robust way. We used EEG resting-state data of 29 dyslexics and 15 typical  
22 readers in grade 3, and calculated weighted connectivity matrices for multiple frequency bands  
23 using the phase lag index (PLI). From the connectivity matrices, we derived weighted  
24 connectivity graphs. A number of local network measures were computed from those graphs, and  
25 37 False Discovery Rate (FDR) corrected features were selected as input to a Support Vector  
26 Machine (SVM) and a common  $K$  Nearest Neighbors (KNN) classifier. Cross validation was  
27 employed to assess the machine-learning performance and random shuffling to assure the  
28 performance appropriateness of the classifier and avoid features overfitting. The best  
29 performance was for the SVM using a polynomial kernel. Children were classified with 95%  
30 accuracy based on local network features from different frequency bands. The automatic  
31 classification techniques applied to EEG graph measures showed to be both robust and reliable in  
32 distinguishing between typical and dyslexic readers.

33 **Keywords:** EEG; Machine Learning; Support Vector Machine (SVM); KNN classifier; Local  
34 Network measures; Dyslexia; Children.

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## 38 **1. Introduction**

39 Developmental dyslexia is a specific reading and spelling disability with a genetic and  
40 neurobiological component and relatively high prevalence rates around 5% (Blomert 2005;  
41 Snowling 2013). Neuroimaging studies have investigated biomarkers of dyslexia using structural  
42 and functional network analyses and there is a growing interest in connectivity abnormalities  
43 between different brain systems that may result in impaired reading (e.g., Finn et al. 2014;  
44 Schurz et al. 2014; Liu et al. 2015). Diffusion tensor imaging studies show reduced connectivity  
45 in the main white matter pathways (see review in Vandermosten et al. 2012). Functional  
46 magnetic resonance imaging (fMRI) studies reported reduced long-range connectivity across  
47 brain systems specialized for reading (e.g., Pugh et al. 2000; Shaywitz et al. 2003; van der Mark  
48 et al. 2011; Schurz et al. 2014), and associated functional networks (Wolf et al. 2010; Finn et al.  
49 2014). Whole brain connectivity studies observed that dyslexics differ from typical readers in  
50 whole brain networks organization, showing increased local processing and less long-range  
51 communication (Liu et al. 2015) and lower global efficiency in dyslexics (Dimitriadis et al.  
52 2018). Collectively, this evidence supports the view that a widespread network of brain regions  
53 may be compromised in developmental dyslexia (Martin et al. 2016).

54 An important objective of the neuroscientific search for biomarkers of dyslexia is to  
55 contribute to the diagnosis and early detection or prediction of reading disabilities. The  
56 classification of individuals suffering from several neuropsychological disorders may take  
57 advantage of using machine learning methods (e.g., Duda et al. 2016; Kessler et al. 2016). These  
58 methods are particularly useful when applied to neuroimaging data as they allow for using  
59 widely distributed information to improve the classification of clinical groups or individuals at  
60 risk. A recent MRI study used a machine learning classifier and reported above chance levels in

61 discriminating dyslexic adults from controls based on gray matter differences (Tamboer et al.  
62 2016). Two related studies employed multivariate pattern analysis of brain activity during a  
63 phonological task to identify poor readers (Tanaka et al. 2011) and predict long-term outcomes  
64 in dyslexic children based on whole-brain activation (Hoeft et al. 2011). The latter study showed  
65 that methods using brain measures outperformed procedures relying on behavioral measures in  
66 predicting reading improvements across the 2.5 years following the experiment. These studies  
67 illustrate the potential of using machine learning techniques in combination with neuroimaging  
68 data to improve the classification and early detection of dyslexia.

69 The present study uses a ML classifier to discriminate between dyslexic and typically reading  
70 children based on functional connectivity using measures derived from the electroencephalogram  
71 (EEG). It has been demonstrated previously that task-independent EEG activity contains  
72 information about how different brain systems communicate and how functional networks may  
73 be intrinsically organized (van den Heuvel and Hulshoff Pol 2010). Importantly, earlier studies  
74 related neural activity at rest to reading ability in children and adults, showing that a resting-state  
75 paradigm can be profitably used to study language networks (Hampson et al. 2006; Koyama et  
76 al. 2010).

77 Given the highly interactive and complex nature of reading, the study of its neurobiology  
78 might benefit from an integrative and holistic view of brain function conceptualized as a  
79 complex network (Bullmore and Sporns 2009). Within that framework, graph theoretical  
80 analysis allows for modeling whole-brain functional connectivity networks as a set of nodes  
81 (vertices) and the connections between them (edges). The multiple measures that can be derived  
82 from a graph are used to describe the network in terms of information transfer and balance  
83 between ‘segregation’ and ‘integration’ (see reviews in Bullmore and Sporns 2009, 2012). Two

84 magnetoencephalographic (MEG) studies of dyslexia examined graph measures and found  
85 dysfunctional long- and short-range functional connectivity in dyslexics during a reading task  
86 (Vourkas et al. 2011) and less organized connectivity at rest (Dimitriadis et al. 2013). In a  
87 previous study, we applied graph analysis to resting-state EEG to compare dyslexics and  
88 typically reading children in grade 3 (Fraga González et al. 2016). The results suggested group  
89 differences in several *global* graph metrics in the theta band suggesting a reduced network  
90 integration and communication between the nodes in dyslexics compared to typical readers.

91 In our previous graph study, we examined global properties of the network that were  
92 described by graph measures averaged across electrodes (Fraga González et al. 2016). For the  
93 current analysis, we will employ data from that study, however, we use a different analysis  
94 approach by extracting local features, i.e., computed per node, and take a step further to clinical  
95 application and deploy artificial intelligence. This local information could reflect aspects of  
96 regional connectivity organization relevant to network development in dyslexia (Liu et al. 2015)  
97 and may provide neural features for the benefit of the SVM classifier performance. Basically, an  
98 SVM is a discriminative classifier formally defined by a hyperplane. Given labeled training data  
99 (supervised learning), the algorithm outputs an optimal hyperplane that categorizes new  
100 examples. Due to its ability to manage large datasets, the algorithm is widely used for binary  
101 classification problems in machine learning. For more details on SVM see (Hsu et al. 2003). We  
102 will use methodological approach that is similar to the one applied in a previous study that, using  
103 resting-state EEG and an SVM classifier, identified 6-month-old infants at familial risk for a  
104 language learning disorder (Zare et al. 2016). The current study uses SVM and KNN to classify  
105 children in 3<sup>rd</sup> grade as dyslexics or typical readers, based upon a large number of local features  
106 derived from functional connectivity matrices in the different frequency bands of the EEG.

107 Cross-validation is employed to assess the resulting classification, and random shuffling is  
108 deployed to assure that the classifying performance is not due to bias in feature selection criteria.  
109 We aimed at assessing the utility of machine learning techniques to find best distinguishable  
110 characteristics in reading difficulties based on functional EEG networks. To the best of our  
111 knowledge, this is the first study to use local EEG features to designing a classifier for dyslexia.

## 112 **2. Methodology**

113 The current analysis is performed on data from a previous study (Fraga González et al. 2016).  
114 We refer to that article for a more extensive description of the EEG recordings and summarize  
115 here only the information needed for the current study.

### 116 **2.1. Participants**

117 The participants of the current study were 44 subjects including 29 third-grade dyslexic children  
118 (mean age = 8.96; SD = 0.40); with a percentile score of 10 or lower on a standard reading test,  
119 and 15 third-grade children ( $8.75 \pm 0.31$  years old) in the control group with the same socio-  
120 demographical background as dyslexic; with no history of reading difficulties and had a  
121 percentile score of 25 or higher on standard reading tests. The participants of the current study  
122 were part of a larger sample of 62 children participating in a larger study. Due to young age of  
123 our participants some participants were excluded due to excessive movement or other artifacts in  
124 the data, or did not complete the resting-state recordings. All participants were native Dutch  
125 speakers, received two and a half years of formal reading instruction in primary education. The  
126 study was approved by the Ethical Review Board of the University and all parents or caretakers  
127 signed informed consent before the children participated. Demographic characteristics and  
128 reading scores of the complete sample are included in S1 Table.

## 129        **2.2. EEG recording and preprocessing**

130        The total duration of the eyes-closed resting state data collected was 2 minutes. EEG data were  
131        collected using 64 channels with sampling frequency of 250 Hz; Biosemi ActiveTwo system.  
132        Data was imported in Brain Vision Analyzer (Version 2.01.5528 © Brain Products) where spline  
133        interpolation was applied to channels with excessive artifacts and segmented in 30 epochs of 4  
134        seconds. Epochs containing excessive noise and artifacts were visually inspected and removed.  
135        For each subject, 10 artifact-free epochs were selected and exported to ASCII files. The data  
136        were imported to Brainwave v0.9.117 (developed by Prof. Cornelis Stam' s research group;  
137        freely available at <http://home.kpn.nl/stam7883/brainwave.html>) where it was re-referenced to  
138        the common average, submitted to power spectral analysis using Fast Fourier Transform (FFT)  
139        and filtered into four frequency bands [delta (0.5-4Hz); theta (4-8Hz); alpha (8-13Hz); beta (13-  
140        30Hz)]. Then, the functional connectivity matrices were obtained in Brainwave and based upon  
141        those matrices weighted network measures were computed using custom MATLAB code  
142        (R2016; The Mathworks, Natick, MA), as well as with functions available as part of the  
143        MATLAB Machine learning and Statistics Toolboxes and the Brain Connectivity Toolbox  
144        (BCT) (Rubinov and Sporns 2010).

## 145        **3. EEG analysis**

### 146        **3.1. Functional connectivity**

147        Functional connectivity was assessed for each segment (10 segments of 4096 data points per  
148        subject) and frequency band with the phase lag index (PLI). The PLI measures the asymmetry of  
149        the distribution of phase differences between two signals. PLI provides a measure of statistical  
150        interdependencies between time series, which reflects the strength of coupling. The major aim of

151 using the phase lag index is to obtain reliable estimates of phase synchronization that are  
152 invariant of the presence of common sources, a feature that may be absent in other connectivity  
153 measures (Stam et al. 2007). Asymmetry of the phase difference distribution indicates that the  
154 likelihood of phase difference  $\Delta\varphi$  being in the interval  $-\pi < \Delta\varphi < 0$  is different from the  
155 likelihood of being in the interval  $0 < \Delta\varphi < \pi$ . This asymmetry indicates a phase difference (or  
156 'lag') between the two time series (Stam et al. 2007). The adjacency matrix is constructed using  
157 formula

$$158 \quad PLI(t) = | \langle \text{sign}(\Delta\varphi(t_k)) \rangle |$$

159 where  $\Delta\varphi$  is the phase difference and  $t_k$  is the  $k^{th}$  sequence. PLI ranges between 0 and 1 where  
160 zero indicates no coupling. Angle between each pair of time series is calculated using Hilbert  
161 transform.

### 162 **3.2. Weighted network and local feature selection**

163 From the previous step, weighted connectivity matrices were derived for each subject. For each  
164 of the individual 64 by 64 matrices, we calculated several local features from weighted network  
165 measures per node. In a weighted graph, each electrode represents a node and all the nodes are  
166 connected by links with a specific weight representing the strength of connectivity (Barrat et al.  
167 2004). The network measures used in this study are summarized in Table 1. We focus on the  
168 main network features that are commonly used in the literature and are measured at local level in  
169 the network (Bullmore and Sporns 2009; Rubinov and Sporns 2010). The chosen measures aim to  
170 quantify how a node contributes in the information flow in the network, in the current study we  
171 try to exploit these local characteristics for classification. The features derived from the weighted  
172 network were averaged across segments for every subject. Note that for each subject, we



173 repeated the calculations for each connectivity matrices per frequency band and segment. For all  
174 network features, the significance of FDR (false discovery rate; Benjamini and Hochberg 1995)  
175 corrected group differences ( $p < 0.05$ ) were examined with t-tests defined as ( $t(F_{TYP}, F_{DYS}), p$ -  
176 value), where  $F$  stands for feature name, and then FDR corrected. Then, to demonstrate that this  
177 method worked well in feature selection, we employed a random shuffling technique. These  
178 steps are described in Fig 1.

**Table 1.** Network metrics and their definitions.

Network measure	Definition
Characteristic path length	The number of edges mediating between two nodes
Degree	The number of edges incident to a node or sum of weights of incident edges (flow)
Efficiency	Quantifies a network's resistance to failure on a small scale
Clustering coefficient	Quantifies how close a given node and its neighbors are to being a clique
Modularity	Fraction of the edges that fall within the given groups minus the expected fraction if edges were distributed at random
Eccentricity	The maximum distance between a reference's node and node $i$ of a graph
Betweenness centrality (BC)	The number of shortest paths running through a node $i$

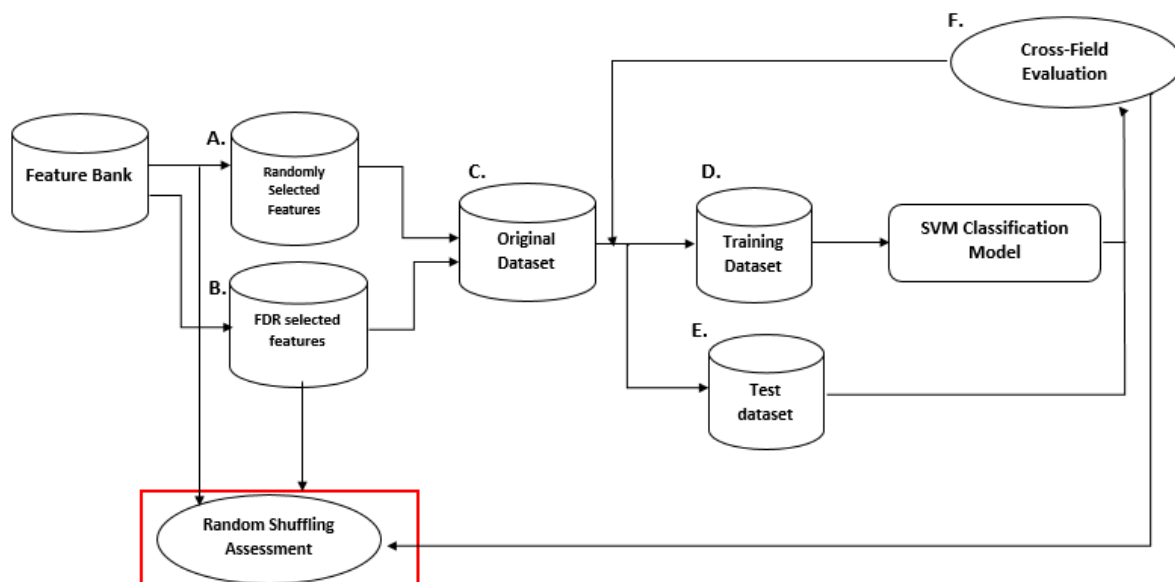
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## 180 **SVM classification and cross-validation**

181 The primary goal of this study was to use local network features for classifying children into two  
182 separate groups. In the current study, 37 features passed the FDR corrected group comparisons.  
183 Those features were used to train the classifier (see Results). Usually, it is difficult to determine  
184 in advance which classifier, and in particular which kernel function, fits the SVM classifier best  
185 from simpler to more complexity degree for a particular set of data. Therefore, starting from non-  
186 parametric classifiers to parametric classifiers, we tested several other classifiers. Here we report  
187 the classification using two kernel functions that resulted in good classification performance:

188 linear and polynomial of degree 3. In addition, we compared the SVM to a simpler common  
189 classifier, i.e., k-nearest neighbors algorithm (KNN) with  $k = 3$  and  $k = 7$ . In KNN  
190 classification, an object is classified by a majority vote of its neighbors, with the object being  
191 assigned to the class most common among its  $k$  nearest neighbors.

192 Subsequently, the leave-one-out-cross-validation (LOOCV) was deployed to assess the  
193 performance of the classifiers averaging performance across  $N$  sets (see Fig 1). LOOCV is the  
194 most common procedure for cross-validation where the number of sets equals the number of  
195 instances in the data set. This approach is used to avoid overfitting and promotes the reliability  
196 and generalizability of the results to a new set of data. The selected features were used as input to  
197 an SVM that performed supervised classification, mapping children into two groups: dyslexic



**Fig 1.** SVM classification and performance assessment by Random Shuffling. We followed two approaches to select features from those available: random selection (A) and selection via  $t$ -tests (B). In both cases the dataset was then divided into a Training set (D) and a Test set (E) using cross-validation. We assessed each selected feature with the SVM classifier. Finally, a random shuffling cross-fold evaluation (F) was performed to ensure the  $t$ -test selected features were the most relevant for classification.

198 children (DYS) and typical readers (TYP).

199 We assessed the classifier's performance using the conventional measures of precision,  
200 specificity, sensitivity, and accuracy. The dyslexic reader group is designated positive and the  
201 typical readers are categorized as negative. The correct detection or "true classification" of  
202 dyslexia is then a true positive (TP). Likewise, correct classification of the typical readers is true  
203 negative (TN). Precision or Positive predictive value (PPV) indicates the proportion of positives,  
204 which are correctly identified as such (e.g., the percentage of children who are correctly  
205 identified as Dyslexic readers). Specificity refers to the percentage of participants correctly  
206 classified as typical readers, which is also known as the true negative rate (TNR). These  
207 performance indices are further described in (Zare et al. 2016).

208 The computations related to the SVM classifier were carried out in MATLAB 10.8.0 (R2016;  
209 The Mathworks, Natick, MA), as well as with functions available as part of the MATLAB  
210 Machine Learning Toolboxes, and in-house MATLAB code.

## 211 **4. Results**

### 212 **4.1. PLI and network features extraction**



9			'C6'	0.0173	-2.4807
10		Modularity	'AF3'	0.0084	-2.7708
11		Efficiency	'FPZ'	0.0157	-2.5194
12			'FP2'	0.0015	-3.3961
13			'AF8'	0.0063	-2.8815
14			'F8'	0.0100	-2.7027
15			'C6'	0.0182	-2.4603
16		Eccentricity	'FP1'	0.0092	-2.7351
17			'FC3'	0.0152	-2.5350
18			'CP1'	0.0088	-2.7497
19			'AF8'	0.0000	-4.8302
20			'FT8'	0.0081	-2.7834
21			'FC6'	0.0123	-2.6207
22			'C6'	0.0072	-2.8285
23			'CP6'	0.0137	-2.5756
24	Theta	Betweenness centrality	'AFZ'	0.0014	-3.4276
25		Modularity	'F7'	0.0059	2.9055
26			'FT7'	0.0049	2.9740
27			CP3'	0.0142	-2.5610
28	'CP4'		0.0089	2.7466	
29	Alpha	Betweenness centrality	'FZ'	0.0037	-3.0773
30			'PO8'	0.0047	-2.9881
31		Modularity	'FC5'	0.0197	-2.4273
32			'FC3'	0.0051	-2.9589
33			'CP3'	0.0112	-2.6577
34			'PZ'	0.0161	-2.5099
35			'CPZ'	0.0014	-3.4211
36			'FC6'	0.0060	2.8975
37	Beta	Modularity	'F4'	0.0152	-2.5345

220

## 221 Machine Performance

222 The results of machine performance after applying LOOCV are indicated in Table 3. The table  
 223 shows that an SVM with a linear kernel provides the statistically best performance among the  
 224 classifiers used to identify children as typical readers and dyslexic readers with high specificity,  
 225 sensitivity, precision, and accuracy.

**Table 3. Machine performance after LOOCV.** Complexity of the model is reduced from left to right.

<b>Classifier</b>	<b>SVM Polynomial kernel</b>	<b>SVM Linear kernel</b>	<b>KNN, K=7</b>	<b>KNN, K=3</b>
<b>Accuracy</b>	90.69	<b>95.34</b>	86.04	81.39
<b>Sensitivity</b>	90.00	96.42	86.66	85.71
<b>Specificity</b>	92.30	93.33	84.61	73.33
<b>Precision</b>	96.42	96.42	92.85	85.71

226

227 As input to the machine, we used a total of 37 features vectors, i.e., approximately 2% of the  
228 features, based in the FDR corrected group comparison. In order to ensure that the subset of  
229 selected features is suitable and unbiased, we used a random-shuffling method (Zare et al. 2016).  
230 In this method: a) all network features enter the classifier's pool irrespective of the feature  
231 selection criteria. Among all network features, 37 features are randomly chosen to feed the  
232 classifier. This way, we assure that feature selection is not biased by the selection method (i.e.,  
233 significant difference across two groups over a network feature); b), machine performance is  
234 evaluated using the conventional measures of precision, specificity, sensitivity, and accuracy; c)  
235 a histogram analysis has to be performed for each of the machine performance parameters (See  
236 Fig. 3). The distribution of parameters shows whether the performance parameters are rare and  
237 incidental ( $p < 0.05$ ), and finally iv) features that contribute to optimal performance are extracted  
238 and compared to those chosen by the initial selection criteria. If those features are fully matched,  
239 we conclude that our feature selection is robust and reliable. In particular, for 1000 rounds, we a)  
240 randomly chose 37 vectors out of the 1792 features; b) calculated precision, sensitivity,  
241 specificity, and accuracy of the machine; d) saved the results in appropriate vectors and drew 4  
242 histograms from 1000 element vectors of precision, sensitivity, specificity, and accuracy. Finally,  
243 as shown in Fig 3, the distribution of accuracy, precision, sensitivity and specificity show that  
244 our selected features are statistically, not random.

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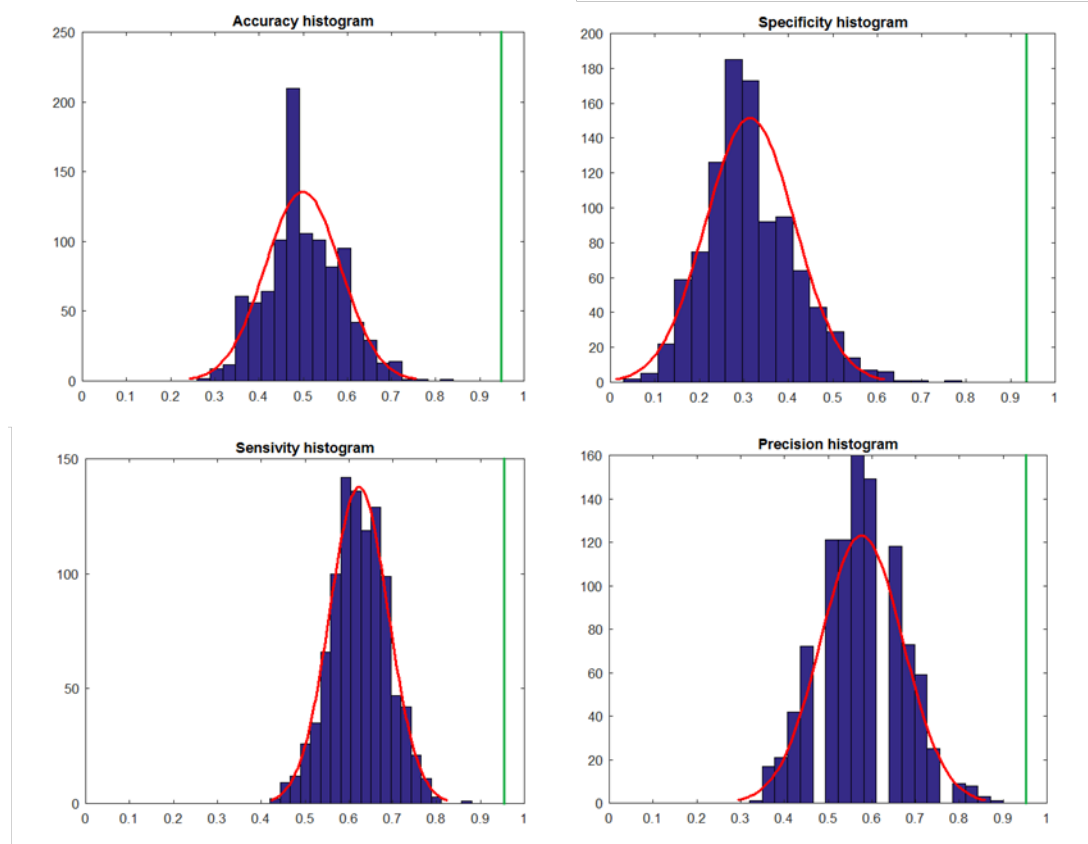
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**Fig 3.** Random shuffling histogram. Red curve shows the distribution of accuracy, specificity, sensitivity and precision for 1000 rounds with the random shuffling of 37 features. The green line shows the results using the 37 FDR corrected features.

255

256 Our random shuffling results indicate that the selected features based on FDR corrected

257 significant differences were robust and reliable.

## 258 **5. Discussion**

259 We applied two classifier to discriminate between dyslexics and typical readers based on local

260 connectivity features derived from EEG resting-state. In our previous study, we showed group

261 differences in how connectivity is organized between dyslexics and typical readers using graph

262 measures that related to global properties of the network (Fraga González et al. 2016, 2018). In

263 the current analysis, we focus on classification of subjects by using a larger number of features  
264 computed per node (i.e., scalp electrode). First, we found group differences associated with  
265 several local network measures that were selected to feed an automatic classifier. Then, our  
266 cross-validation analysis showed that the classifier could identify dyslexic readers with high  
267 accuracy (> 90%). Our random shuffling analysis showed that the selected features, most of  
268 which were associated with the delta frequency band, were useful to obtain a high accuracy  
269 classification that was not possible to achieve by a random selection of the network features. The  
270 current results are consistent with the data of a previous MEG study using sensor-level  
271 information (Dimitriadis et al. 2018). The results of this study showed that a higher classification  
272 of adults with reading difficulties was possible using sensor-specific network measures  
273 compared to using global (averaged across nodes) measures. The current results extend those  
274 and previous findings relating resting-state activity to reading abilities (Koyama et al. 2011) and  
275 suggesting differences in connectivity organization in dyslexia (Finn et al. 2014; Schurz et al.  
276 2014).

277 Our classifier used network features derived from connectivity matrices in different  
278 frequency bands. The local network features describe different aspects of connectivity between  
279 the nodes, for example, how relevant a node is in the whole network or how well connected it is  
280 to its neighbors (e.g., Stam 2014). Importantly, oscillations at different frequency bands have  
281 different temporo-spatial features. Higher frequencies seem to relate to more local activity, i.e.,  
282 smaller networks, while slower oscillations modulate larger networks with more widespread  
283 activity (Buzsáki and Draguhn 2004). It is likely that different aspects of dyslexia are manifested  
284 at multiple levels of neural organization. Indeed, previous research shows that reading  
285 impairments in dyslexia may result from a heterogeneous cluster of cognitive characteristics



286 (Leinonen et al. 2001; Menghini et al. 2010; Pacheco et al. 2014). This is supported by evidence  
287 suggesting similarly complex and heterogeneous neurobiological profiles (e.g. Richlan et al.  
288 2009; Finn et al. 2014). The current results suggest that EEG features provide important  
289 information about the underlying neurocognitive profiles in dyslexia, which can be used to  
290 classify individuals based on task-unspecific electrophysiological data. Recently, a study used  
291 structural and functional MRI data to classify a sample of 22 dyslexics and 27 typically reading  
292 adults (Tamboer et al. 2016). The study reported accuracy levels around 80% and detected  
293 specific occipital and parietal brain regions that contributed most reliably to the classification.  
294 We obtained high classification accuracy using local EEG features supporting the potential  
295 utility of using automatic classifiers in identifying individuals with dyslexia. However, the use of  
296 scalp EEG does not allow to draw conclusions about the underlying sources defining those  
297 features. Future studies using source modeling in MEG recordings could bring new insights into  
298 what sources are more relevant for classification.

299 For the present findings to have clinical implications, e.g., in diagnostics and early detection  
300 of reading disabilities, the generalizability of classification should be further investigated. In the  
301 study by Tamboer and colleagues (2016), classification performance dropped to around 60%  
302 when the trained classifier was applied to an independent sample. We only performed  
303 classification within the available dataset and it would be important to assess the current  
304 classifier's performance within additional datasets (Pulini et al. 2018). In addition, to further  
305 advance on the relation between EEG network features and cognitive deficits in dyslexia,  
306 longitudinal studies should examine whether the current approach could be used to predict  
307 reading improvements or treatment outcomes. In relation to this, a previous study used structural  
308 and functional MRI data to predict future performance in children with dyslexia and found

309 higher accuracy in prediction using brain measures compared to behavioral tests (Hoeft et al.  
310 2007).

311 This study has several limitations. First, the current study included almost twice as many  
312 typical readers as readers with dyslexia. This bias is relevant to machine-learning based  
313 diagnostics as an imbalance sample results in a disproportionate representation of one of the  
314 classes in the training (Mazurowski et al. 2008). Secondly, this and other studies include a gap  
315 between typical readers (i.e., readers with a reading performance  $> 25\%$ ) and readers with  
316 dyslexia (i.e., readers with a reading performance  $< 10\%$ ). Obviously, such a gap is not present  
317 in the real world and might compromise our classifier when applied in a natural setting. Thirdly,  
318 the ratio of readers with dyslexia to typical readers is far off from the prevalence rates in the  
319 general population (1:20). Future studies should determine the sensitivity of the machine  
320 classifiers to changing odd ratios.

## 321 **General conclusions**

322 This study builds upon the notion that dysfunctional connectivity between local specialized  
323 networks may be involved in dyslexia rather than global network measures studied in (Fragza et.  
324 al., 2016). We therefore focus on local network properties derived from EEG functional  
325 connectivity at rest and show that they can be used to classify individuals as dyslexics and  
326 typical readers. The current study presents an interesting and novel biologically-based method to  
327 analyze multidimensional data derived from EEG functional connectivity networks. Further  
328 research should help elucidating the clinical applicability of EEG-based classification and  
329 functional significance of these measures in relation to reading deficits in dyslexia. The current  
330 study adds to previous studies that encourage the application of machine learning techniques to

331 neuroimaging data in order to improve subject classification in the context of reading disabilities  
332 (Tamboer et al. 2016; Dimitriadis et al. 2018). This approach may benefit from increasingly  
333 large data sets available for data-driven analysis.

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## 451 Supporting information

S1 Table. Sample characteristics and descriptive statistics of reading accuracy and fluency scores.

	Typical Readers <i>M (SD)</i>	Dyslexics <i>M (SD)</i>	<i>p</i> -value	$\eta^2$
<b>N</b>	15	29		
<b>Sex ratio (m:f)</b>	6:9	16:13		
<b>Handedness (L:R)*</b>	2:10	2:27		
<b>Age</b>	8.75 (0.31)	8.96 (0.40)	.088	0.07
<b>RAVEN – IQ test<sup>a</sup></b>	6.70 (1.51)	7.11 (1.51)	.395	0.02
<b>3DM Word reading - accuracy<sup>b</sup></b>				
<b>High Frequency</b>	99.28 (1.05)	93.10 (5.93)	.000	0.27
<b>Low Frequency</b>	98.32 (2.54)	86.31 (14.48)	.003	0.19
<b>Pseudo</b>	88.70 (8.48)	73.33 (17.43)	.003	0.20
<b>Total [T]<sup>c</sup></b>	51.40 (8.00)	33.72 (12.58)	.000	0.37
<b>3DM Word reading - fluency [T]</b>				
<b>High Frequency</b>	54.27 (7.58)	31.38 (6.14)	.000	0.74
<b>Low Frequency</b>	56.80 (8.98)	32.07 (6.46)	.000	0.72
<b>Pseudo</b>	54.93 (9.71)	30.93 (6.37)	.000	0.70
<b>Total</b>	55.93 (9.51)	31.00 (5.40)	.000	0.75
<b>One-Minute Test -fluency [SS]<sup>d</sup></b>	12.07 (2.94)	3.97 (1.97)	.000	0.74
<b>Text Reading - fluency[T]**</b>	55.27 (8.41)	33.21 (6.30)	.000	0.70
<b>3DM Spelling - accuracy[T]</b>	51.73 (8.62)	36.21 (6.70)	.000	0.51
<b>3DM Spelling - fluency[T]</b>	54.33 (9.90)	36.55 (6.01)	.000	0.57
<b>3DM Phoneme deletion - accuracy [T]**</b>	53.73 (8.39)	39.61 (8.32)	.000	0.41
<b>Letter-speech sound associations [T]</b>				
<b>L-SS identificacion - accuracy</b>	46.87 (8.65)	43.34 (12.99)	.350	0.02
<b>L-SS discrimination – accuracy**</b>	50.80 (10.28)	44.43 (9.63)	.050	0.09
<b>L-SS identificacion - fluency</b>	51.53 (7.67)	41.79 (6.97)	.000	0.30
<b>L-SS discrimination - fluency**</b>	51.73 (7.36)	45.46 (8.95)	.025	0.12
<b>3DM Naming speed scores[T]**</b>				
<b>Letters</b>	50.93 (6.95)	36.57 (8.05)	.000	0.45
<b>numbers</b>	52.73 (10.67)	36.21 (8.50)	.000	0.43
<b>Total</b>	50.80 (7.73)	35.54 (9.15)	.000	0.42

<sup>a</sup> C scores (M = 5, SD = 2). <sup>b</sup> Raw scores. <sup>c</sup> T scores (M = 50, SD = 10). <sup>d</sup> SS scores (M = 10, SD= 3).

\*Data missing for 3 participants; Typical N = 12. \*\* Data missing for one participant; Dyslexics N = 28