Phase-amplitude markers of synchrony and noise: A resting-state and TMS-EEG study of schizophrenia

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Significance statement

We demonstrate that TMS-evoked potentials in schizophrenia are characterized by a reduction of signal-to-noise ratio and of phase locking, along with a facilitation of excitability. This is in line with the known literature, that has shown similar hallmarks in evoked potentials in schizophrenia. We introduce a measure for noise in resting-state EEG, which is related to the signal-to-noise ratio, and find that it exhibits a clear reduction in schizophrenia, resulting in a resting-state EEG that is similar in its characteristics to noise. Our study gives evidence to the previously introduced noise hypothesis, which states that the brain activity in schizophrenia is noisy, resulting in a reduction of the ability of neuronal populations to form stable, locally and temporally correlated activity.

Abstract

The electroencephalogram (EEG) of schizophrenia patients is known to exhibit a reduction of signal-to-noise ratio and of phase locking, as well as a facilitation of excitability, in response to a variety of external stimuli. Here we observe these effects in transcranial magnetic stimulation (TMS)-evoked potentials and in the resting-state EEG. To ensure veracity of our results we used three weekly sessions and analyzed both resting state and TMS-EEG data. Our analysis of signals and noise confirms the known results for the TMS responses, but is also indicative of lower signal-to-noise ratio in the resting state due to alterations of the amplitude distribution. Specifically, we investigated the instantaneous amplitude in narrow-band filtered EEG for fluctuations deviating from the (pink) noise of EEG. We used a form of mean-normalized variation (quartile coefficient, QC) as a marker that can compare narrow-band EEG amplitude fluctuations to pure narrow-band Gaussian noise. We find that on time scales of seconds to tens of seconds, amplitude fluctuations in the alpha and beta frequency bands in the resting state of healthy controls are larger than their fluctuations in schizophrenia patients. This suggests that the EEG-measured cortical activity patterns of schizophrenia patients are more similar to noise, demonstrating the utility of the QC marker. Taken together, our results both support previous findings and suggest that the ability of neuronal populations to form stable, locally and temporally correlated activity is reduced in schizophrenia.

1 Introduction

Schizophrenia is a mental disease with a complex pathology that dynamically evolves across the adult lifespan (Krystal et al., 2017). Several decades of research in schizophrenia have provided extensive evidence to the pervasive, globally occurring structural, physiological, functional and genetic abnormalities that characterizes the disorder. Abnormalities of brain tissue structure from the scale of synapses to whole brain regions have been described, with connectivity degradation occurring both locally and long-range. Correspondingly, a range of profound functional abnormalities were observed in activity, from cell assemblies to large-scale networks (Uhlhaas and Singer, 2010; Krystal et al., 2017).

One way to probe the functional abnormalities in schizophrenia is by studying dynamics of brain activity using EEG in stimulus-response paradigms. Generally, the main alterations of evoked responses in schizophrenia concern reductions in amplitudes and in phase locking (Winterer et al., 2000a, 2004; Spencer et al., 2003; Frantseva et al., 2012; Shin et al., 2015), as well as facilitated excitation in late-stage response (Radhu et al., 2015; Frantseva et al., 2012; Rogasch et al., 2014), increased inter-trial variability (Winterer et al., 2000a, 2004), and altered spectral power (Winterer et al., 2000a; Frantseva et al., 2012).

A hypothesis to explain these findings, first formulated by Winterer et al. (2000a), suggests the presence of inherent noise in brain activity. This manifests itself as stimulus-unrelated background activity that interferes with stimulus-evoked responses and thus leads to increased inter-trial variability. Further work by Rolls et al. (2008) conceptualized this hypothesis within a dynamical systems framework, with altered stability properties of attractors. Krystal et al. (2017) suggested that although the large inter-trial variability observed in schizophrenia can result from random background activity that degrades regular signals, it may also lead in itself to the creation of an aberrant signal. This suggests that not only evoked activity should be affected by such noise, but that the resting state activity in schizophrenia should exhibit correlates of abnormal activity as well. Indeed, various alterations of the resting-state EEG in schizophrenia have been reported. General findings include alterations of power spectra (Uhlhaas and Singer, 2010) and abnormalities of spatial activity in analyses of microstates (Rieger et al., 2016; Michel and Koenig, 2018). Notably, temporal activity alterations in long-range time correlations (LRTC) (Nikulin et al., 2012; Sun et al., 2014; Moran et al., 2019) were found, demonstrating that brain activity in patients shows reduced temporal auto-correlations on the timescale of tens of seconds, as well as reduced amplitude excursions (Sun et al., 2014).

This hypothesis that noise and its regulation is at the heart of alterations of functional activity in schizophrenia has been suggested as a low-level mechanism to explain both physiological and behavioral findings (Northoff and Duncan, 2016; Winterer et al., 2000a; Rolls et al., 2008). Alterations in global activity can shape the processing of stimulus-induced activity and may provide the basis for the reported changes in cognitive, affective and social functions (Northoff and Duncan, 2016). Ultimately, these alterations may underlie the unstable symptoms and symptom severity characteristic of the disorder (Habtewold et al., 2019; Bota et al., 2011). Despite the apparent popularity of the noise hypothesis, the fundamental question regarding the nature of this postulated noise remains to be answered. This regards its manifestations at the molecular, synaptic, or cellular level, as well as its properties, such as more deterministic or more random characteristics, permitting different interpretations of variability in brain activity (Faisal et al., 2008).

Here, we formulate the noise hypothesis such that it applies to brain activity in response to a stimulus as well as in resting state: The presence of noise is a characteristic of brain activity in schizophrenia, which reduces the capacity of the brain to achieve the formation of spatially and temporally stable correlated activity in neuronal populations.

We evaluated the strength of these correlations in population activity using markers derived from resting-state and TMS-EEG repeated-sessions experiments with schizophrenia patients and healthy controls. In TMS-EEG, we evaluated the signal-to-noise ratio, phase locking to stimulus, and post-stimulus excitability suppression. In resting-state EEG, we analyzed how amplitude averages and amplitude fluctuations compare to random noise. Generally, we find a reduction of these markers in the schizophrenia group. We suggest the interpretation that the ability to create stable spatiotemporal correlations of brain activity is reduced, consistent with the noise hypothesis.

2 Materials and methods

The study was approved by the Shaar Menashe Mental Health Center Institutional Review Board. All participants were reimbursed the equivalence of 35 US dollars for participating in each EEG recording sessions.

2.1 Experiments

We record TMS-evoked and resting-state EEG activity in schizophrenia patients and healthy controls, with three repetitions for each participant. Evaluating both groups three times with one week between each session strengthens the reliability of the results (see also (Kerwin et al., 2018)), as cortical responses may vary with changes in symptoms (Naim-Feil et al., 2019). An advantage of TMS-EEG is that it does not require active participation and attention of the schizophrenia patients (Daskalakis et al., 2002; Rogasch et al., 2014).

2.2 Subjects

Thirty healthy controls without any history of psychiatric illness, drug abuse or head injury were recruited through local advertisements. Three subjects were excluded because not all three sessions were attended, yielding 27 datasets for control.

Thirty in-unit schizophrenia patients at Shaar Menashe Mental Health Center qualified for the study according to DSM IV-TR Schizophrenia (DSM, 2000). Nine subjects were excluded because not all three sessions were attended, yielding 21 datasets of schizophrenia patients. Each patient was evaluated by a trained psychiatrist using the Scale for the Assessment of Positive Symptoms (SAPS) and the Scale for the Assessment of Negative Symptoms (SANS) to quantify clinical symptoms of schizophrenia (Andreasen, 1984, 1989).

All subjects completed a general demographic questionnaire and TMS safety questionnaire (Rossi et al., 2011). For demographic and clinical data, see Table 1. Each recording session was supervised by a trained psychiatrist, who assured that epileptic activity was absent in the EEG of all subjects.

2.3 EEG recording

EEG was recorded from 64 electrodes using a Biosemi ActiveTwo amplifier (BioSemi, Netherlands) at a sampling rate of 1024 Hz. TMS was applied with a Magstim Rapid (Magstim, UK) and a figure-of-eight coil at a fixed strength of 80 percent maximal stimulator output. There were three recording sessions. Each session was recorded at the same time of day with one week between the sessions. In each session, there were two stimulation sites (above frontal and central-parietal electrodes, FC2 and either FC2 or CP2). At each of these sites, a real stimulation measurement was always coupled to a sham stimulation (by placing the TMS coil perpendicularly to the stimulation site). Each such measurement (e.g., real or sham stimulation over FC2) comprised of around 100 single TMS pulses delivered manually at $\sim$3 s inter-pulse intervals. Each of the three stimulation sessions was preceded by a resting-state recording (duration mean$\pm$std: 260 s$\pm$60 s) in which subjects were requested to keep their eyes open. Here we report comparative analysis only for the real stimulation, as the sham stimulation is not relevant to the questions of this paper. Results are also only analyzed for stimulation over the FC2 electrode, as this stimulation site had the most complete data sets.

To maintain consistency between sessions, several measures were undertaken. First, the same EEG cap was used for all sessions with the exact same cap location. Second, a custom-built mobile, manually adjustable stand for the TMS coil was used in order to keep the coil position and orientation with respect to the FC2 electrode across sessions. Third, sessions were conducted at the same time of day and subjects were requested to maintain their sleep, coffee, and cigarette intake (which was monitored) constant for the days of the experiment. Furthermore, subjects listened to white noise through headphones during the sessions to reduce auditory distraction.

	Patients	Controls
Number of subjects	21	27
Gender (m + f)	19 + 2	21 + 6
Age (years)	40 ± 8	35 ± 11

Duration of illness (years)	21 ± 8		
Antipsychotics	typical	atypical	combination
No. (percentage) of patients	7 (33 %)	12 (57 %)	2 (10 %)
	Session 1	Session 2	Session 3
SAPS global	11.0 ± 5.2	10.0 ± 4.2	9.8 ± 5.3
(a) Hallucinations	3.0 ± 2.4	2.9 ± 2.1	2.6 ± 2.1
(b) Delusions	6.3 ± 7.7	5.3 ± 6.1	4.9 ± 5.7
(c) Bizarre behavior	10.0 ± 5.2	10.9 ± 4.9	9.9 ± 6.2
(d) Thought disorder	11.2 ± 10.5	10.7 ± 9.8	9.6 ± 10.0
SANS global	20.5 ± 3.6	20.1 ± 4.3	18.9 ± 4.2
(a) Affective flattening	28.4 ± 6.8	27.9 ± 7.8	26.8 ± 7.1
(b) Alogia	10.2 ± 5.8	9.9 ± 5.6	9.7 ± 4.9
(c) Avolition	11.9 ± 3.6	12.0 ± 3.5	11.2 ± 3.5
(d) Anhedonia	16.0 ± 3.4	16.2 ± 3.2	15.1 ± 4.1
(e) Attention	5.1 ± 2.2	5.2 ± 2.4	5.2 ± 2.0

Table 1: Demographic and clinical data.

2.4 EEG data processing

Resting-state EEG and TMS-EEG data were processed offline in several steps. In the TMS-EEG datasets, two additional pre-processing steps were applied. First, the procedure of Freche et al. (2018) was used to remove the TMS-induced discharge artifacts, and subsequently, the data of 25 ms duration following the TMS-pulse application, which could not be easily reconstructed at this sampling rate, were linearly interpolated. Afterwards, all datasets were high-pass filtered at 1 Hz and low-pass filtered at 150 Hz followed by a notch filter at 50 Hz using FIR filters by applying EEGLabs eegfiltnew function. Bad electrodes were removed from any further analysis following visual inspection. Remaining artifacts due to muscle activity, eye blinks, etc. were removed using Independent Component Analysis (ICA). The TMS-EEG data were subsequently epoched into trials for a time window of 1 s before and 2 s after each pulse. Finally, EEG signals were re-referenced by subtracting the signal average. In resting-state EEG datasets, only the first 182 s duration was used for further analysis. After further time-frequency decomposition (see Section 2.5, the 1 s at the beginning and at the end were removed to accommodate for edge effects. In the case of spectral power density computations (see Section 2.5), the beginning and ending seconds were also discarded to ensure the same length, even though there were no edge effects. Six datasets (5 sessions of different controls, 1 session of one patient) had a duration below 182 s and were therefore excluded from the resting-state EEG data analysis.

Care was taken during the data acquisition to ensure that the resting-state EEG recordings did not have any bad electrodes. However, in the TMS-EEG recordings, bad electrodes did occur, and in these datasets bad electrodes had to be removed, on average 1.3 electrodes in the controls group and 6.3 electrodes in the patients group, per dataset. About 50 % of the electrodes deleted were the FC2 electrode (stimulation site) or its nearest-neighbor electrodes, which were randomly prone to occasionally touching the coil.

2.5 Data analysis

2.5.1 Time-frequency decomposition, phase locking value (PLV), relative power, power spectral density

Time-frequency decompositions were computed using Morlet wavelets in the range of 2 Hz to 45 Hz with 2 cycles at the lowest and 15 cycles at the highest frequency in logarithmically spaced steps (cf. Bertrand et al. (2000)).

The PLV was computed from the phase of the time-frequency for each frequency and time point (Tallon-Baudry et al., 1996). It ranges between 0 and 1, where larger values indicate stronger phase locking between trials. The PLV was used to compare phases after the TMS pulse across trials.

Relative power was derived for each frequency, dividing by mean baseline power for baseline-normalization, and then converted to decibels. The baseline power was obtained as the mean power in the pre-stimulus window of 300 ms to 700 ms, averaged over all trials. This window falls outside the $2\sigma_t$-wide zone of influence of the trial boundaries and of the stimulation artifact, where σ_t is the (frequency-dependent) standard deviation in time of the Morlet wavelet (cf. Bertrand et al. (2000)).

For statistical analyses of the TMS-EEG data, time-frequency data were further processed in two steps. First, by down-sampling in time to 128 Hz and in frequency by averaging over the frequency bands, i.e. the delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma bands (30-45 Hz). Second, by averaging over time-frequency windows of interest. Furthermore, to reduce inter-trial variation, power was averaged over all trials of a given single session per subject. To take the same number of trials for every subject, only the first 70 trials surviving artifact removal were considered.

The power spectral density (PSD) was obtained for each electrode in the resting-state EEG by first computing the Fourier spectrum in a moving window of 2 s duration and 1 s overlap, and then taking the median of these windows.

The alpha peak location for each subject was obtained in the resting-state EEG by manual inspection of the average of the power spectral densities of all electrodes. For all three sessions of 1 control subject and one session of 1 patient, an alpha peak could not be detected, and therefore these subjects were not accounted for the peak location analysis.

2.5.2 Quartile coefficient of dispersion (QC)

According to the common view of EEG, there are two types of components that constitute the measured activity (Sauseng et al., 2007). One originates from spontaneous, ongoing activity, and is also called background activity. The other originates from short-lived and locally correlated bursts of synchronized activity such as event-related potentials. The first can be regarded as background noise and the second as intervals of modulated oscillatory signals.

Here we use a simple marker that can indicate whether modulated oscillations are present in a white noise signal. A common measure for the spread of a distribution based on its percentiles is the quartile coefficient (QC). Defining Q_1 as the percentile below which 25 percent of the distribution resides and Q_3 the corresponding value for the 75-th percentile, QC is defined by $(Q_3 - Q_1)/(Q_3 + Q_1)$. It is well-known that narrow-band-filtering of pure white noise yields a Rayleigh-distributed instantaneous amplitude (McClaning, 2012). This distribution has the property that its QC is independent of the amplitude of the underlying white noise, implying that the amplitude average is proportional to its fluctuation average. Furthermore, it has a known analytic expression with $QC_{Rayleigh} \approx 0.3741$. Thus, a signal with a QC different from $QC_{Rayleigh}$ implies the presence of non-noise components such as oscillatory signals.

For example, a pure-noise narrow-band signal with an additional constant oscillation at the mid-band frequency would increase the mean of the amplitude and hence the QC would be smaller than $QC_{Rayleigh}$. Another example is a pure-noise narrow-band signal with additional intervals of oscillatory bursts. This will increase the variation of the signal amplitude, leading to an increase in QC relative to $QC_{Rayleigh}$.

For the resting-state EEG analysis of Section 3.4, the QCs were derived for every frequency from 1 to 45 Hz from the time-frequency decomposition. For each electrode, the QCs were computed in a moving window of 40 s duration and 20 s overlap, and then the median of the QCs of all windows was taken.

2.5.3 Data visualization

All boxplots were plotted such that the box edges correspond to the 20-th to 80-th percentile of the underlying data. The center dot indicates the mean.

For visualization purposes, major electrode groups were aggregated and averaged. This constituted the following electrode aggregates: frontal-1 (FP1, FPz, FP2), frontal-2 (AF7, AF3, AFz, AF4, AF8), frontal-3 (F7, F5, F3, F1, Fz, F2, F4, F6, F8), frontal-4 (FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8), central-1 (T7, C5, C3, C1, Cz, C2, C4, C6, T8), central-2 (TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8), parietal-1 (P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10), parietal-2 (PO7, PO3, POz, PO4, PO8), occipital (O1, Oz, O2, Iz).

2.6 Statistical analysis

Each statistical analysis was performed at each electrode separately rather than correcting for multiple comparisons. The purpose of these single-electrode analyses was to evaluate phase and amplitude markers for correlated neural activity locally, i.e. at the single-electrode level, in the context of the noise hypothesis as stated in the introduction. Furthermore, it allows to observe that the topographical distribution of all of the significantly different electrodes does not occur randomly on the head but rather follows physiologically reasonable patterns such as hemispheric symmetry or proximity to the TMS stimulation site.

Statistical comparisons of relative power and PLV were done for selected time-frequency windows and performed as follows. For each subject and each electrode, the quantity for the data inside the time-frequency window were averaged to a single number. To test for group differences for a given electrode, we used the following two-level model. The first level describes the session-specific effects, and the second the subject-specific effects. For a quantity Y_{ij} of session i and subject j,

$$\begin{aligned} &\text{level 1 (session-specific):} && Y_{ij} = \beta_{0j} + R_{ij} \\ &\text{level 2 (subject-specific):} && \beta_{0j} = \gamma_{00} + \gamma_{10}\, GROUP_j + U_{0j} \end{aligned}$$

where the factor $GROUP$ has the levels $Control$ and $Patient$. The model has the fixed effects γ_{00}, γ_{10} and the random effects R_{ij}, U_{0i} with $R_{ij} \sim N(0, \sigma)$, $U_{0j} \sim N(0, \tau_{00})$, where $N(a, b)$ denotes a normal distribution with mean a and standard deviation b. The effects R_{ij} capture between-session (i.e. within-subject) variability. The effects U_{0j} encapsulate the between-subject variability and also incorporate the assumption of homogeneity of subject variance. Model fitting and significance testing was done with Matlab's fitlme function. Notably, we repeated the (electrode-wise) statistical tests for Figs. 2B, 3B using the Wilcoxon rank sum test, which disregards the session structure. The results are very similar concerning the location of electrodes exhibiting a statistically significant difference between groups.

The same testing procedure was also applied to the comparison of the alpha peak locations in Figs. 4B.

Statistical tests for spectral power and quartile coefficients of instantaneous amplitudes were done using the Wilcoxon test, because the amplitude distribution is strongly skewed and non-Gaussian. Consequently, we ignored the dependence of sessions of each subject and instead treated them as 'independent subjects'.

3 Results

3.1 Power modulation due to the TMS pulse

Fig. 1 depicts the overall effect of the TMS pulse on the EEG amplitude. We computed time-frequency decompositions for each electrode and present the derived amplitudes in decibels, once as averages for the electrode aggregates (Fig. 1A, see Methods), and again as topographic plots of averages over consecutive time windows (Fig. 1B).

Three main qualitative effects are immediately apparent across the different time scales, ranging from tens of milliseconds to seconds and affecting several frequency bands. First, there is a reduction of the excitatory response in patients, which can be observed in two time-frequency windows. One is an immediate response to the TMS-pulse until around 300 ms in the delta, theta, and alpha bands (yellow and pinkish

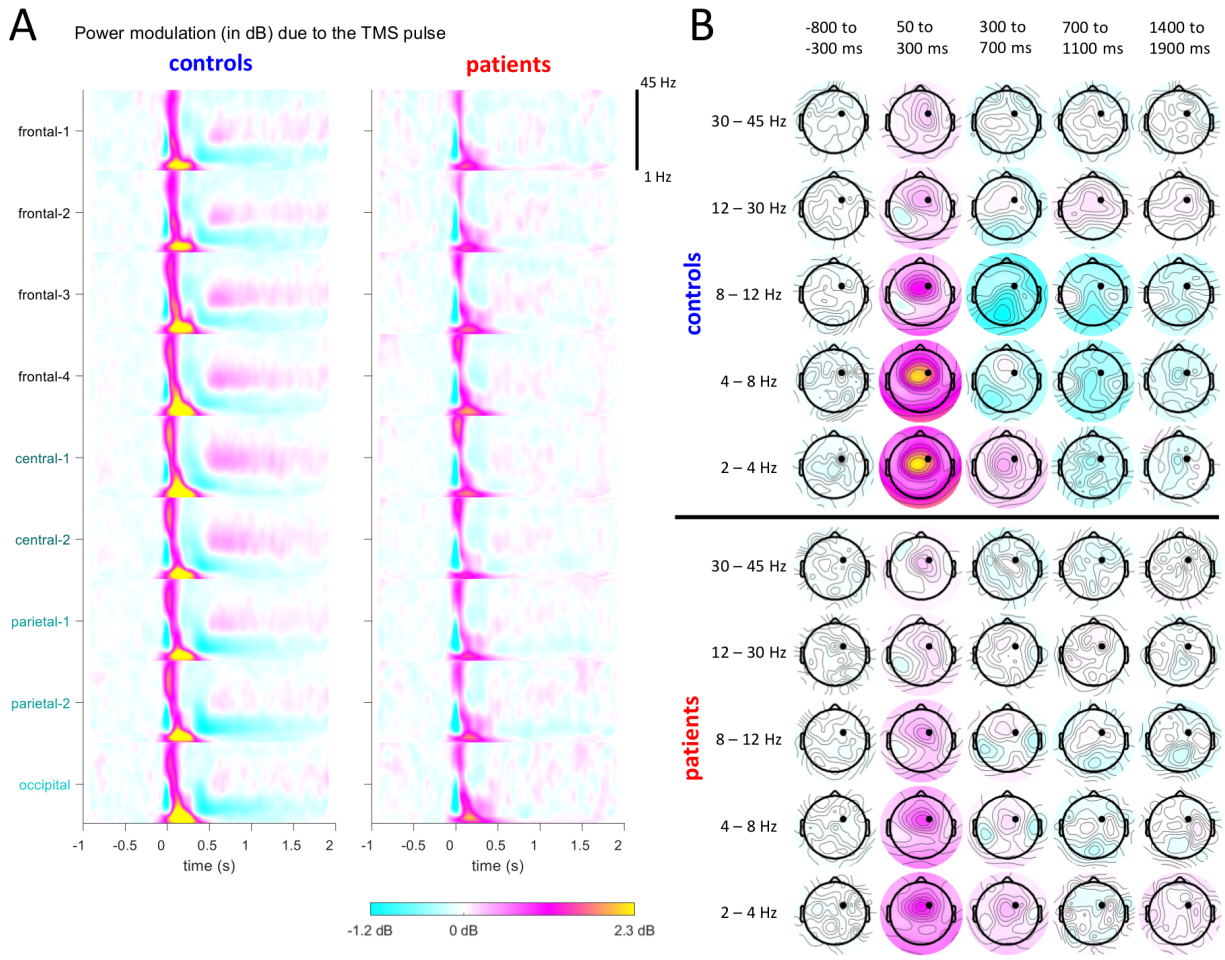

Figure 1: **A.** Time-frequency decompositions for electrode aggregates (averaged across trials). TMS was applied at time 0. The smearing in the time-frequency plot around time zero is due to the artifact removal process which introduces a gap of 25 ms in the data following the pulse onset. **B.** Topographical plots for different time-frequency windows (averaged over windows and across trials). The stimulation site FC2 is marked by a black dot.

colors in Fig. 1B). The other appears in more central electrodes in the beta and gamma bands from around 500 ms to around 1 s (with white-pinkish in controls and white-bluish in patients, Fig. 1B).

The second effect is a facilitation of excitability, observable in two time-frequency windows. One is in the theta and alpha band, starting at around 300 ms and lasting at least until 1 s. The second occurs in the delta band after 700 ms until around 1.5 s. In controls, this effect appears as the bluish topographic plots in Fig. 1B, which are absent in patients.

The third effect we observe suggests a transition from a reduction in excitability in controls to facilitation of excitability in patients. This effect is visible in the time-frequency plots (mostly in the central-posterior-occipital electrodes), in the theta and alpha bands starting around 300 ms and lasting till around 1 s. It is also visible in the topographic plots that appear bluish (i.e. attenuated) in controls but have reddish (i.e. facilitated) additions for patients.

To quantify these three main effects, we delineated the time-frequency windows in which these effects are most pronounced and performed a post-hoc analysis in these windows. This is presented in Fig. 2. Alterations in response excitability are especially apparent in time-frequency window 2, where the mean

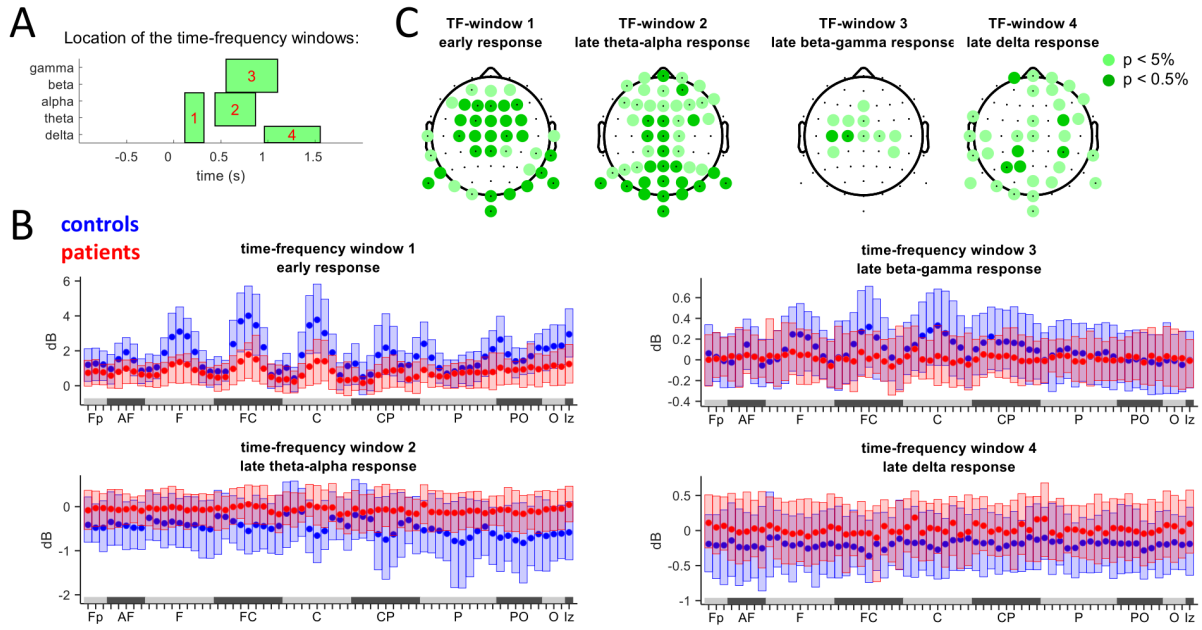

Figure 2: **A.** The different time-frequency windows that we consider for post-hoc statistical testing. **B.** Boxplots of the power values of each time-frequency window for each electrode (x-axis: 64 electrodes aggregated by groups. Order inside a group is band-wise from the right to left hemisphere.) **C.** Statistically significant group differences of power modulations. Each test was applied separately to each electrode.

power response at frontal, central, posterior, and occipital electrodes (midline FC-C-CP) turns from negative (power attenuation) in controls to positive (power facilitation) in patients. An electrode-wise comparison between groups extracted the electrodes that showed statistical significant differences between patients and controls in each window.

The differential alterations of excitability that we verified with TMS-EEG in our patient group thus include a reduced excitability in early responses and a facilitated excitability as well as a shift from attenuation to facilitation of excitability in later responses.

3.2 Phase locking to the TMS pulse

We use the phase-locking value (PLV) to assess phase angle similarity following the TMS-pulse at each electrode separately, across trials. The phases were derived from the time-frequency decompositions used for Fig. 1. Fig. 3A shows the PLVs for each frequency and for all electrode aggregates, indicating that PLVs are generally reduced in patients. This is shown by a post-hoc analysis for the time-frequency windows of Fig. 3B. The PLVs, at all frequency bands, show most significant differences at more central and frontal electrodes, which are closest to the stimulation site, but also at posterior electrodes. We conclude that reduction of phase-locking to a stimulus can be verified with TMS-EEG in our patient group.

3.3 Spectral power in resting-state EEG

The resting-state EEG was also assessed for differences in power spectra and amplitude fluctuations. The power spectral densities (PSDs) averaged for all electrode aggregates are depicted in Fig. 4A, with several alterations noticeable. There is an increase of power in lower frequency bands in patients and generally an elevated power in more frontal electrodes. Furthermore, the location of the mean alpha peak is shifted towards lower frequencies (controls 9.8±0.9 Hz, patients 9.0±0.8 Hz). Both effects are statistically significant (Figs. 4B-D), with the session effects ignored in this case (see Methods).

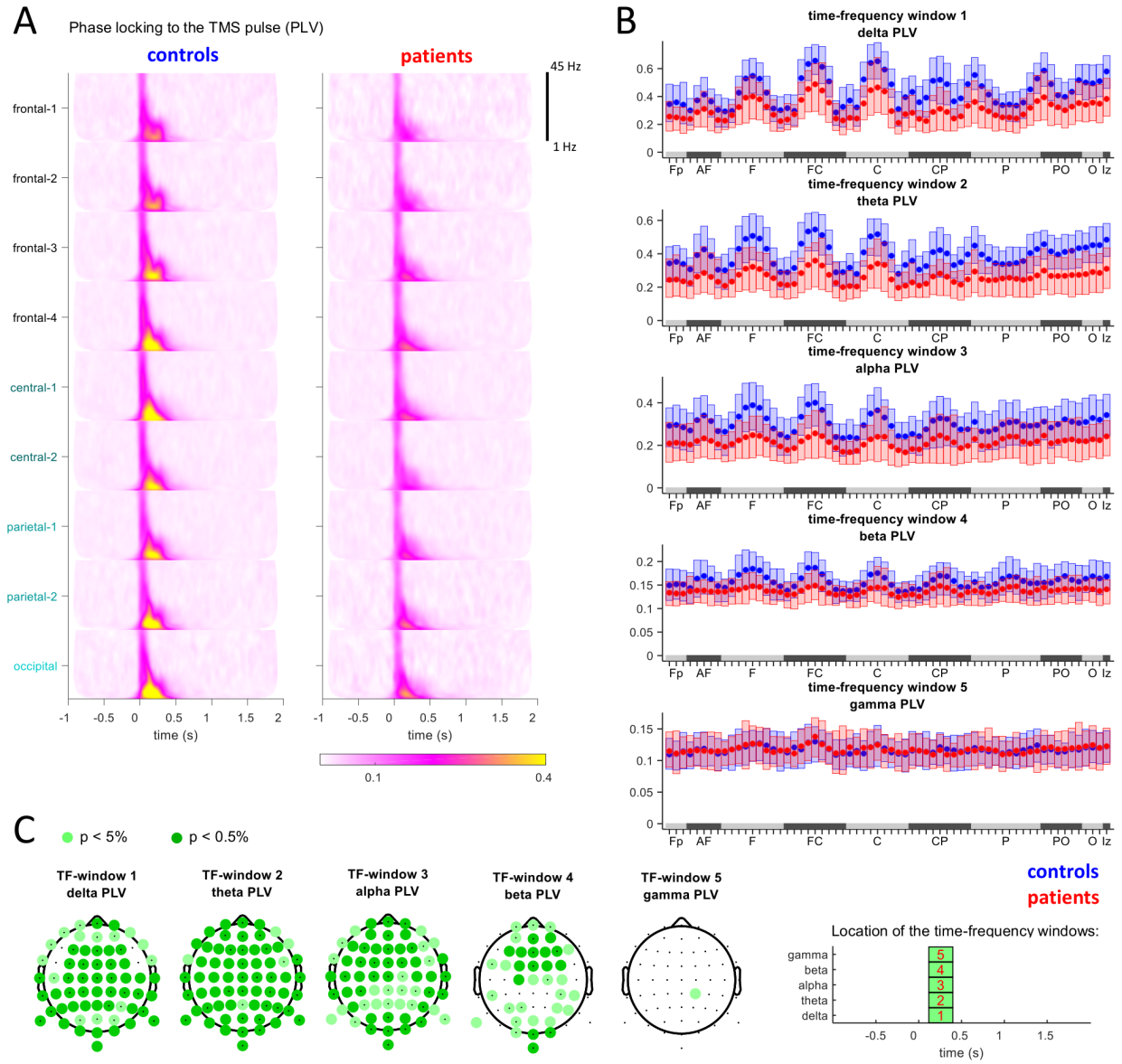

Figure 3: **A.** Phase locking value (PLV) for controls and for patients (displayed are averages of major electrode groups across trials). TMS was applied at time 0. **B.** Boxplots of the PLV values for selected time-frequency window, for each electrode. The time-frequency windows are specified in the bottom-right panel. **C.** Statistically significant group differences of PLV. Each test was applied separately to each electrode.

We conclude that the resting-state EEG spectrum of the patient group exhibits alterations from control spectra, especially in the frontal electrodes. Decomposition into frequency bands suggests that in most electrodes these effects are due to the theta band, while in frontal locations they occur also in the delta, beta, and lower gamma bands.

3.4 Amplitude fluctuations in resting-state EEG

We next tested for alterations in amplitude fluctuations at each frequency. A simple possible marker is the amplitude variation. It has to be normalized by the amplitude mean, which corresponds to the spectral

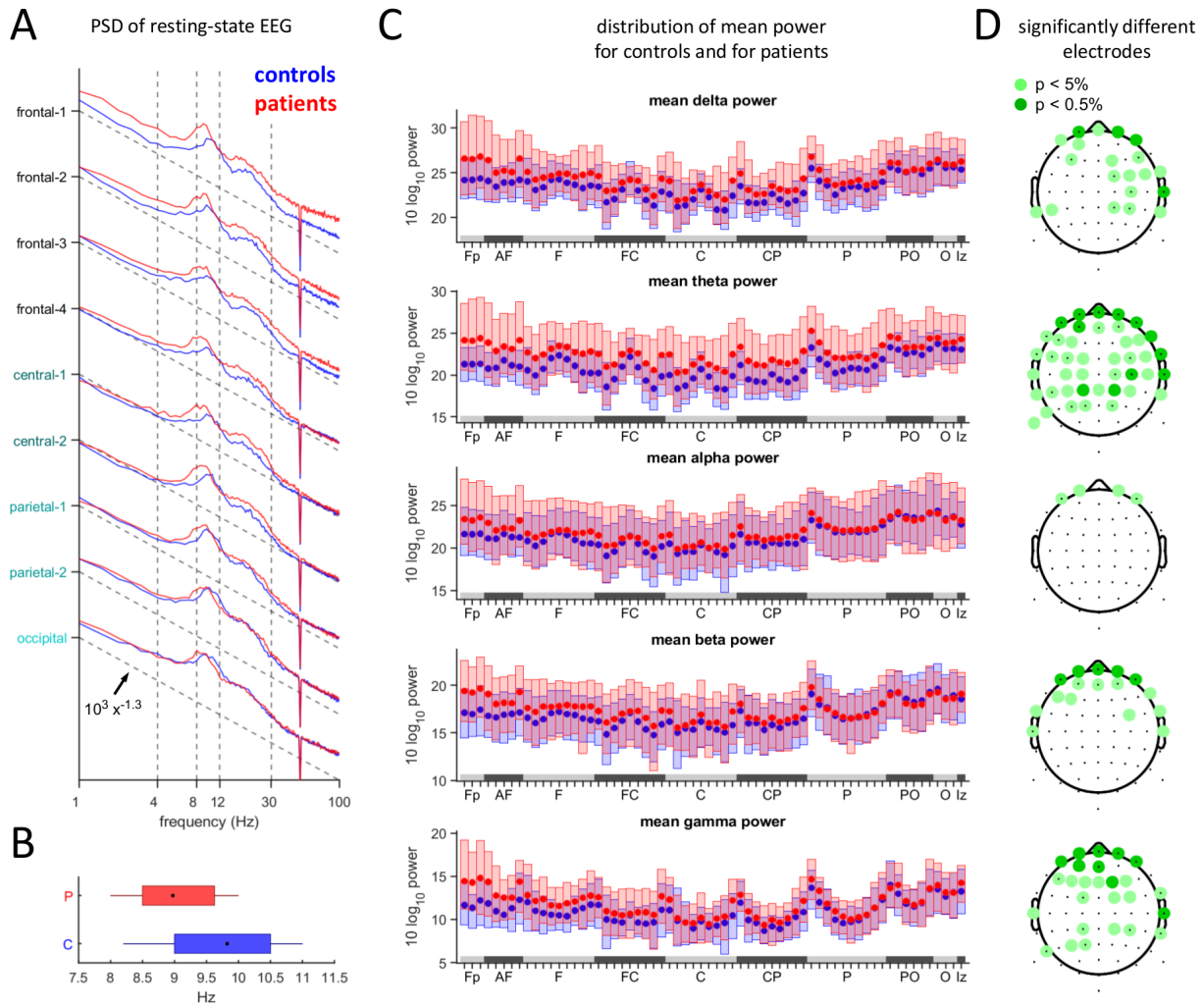

Figure 4: **A.** Log-log plots of resting-state EEG spectral power densities (PSDs) relative to a power law $10^3 x^{-1.3}$ (dotted line) for comparison. **B.** Alpha peak location for patients and controls. The black dot marks the mean, whiskers indicate the first and the third quartile. **C.** Boxplots of spectral power for the different frequency bands, for each electrode. **D.** Statistically significant group differences of spectral power in the different frequency bands. Test applied to each electrode separately.

power, because it shows large differences between subjects. This quantity is called coefficient of variation (CV). Because the CV is sensitive to outliers, in our analysis we replaced it by the similar but more robust quartile coefficient of dispersion (QC). Fig. 5A shows the QCs of the two subject groups averaged for different electrode aggregates. The QC of a pure white noise signal is denoted by $QC_{Rayleigh}$ and is shown as a dashed line. Deviations of the computed QCs from $QC_{Rayleigh}$ indicate the presence of signals that are non-noise (see Methods).

Boxplots for each electrode are shown in Fig. 5B, averaged over frequency bands. Two effects are evident. First, QCs of controls are generally larger in the alpha and beta range, whereas some differences exists in the delta and gamma bands, where patients show larger QCs. This is corroborated by statistical tests (Fig. 5C). Second, the differences of the QCs between the groups do not coincide with differences of PSDs shown in Fig. 4.

We conclude that the resting-state EEG of the patient group exhibits a reduction of instantaneous

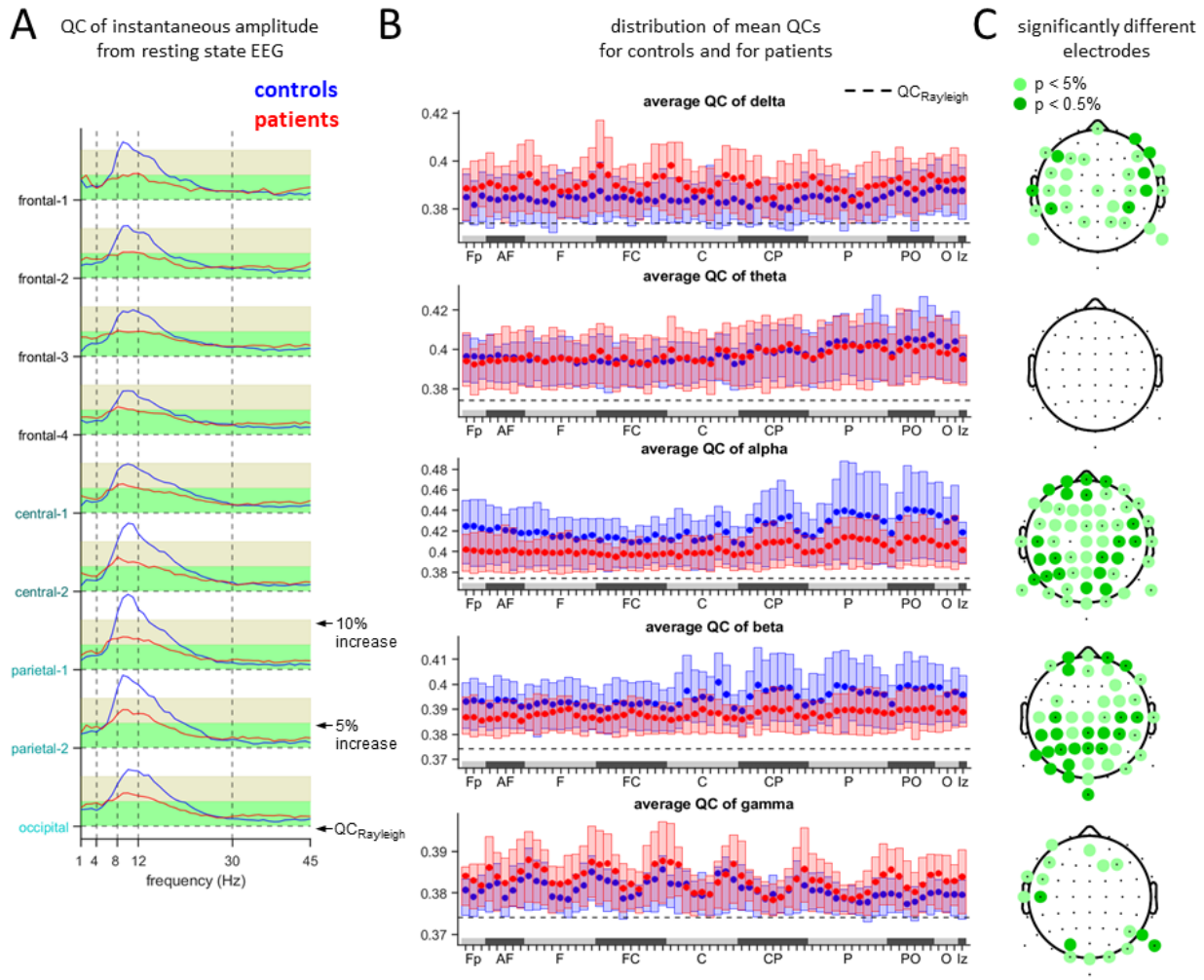

Figure 5: **A.** The quartile coefficient (QC) of the instantaneous amplitudes for different frequencies and electrode groups. The quartile coefficient $QC_{Rayleigh}$ of amplitude fluctuations of a Gaussian noise signal is marked by the horizontal dashed lines. **B.** Boxplots of the QCs for the different frequency bands, for each electrode. The quartile coefficient $QC_{Rayleigh}$ of white-noise amplitude fluctuations is marked by the horizontal dashed line. **C.** Statistically significant group differences of QCs in the different frequency bands. Test applied to each electrode separately.

amplitude fluctuations predominantly in the alpha and beta bands. In terms of the QC marker, the EEG in patients are closer to the value expected for random noise.

4 Discussion

A hallmark of schizophrenia is the appearance profound, global alterations of brain activity (Uhlhaas and Singer, 2010). The previously suggested noise hypothesis (Winterer et al., 2000a; Rolls et al., 2008) on the nature underlying these alterations postulates the existence of inherent noise in brain activity in schizophrenia that degrades the brains ability to form stable spatial and temporal correlations between cells and cell populations. Stated in this form, the hypothesis can be evaluated for stimulus-evoked activity and for resting-state activity of the brain. Using TMS-EEG and resting-state EEG, we investigated various markers to evaluate the strength of coordinated population activity. Our analysis of the TMS-EEG confirms

previously reported findings of evoked response properties based on power modulations and phase locking. In addition, we find clear differences of the resting-state EEG, which appear in the spectral power and the instantaneous amplitude. Using a fluctuation analysis of the instantaneous amplitude, we demonstrate that the schizophrenia resting-state data looks more similar to random noise than data from healthy controls. Overall, our results support the noise hypothesis in schizophrenia. In the context of the question to what extent intrinsic background activity in schizophrenia is more oscillatory than random, we provide support for the notion of more randomness in the EEG of schizophrenia patients. We point out that this randomness does not necessarily coincide with the inherent noise postulated by the noise hypothesis, however it may be indicative of its presence.

4.1 Alterations of evoked response processing

TMS application at the frontal-central site FC2 evoked strong responses lasting for more than 1 s. Our focus on spatial and temporal correlations and their relation to noise highlights that the power is modulated differently in the patient than in the control group, in different time windows and frequency bands (Fig. 1). While in controls there was increased power in various frequency bands in early time-frequency windows (Fig. 2A,B), in patients power was reduced. This contrasted later time-frequency windows, where patients exhibited increased power relative to the controls, which was strongest in the delta, theta, and alpha bands. The different time scales of the windows may be interpreted as different responses to the TMS, namely as direct, local activation of the pulse, and as late-stage, long-range responses activated by the direct response (Frantseva et al., 2012; Radhu et al., 2015; Rogasch et al., 2014). In this picture, the reduced signal-to-noise ratio may be interpreted as reduced excitability, and the facilitated excitability at later stages as reduction of inhibition. Together, this may be summarized as an altered excitation-inhibition balance.

These phenomena in the response to the TMS are consistent with the many known structural changes of brain tissue in schizophrenia. Indeed, alterations in connectivity have been reported (Krystal et al., 2017; Mikanmaa et al., 2019) during different developmental stages of the disease spectrum. Consistent with the excitability is a modification of local connectivity, such as a reduction of GABAergic cell density, myelination, connectivity, and alterations of gray matter density in progressed stages (Glahn et al., 2008). Consistent with alterations of signal propagation are abnormalities in long-range connectivity, such as changes of white-matter tracts (Tonnesen et al., 2018). In the context of TMS application, white matter integrity was demonstrated to directly influence how TMS-evoked activity spreads in the brain (Kearney-Ramos et al., 2018).

The power reduction of the TMS responses was accompanied by a reduction in locking of phase to the pulse, evaluated by the PLV. Because both amplitude and PLV are related measures, this analysis is not independent of our findings regarding the changes in power. As expected, and reported previously for other paradigms (Winterer et al., 2000a, 2004; Spencer et al., 2003), schizophrenia patients exhibit a reduction of phase locking. Indeed, we observe a significant reduction of PLV in the delta, theta, alpha, and beta bands (Fig. 3). We note that the PLV can be artificially increased by volume conduction, which however would affect both groups to the same extent, and therefore these effects would work to reduce group differences rather than increase.

Our findings replicate previous reports for TMS-EEG in schizophrenia, such as Frantseva et al. (2012); Ferrarelli et al. (2012); Radhu et al. (2015); Ferrarelli et al. (2019); Rogasch et al. (2014); Shin et al. (2015) (see also Kaskie and Ferrarelli (2018)), and confirm previous observations in behavioral evoked-response paradigms (Winterer et al., 2000a; Spencer et al., 2003). Alterations of long-range connections and inter-area synchronization in schizophrenia were reported in Hirvonen et al. (2017).

4.2 Alterations of resting-state power spectra

Various differences in the resting-state EEG spectra of schizophrenia patients were reported (Winterer et al., 2000a; Uhlhaas and Singer, 2010; Goldstein et al., 2015), though inconsistencies in the literature have been pointed out (Hunt et al., 2017; Newson and Thiagarajan, 2019). In our dataset, we identified a significant shift of the alpha peak to lower frequencies (slowing). This finding replicates Goldstein et al. (2015); Garakh et al. (2012); Yeum and Kang (2018); Murphy and Öngür (2019), and may be related to symptoms (Garakh et al., 2012) or duration of illness (Goldstein et al., 2015). Other spectral power differences only appeared

at frontal electrodes (Fig. 4A, B) with the exception of the theta band, which also shows differences in some parietal electrodes. However, the significant difference in theta power may be an artifact of our fixed definition of frequency bands together with the alpha peak slowing.

4.3 Neuronal noise and alterations of resting-state amplitude fluctuations

Beyond the differences in the spectra, several other alterations of the resting-state EEG in schizophrenia have been reported. This includes analyses of microstates (Rieger et al., 2016; Michel and Koenig, 2018), long range temporal correlations (LRTC) (Nikulin et al., 2012; Sun et al., 2014), and amplitude excursions (Sun et al., 2014). While the origin of these differences is not known, they are consistent with the noise hypothesis. We quantified the variability of resting-state amplitude fluctuations at different frequency bands in a simple and straightforward way, using the QC for moving time windows of 40 s. Significant differences appear in several frequency bands (Fig. 5), most notably in the alpha and beta bands. Both were also reported previously to exhibit significant reductions of LRTC in schizophrenia by Nikulin et al. (2012), whereas Moran et al. (2019) reports LRTC attenuations only for the beta band.

QC is a measure similar to the coefficient of variation (CV), and can be viewed as evaluating the incidence and strength of random events, occurring when the instantaneous amplitude deviates from the amplitude average. These deviations are therefore indicative of a short-lived, oscillatory event. A larger QC can be considered as representing a richer repertoire of events and hence of cortical activity, although it formally equals a noise-to-signal ratio. Support for this view comes from experimental measurements of the spiking activity in rodents (de Vasconcelos et al., 2017; Fontenele et al., 2019), in which the CV, computed on the timescale of tens of seconds, was used to characterize different cortical states.

A second interpretation of the QC that goes beyond the mere detection of group differences is that a signal with a QC that is closer to $QC_{Rayleigh}$ (see Methods) is indicative of increased randomness. However, this interpretation is not as straightforward and relies on additional assumptions.

The first assumption regards our model of the narrow-band filtered EEG signals, which we assume to consist of two parts. One part comprises the modulated oscillatory events and consists of oscillations around the center frequency of the band. The amplitude envelope of this part can vary slowly compared to the center frequency. The other part comprises of white noise with a constant strength. Hence, as the amplitudes of the event occurrences tend to zero, the QC of the instantaneous amplitude approaches $QC_{Rayleigh}$.

The second assumption regards the relationship between amplitude and duration of the oscillatory event occurrences. Generally, the shorter the coverage by oscillatory events and the larger the event amplitudes, the larger is the QC. Furthermore, longer coverage by oscillatory events can make the QC very small, and even smaller than $QC_{Rayleigh}$ if the event amplitudes are large enough (see the examples discussed in Methods). So the interpretation that resting-state EEG activity is closer to noise is only true if we exclude that the majority of patients had rather long and rather strong occurrences of oscillatory events that are fine-tuned such that their QCs are close to $QC_{Rayleigh}$. In other words, this interpretation relies on the reasonable assumption that such very specific fine-tuning is unlikely.

4.4 Specificity of the investigated features for schizophrenia

Classification studies of intrinsic activity and evoked potentials in schizophrenia and psychosis indicate that achieving a comprehensive explanation that links alterations of intrinsic activity and evoked potentials would be difficult (Hudgens-Haney et al., 2017; Rolls et al., 2017). In fact, Clementz et al. (2017) were constituted three different 'biotypes from a battery of properties, which do not coincide with clinical classification schemes. Hudgens-Haney et al. (2017) found alterations, corresponding to the biotypes, in EEG background activity and in certain evoked potentials. Although the origin of these phenomena is not clear, it is consistent with the large overlaps between the healthy range and the patient range in our measurements (see e.g. the boxplots in Figs. 2-5).

To conclude, our results corroborate and expand the previously reported evidence for the noise hypothesis in schizophrenia, obtained by investigating evoked potentials and resting state data. In TMS-EEG, we describe and confirm various alterations of evoked potentials. In resting-state EEG, we confirm alterations of amplitude fluctuations schizophrenia, using a new analysis based on a simple ratio measure of dispersion and

mean. We suggest to distinguish between the extent of abnormal randomness and of abnormal oscillations in the brain activity, and note that this generalizes to both evoked potentials and resting-state EEG. A reasonable interpretation of our findings supports the possibility that the schizophrenia brain is characterized more by abnormal randomness.

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