Large-Scale Maps of Altered Cortical Dynamics in Early-Stage Psychosis Are Related to GABAergic and Glutamatergic Neurotransmission

Short title: Large-scale dynamical signatures of psychosis

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Abstract
Psychotic disorders present a challenge for research and clinical practice. Their pathogenesis is poorly understood, symptoms vary widely between patients, and there is a lack of objective biomarkers. Evidence points to a distributed nature of the underlying synaptic alterations in the cerebral cortex. Using magnetoencephalography source imaging, we mapped alterations of neural population dynamics in psychosis across the human cortex. Individuals with early-stage psychosis exhibited characteristic patterns of changes in neural dynamics, in opposite directions for different cortical areas. These patterns were similar for first-episode psychosis and clinical high-risk for psychosis. Different components of these large-scale patterns resembled the effects produced in the healthy brain by pharmacological manipulations of either GABA-A or glutamate (NMDA) receptors. The expression of the GABA-A-component in first-episode psychosis patients was related to positive symptoms, and the expression of the NMDA-component to negative symptoms. Our study opens a window on the large-scale pathophysiology of psychosis.

Teaser
Cortex-wide changes in neural dynamics in early-stage psychosis relate to GABA-A or NMDA receptors and clinical symptoms.

Introduction

Psychotic disorders, such as schizophrenia, present a major burden to society (*1–3*). Schizophrenia is characterized by positive and negative symptoms as well as by cognitive deficits, which may originate from diverse underlying mechanisms (*4*). Schizophrenia is a neuro-developmental disorder, with aberrations in brain circuitry emerging long before symptoms typically manifest during adolescence (*3*). Recently, criteria have been developed to allow the detection of individuals at clinical high-risk for psychosis (CHR-P) (*5*). Approximately 25% of CHR-P individuals transition to psychosis within 3 years of follow-up (*6*).

Aberrations in several neurotransmitter systems have been implicated in the pathogenesis of psychotic disorders, including disturbances of GABAergic cortical inhibition (*7–10*) and glutamatergic excitation, specifically via NMDA receptors (*11*, *12*). An important research goal is to uncover the underlying multi-scale mechanisms, ranging from neurotransmitters to cortical circuit dynamics to symptoms. The identification of non-invasive neurophysiological markers that are sensitive to these multi-scale mechanisms is of particular practical relevance for the early detection, diagnosis, and individualized treatment of psychotic disorders.

Cortical circuits exhibit an intricate arrangement of excitatory and inhibitory synaptic connections. The detailed properties of cortical circuits, such as the ratio between excitatory and inhibitory synaptic interactions, shape the mechanisms of cognitive behaviors that involve working memory, accumulation of evidence, and deliberative decision-making (*13–21*). These microcircuit properties are disturbed in schizophrenia and related disorders, such as autism, whereby a major focus has been on the ratios between synaptic excitation and inhibition within cortical areas (*11–13*, *22–25*). Simulations of neural circuit models show that changes in such microcircuit properties produce characteristic changes in the dynamics of spontaneous neural mass activity, as expressed in local field potentials (*26–32*). Such neural mass signals can be mapped with high spatio-temporal precision in the human brain using MEG source imaging (*33*, *34*). Indeed, recent E/MEG studies of psychosis have identified deviations in several markers of spontaneous cortical population activity at rest (*35–41*).

A separate line of research has shown that properties of cortical microstructure, including synaptic inhibition via GABA-A receptors and excitation via NMDA receptors, are not homogeneous but exhibit systematic spatial patterns across cortex, which reflect the hierarchical ordering of cortical areas (*17*, *42*). Similar large-scale patterns exist for features of cortical dynamics (*17*, *29*, *43–47*). Likewise, microscopic properties of local circuits, such as the number of excitatory synaptic spines or the density of inhibitory interneurons, exhibit systematic large-scale variation across the cerebral cortex, one component of which reflects the anatomical cortical hierarchy (*42*). These insights into the large-scale organization of cortical circuits and dynamics parallel the mounting evidence for the idea that the circuit dysfunctions underlying psychotic disorders are also expressed across many cortical areas (*3*, *24*). However, the large-scale organization of the distributed alterations in microscopic circuit properties has remained unknown. Specifically, it is unclear how such distributed alterations in circuit properties relate to changes in large-scale cortical dynamics and, ultimately, psychotic symptoms.

Here, we developed an MEG approach to address the hypothesis that the large-scale patterns of altered cortical dynamics in psychosis result, at least in part, from the local alterations in GABA-A or NMDA receptors. Inspired by recent advances in large-scale computational neuroanatomy (*17*, *42*, *46–48*) and clinical neurophysiology (*49*, *50*), our approach aimed to (i) identify putative large-scale neurophysiological signatures of early-stage psychosis and (ii) quantitatively relate these signatures to large-scale patterns of GABA-A or NMDA receptor expression and function. To this end, we mapped the patterns across many cortical areas (*44*, *51*) of the changes of spontaneous cortical dynamics induced by psychosis or by pharmacological manipulations of GABA-A or NMDA receptors in healthy participants. We used pattern analysis techniques to test for the reliability of, and relationship between, these large-scale patterns.

Based on results from invasive electrophysiology (*17*, *29*, *43*, *52*), we predicted, and confirmed, that several parameters of spontaneous cortical dynamics were systematically related to the anatomical cortical hierarchy. We also expected the large-scale patterns of the *changes* in cortical dynamics induced by both psychosis or by pharmacological manipulations of GABA-A and NMDA receptors in healthy participants to be widespread across cortex. Critically, we predicted that different components of the psychosis-induced activity patterns reflected (i.e., were similar to) the pharmacologically induced activity patterns, due to the involvement of both GABA-A and NMDA receptors in the pathogenesis of psychosis.

Our approach uncovered widespread large-scale patterns of changes in cortical dynamics in psychosis, which were remarkably similar between individuals with first-episode psychosis and CHR-P. These patterns enabled prediction of individual clinical status and resembled the patterns of changes in cortical dynamics induced by manipulating GABA-A or NMDA receptor function, with a more consistent association with the GABA-A patterns. Differences in those spatial patterns of cortical dynamics between first-episode psychosis patients related to individual symptomatology: the expression of the activity component resembling the effects of GABA-A manipulation in the healthy brain was related to positive symptoms, while the expression of the "NMDA-manipulation component" was related to negative symptoms.

Results

We analyzed resting-state MEG data from two previously published studies (*35*, *53–57*). The clinical dataset was collected at the University of Glasgow in a group of CHR-P participants (N=117), a group of first episode psychosis patients (FEP; N=32), and a group of healthy controls (HC; N=45; see Materials & Methods for details on the samples). The pharmacological dataset was collected at the University Medical Center Hamburg-Eppendorf and measured the effects of double-blind oral administration of the GABA-A agonist lorazepam (LZP) and the NMDA receptor antagonist memantine (MEM), each compared to placebo within a group of 20 healthy participants (cross-over design, with at least 1 week between successive sessions to allow for full elimination of the drugs; see Materials & Methods). All groups completed a block of eyes-open resting-state, fixating a central cross on an otherwise blank screen.

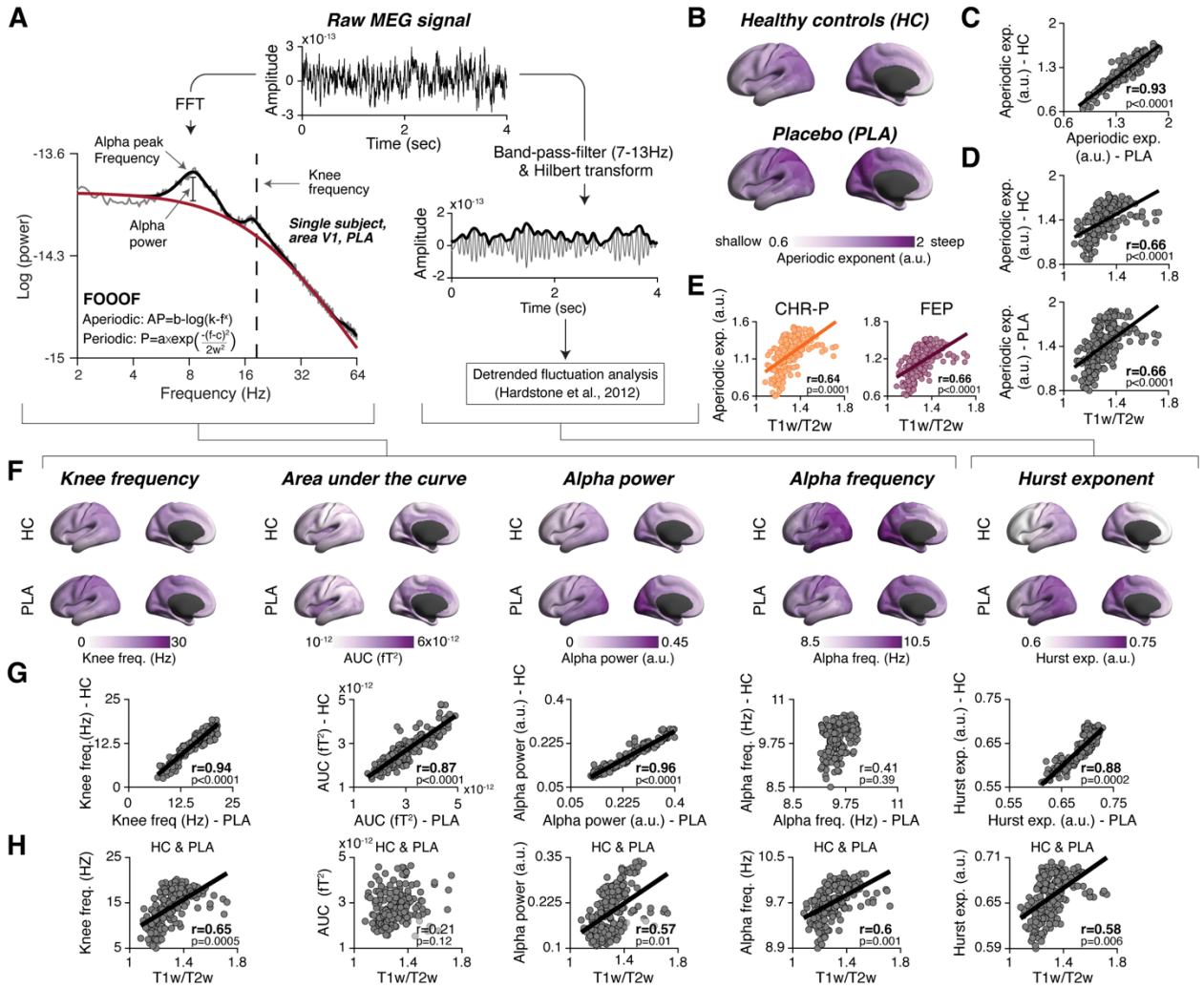

Figure 1: Large-scale spatial patterns of local cortical population dynamics. (A) Raw MEG signals (top; single-participant, V1; placebo condition) were submitted to fast Fourier transform (FFT; left) or band-pass filtered and submitted to Hilbert transform (right). Left: Power spectral density (PSD, gray) of resting-state MEG signal. Black and red lines are the fitted periodic and aperiodic components, respectively (Materials & Methods). Right: Alpha (8-13Hz) amplitude envelope of MEG signal were subjected to detrended fluctuation analysis to estimate the Hurst exponent. **(B)** Cortical spatial distribution of the aperiodic exponent across 180 areas. Here and in all following figures, homotopic regions from left and right hemispheres were averaged and results are presented on left hemisphere for illustration only. **(C)** Across-area correlations between the maps of aperiodic exponent in both samples shown in panel B. Spearman's correlation coefficients and p-values (permutation tests; corrected to account for spatial autocorrelations) are noted in each panel. Each dot represents a single parcel. Black line: linear fit. **(D)** Spatial similarities (across-area correlations) between the maps of aperiodic exponents (for each dataset) and of a structural MRI maker of cortical hierarchy (the ratio between T1w to T2w images). **(E)** same as D, for the two clinical groups: clinical high risk (CHR-P; orange) and first episode psychosis (FEP; purple) **(F)** Cortical spatial distribution of five additional parameters of cortical dynamics. Top row, healthy control (HC). Bottom row, placebo condition (PLA). **(G)** Across-area correlations between maps of dynamics parameters of PLA condition and HC. **(H)** Spatial similarities (across-area correlations) between maps of dynamics paraments, pooled across PLA and HC and of a structural MRI maker of cortical hierarchy (the ratio between T1w to T2w images).

A multi-parameter assay of local cortical population dynamics

We parameterized spontaneous cortical network dynamics in the clinical and pharmacological datasets in terms of a set of six parameters (Fig. 1 and Materials & Methods). The power spectra of local MEG signal fluctuations were decomposed into oscillatory (periodic) and non-oscillatory (aperiodic) components (Fig. 1A left; Materials & Methods and (*58*)), from which we extracted a total of five parameters: the (i) exponent, (ii) "knee frequency", and (iii) area under-the-curve (of aperiodic fit only) of the aperiodic component. We further extracted the (iv) power and (v) peak frequency specifically from the periodic fit to the alpha (7-12 Hz) frequency range. In a separate analysis (Fig. 1A right; Materials & Methods), we computed the so-called (vi) Hurst exponent to quantify long-range temporal correlations in the fluctuations of alpha-band amplitude envelopes (*59*).

The above parameters were selected because these parameters have been related to key microcircuit properties, which may be altered in schizophrenia (*3*, *6*, *9*, *10*, *28*, *29*) and related mental disorders such as autism (*20*, *22*, *60*, *61*). Specifically, the aperiodic exponent of the overall power spectrum and Hurst exponent of alpha-envelope fluctuations have both been linked to the ratio between local synaptic excitation and inhibition (*27*, *28*, *30–32*). The knee frequency has been linked to the intrinsic timescale of cortical activity (*29*, *52*) , which, in turn, depends on the strength of recurrent excitation (*17*). The area under the curve of the aperiodic fit is a proxy of population firing rates (*26*) . Work on neural oscillations has implicated gamma-band responses as a marker of excitatory-inhibitory interactions within cortical microcircuits (*31*, *34*, *62*, *63*) and of aberrations thereof in psychosis (*24*, *55*). For parameters (iv) to (vi), we here focused on the alpha-range rather than gamma-range. This was because our approach relied on large-scale (across-area) spatial patterns and alpha peaks are generally more prominent and widely distributed at rest (*34*), and were more consistently detected in our data across cortical areas and participants. Please note that the aperiodic parameters (i) to (iii) were based on the entire frequency range of the power spectra analyzed here, so our parameter set provided a rich summary of cortical dynamics.

Large-scale spatial patterns of local cortical dynamics

The above six parameters of local cortical dynamics (henceforth called "dynamics parameters") were comprehensively mapped across 180 well-defined areas covering the cortical surface (*48*). Throughout, we averaged across corresponding areas from the left and right hemispheres and visualized the resulting parameter maps on the surface of the left hemisphere. This approach enabled us to characterize large-scale spatial patterns of changes in cortical dynamics in CHR-P and FEP-groups versus control groups, or under pharmacological interventions versus placebo conditions in healthy individuals.

All dynamics parameters exhibited a heterogenous spatial pattern, with a smooth change across areas (Fig. 1). This spatial pattern reflected the pattern of structural MRI T1w/T2w ratios (*45*) across cortical areas (Fig. 1D, H; Fig. S1A, B). The T1w/T2w ratio tracks local myelin density (*64*), and recent work has established it as an inverse proxy of an area's position in the anatomical hierarchy, an important principle governing large-scale cortical organization (*42*). Specifically, we found that the spatial patterns of the exponent of the aperiodic component (*33*) were both positively correlated with the T1w/T2w ratio in the control groups or conditions of both data sets (Fig. 1D: r(180)=0.66,

$p<10^{-4}$; spatial autocorrelation-preserving permutation tests; Materials & Methods) and strongly correlated among one another (Fig. 1C: $r(180)= 0.93$, $p<10^{-4}$). In other words, the exponent of the aperiodic component became systematically smaller across the cortical hierarchy, with larger exponents (i.e., steeper decay of power with frequency) for early sensory cortices and smaller exponents (i.e., flatter decay) for prefrontal cortex. The aperiodic exponent has been proposed as a non-invasive proxy of the local excitation-inhibition ratio (*28*), which, in turn, increases as a function of cortical hierarchy (*17*). Likewise, the maps of the knee frequency, an inverse measure of intrinsic neural timescales (*29*, *52*) showed a decrease of knee frequencies from sensory to association cortex, in line with slower neural timescales in higher-tier areas (*17*, *43*, *44*).

The maps of the other parameters (Fig. 1F) were, likewise, correlated with the T1w/T2w ratio maps for all but one (area-under-the-curve) in both datasets (Fig. 1H; Fig. S1 A, B) and exhibited robust correlations among one another (Fig. S1 C,D). This was the case in the data from both studies, whereby the spatial patterns of all parameters except of alpha peak frequency were strongly correlated between these two samples (Fig. 1G). Similar spatial correlations to T1w/T2w ratios were also evident in both clinical groups and both pharmacological conditions (Fig. 1E; Fig. S1 A, B). Thus, the relationship between circuit dynamics and cortical hierarchy is overall robust to rapid (within-session) perturbation of synaptic transmission or protracted clinical aberrations of circuit function.

The above results replicate the finding from previous invasive recordings (*29*, *43*), that parameters of cortical dynamics (specifically, the knee frequency) reflect the cortical hierarchy. Our results go beyond previous findings in showing that the cortex-wide spatial patterns of cortical dynamics (i) are highly reproducible across independent samples obtained in separate MEG laboratories, and (ii) reflect cortical hierarchy also in patients with early-stage psychosis, indicating that the functional cortical hierarchy is overall preserved in this clinical condition.

Reproducible cortex-wide patterns of psychosis-related changes in neural dynamics

We went on to assess the spatial maps of the *differences* in dynamics parameters between CHR-P or FEP groups versus controls and between the drug versus placebo conditions. We computed the difference maps between the average maps for each of the two clinical groups (CHR-P or FEP) versus the HC group. In the following, we refer to the parameter difference maps between the clinical groups (CHR-P or FEP or both pooled) versus the HC group as "psychosis signatures". We defined the psychosis signatures in terms of the difference maps rather than the maps of raw parameters in the patient groups, to isolate the patterns specific to psychosis (the raw maps were similar across groups and largely explained by cortical hierarchy in both; Fig. S1). GABA-A and NMDA receptors (*47*, *65*, *66*) as well as the circuit dysfunctions in schizophrenia (*3*, *24*) are expressed across many cortical areas, but with heterogeneous distribution, possibly over and above the large-scale gradient determined by anatomical hierarchy. We, therefore, reasoned that the psychosis signatures of the clinical populations might exhibit characteristic large-scale spatial patterns.

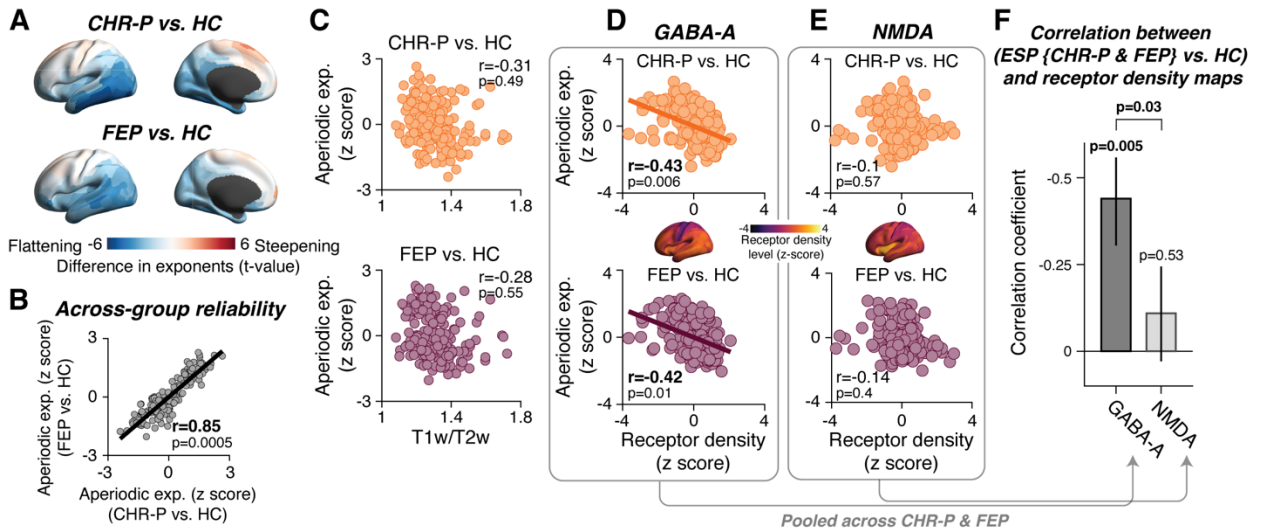

Figure 2: Reproducible large-scale pattern of psychosis signature on exponent of aperiodic activity. **(A)** Cortical distributions of the psychosis signatures on the aperiodic exponent. Psychosis signatures are computed as group-level, non-thresholded t-maps of the difference between the respective clinical group versus HC group. CHR-P: clinical high risk; FEP: first episode psychosis; HC: healthy control. **(B)** Spatial similarities of psychosis signatures on aperiodic exponent in the two clinical groups. Black line: linear fit. **(C)** Spatial similarity between the maps of psychosis signatures on aperiodic exponent and of T1w/T2w ratios. Each dot represents a single cortical area. **(D, E)** Spatial similarity of maps of psychosis signature on aperiodic exponent and maps of GABA-A (D) or NMDA (E) receptor densities (insets), separately for both clinical groups (top/orange: CHR-P; bottom/purple: FEP). Lines: linear fit. **(F)** Differences in similarity between map of psychosis signature on aperiodic exponent (pooled across CHR-P and FEP groups) and GABA-A versus NMDA receptor densities; significance of difference in correlation tested by means of two-sided permutation test. Error bars are 95% bootstrap confidence interval. Throughout, r-values are Spearman's correlation coefficients, p-values were assessed using spatial autocorrelation-preserving permutation tests. In all scatter plots, data points are cortical areas and lines are linear fits for significant correlations. Receptor density maps were taken from reference (*47*).

We show the difference maps for the aperiodic exponent in Fig. 2A and for all other parameters in Fig. S2 A-E. Exponents tended to be smaller for the clinical groups compared to the HC group in occipital, temporal, and parietal areas including the visual and auditory cortices (blue in Fig. 2A), indicating a flattening of the decay of power with frequency. This is in line with an increase in the local E/I ratio as has been postulated for schizophrenia (*12*, *23*, *24*). However, exponents in frontal cortical areas, especially around the midline, tended to be larger in the clinical groups indicating a steepening of the power decay (red in Fig. 2A), in line with some EEG results (*36*, *67*). In other words, the psychosis signature exhibited heterogeneity across cortex for the aperiodic exponent (Fig. 2A). The same was true for other parameters (Fig. S2 A-E).

Notably, the local difference scores evident in the (non-thresholded maps) of parameter changes were fairly subtle. They are assessed statistically using mass-univariate testing below (see section *Weak local effects of psychosis or pharmacology*). Here, we focused on the *spatial patterns* of parameter changes, asking whether they were meaningful and informative about underlying mechanism and clinical status.

We first tested whether these spatial patterns were (i) consistent across the two clinical groups, and (ii) related to cortical circuit architecture. The spatial patterns of parameter changes were remarkably similar between CHR-P and FEP groups (r(180)=0.85, p=0.0005; Fig. 2B). A similar consistency between the two clinical groups was observed for the maps of the psychosis-related changes in the other parameters (Fig. S2 F). This strong consistency of the spatial patterns of parameter differences between two independent datasets and groups with different clinical characteristics implies that the heterogeneity evident in the spatial patterns shown in Fig. 2A are not due to measurement noise, and stable markers of the pathophysiology of psychosis that are already detectable in the pre-diagnostic (CHR-P) stage. This observation supports our use of the term "psychosis signature" to refer to these spatial patterns.

Interestingly, for both clinical groups (FEP and CHR-P), the psychosis signatures were unrelated to anatomical hierarchy (Fig. 2C; Fig. S3 C), but instead resembled the cortical distributions of GABA-A receptor densities (Fig. 2D): Areas in which exponents tended to decrease in psychosis (blue in Fig. 2A, indicating flattening of power spectra) were areas with higher-than average GABA-A receptor densities, and conversely for areas with larger exponents (Fig. 2D). By contrast, there was no such relationship between the psychosis signature for either clinical group and NMDA receptor densities (Fig. 2E). Correspondingly, the psychosis signature was significantly more strongly correlated with the GABA-A receptor density map than with the NMDA receptor density map (Fig. 2F), although both receptor density maps, obtained from the same PET study of healthy participants (*47*), were weakly correlated with one another (r(180)= 0.24, p=0.02).

A possible explanation of the absence of correlation with NMDA receptor density maps may be a smaller across-cortex variation in the latter, compared to the GABA-A receptor density maps. This possibility is not supported by the data, because both receptor maps (insets in Fig. 2D, E) had similar statistical properties (spatial variance: GABA-A: 0.95, NMDA: 0.93; spatial autocorrelation Moran's I: GABA-A: 0.074, NMDA: 0.06; see Materials & Methods). Except for alpha power (GABA-A receptor densities vs. FEP signatures), and alpha peak frequency (NMDA receptor densities vs. CHR-P and FEP signatures), such spatial relation to GABA-A receptor density maps were not evident for the other parameters of circuit dynamics (Fig. S3 A, B). In sum, the spatial patterns of the change in the aperiodic exponent in CHR-P and FEP-groups compared to the HC group reflects the spatial distribution of GABA-A (but not NMDA) receptors in the healthy brain. This points to a role of the cortical distribution of GABAergic neuronal inhibition, and the resulting effect on local cortical excitation-inhibition ratios in early-stage psychosis.

Classification of clinical groups based on large-scale dynamics

An important issue from the perspective of biomarker development is the diagnostic value of the spatial patterns of neurophysiological markers that we analyzed here. To quantify this in a rigorous fashion, we trained multivariate pattern classifiers to predict clinical status based on the individual spatial patterns of dynamics parameters; Materials & Methods). We found above-chance classification of the clinical status of individual participants whose data were not used for training, for both comparisons (FEP vs. HC, CHR-P vs. HC; Table 1). This was true for classifiers that used the spatial patterns containing all six parameters as features, as well was for classifiers that only used the maps of changes in aperiodic exponent (as a proxy of excitation-inhibition ratio, see above), or of the aperiodic exponent and knee frequency (proxy of neural timescale; Table 1). While the

classification of CHR-P was more accurate and highly statistically significant for all combinations of features, classification of FEP was overall less accurate for all combinations and only statistically significant for the classifier based on exponent maps (marginally significant for the ones using combinations of parameter maps; Table 1). The slightly lower reliability of the FEP classifier compared to the CHR-P classifier could reflect the smaller size of the FEP sample (N=32 for FEP versus N=117 for CHR-P).

Parameter combination	**Classification problem**	**Classification accuracy (p-value)**	**Area under ROC**
Aperiodic exponent only	CHR-P vs HC	0.66 (**0.008**)	0.68
	FEP vs. HC	0.63 (**0.048)**	0.58
Aperiodic exponent & knee frequency	CHR-P vs HC	0.67 (**0.005**)	0.67
	FEP vs. HC	0.62 (0.063)	0.6
All 6 parameters	CHR-P vs HC	0.65 (**0.01**)	0.65
	FEP vs. HC	0.61 (0.07)	0.55

Table 1: Accuracy of classifying clinical groups based on patterns of dynamics parameters. Classification accuracies are cross-validated and p-values from permutation testing (see Materials & Methods for details). P-values of classification accuracies are from two-sided permutation tests across participants.

From the continuous outputs of the classifiers (see Materials & Methods), we also calculated the area under the receiver-operating curve (ROC) (*68*) that quantifies the overlap of the distributions of these classifier outputs. The resulting values can be interpreted as the probabilities that a randomly chosen individual is correctly identified as belonging to the CHR or FEP groups versus the HC group based on the classifier output, which is a useful quantification of the potential clinical utility. These values ranged between 0.55 and 0.68 for the different comparisons performed using different feature combinations (Table 1). Overall, the classification results highlight the potential utility of the here-identified psychosis signatures as part of an assay for early detection of psychosis.

Reproducible patterns of pharmacologically induced changes in neural dynamics

We next assessed whether and how the large-scale neurophysiological psychosis signatures identified above related to the changes in cortex-wide dynamics induced by pharmacological manipulations of GABA-A and NMDA receptors in healthy participants. Administration of lorazepam (GABA-A receptor stimulation) and memantine (NMDA receptor blockade) produced widespread changes in the aperiodic exponent compared to placebo. In the following, we refer to the corresponding difference maps as “drug effect maps”. Again, we show the difference maps for the aperiodic exponent in Fig. 3A and for all other parameters in Fig. S3 A-E. Like the psychosis signatures, the drug effects differed across cortical areas, with smaller exponents (blue in Fig. 3A,B) in some areas and larger exponents in other areas (red in Fig. 3A,B). Similar heterogeneity was observed for the drug effects on other dynamics parameters (Fig. S2 A-E).

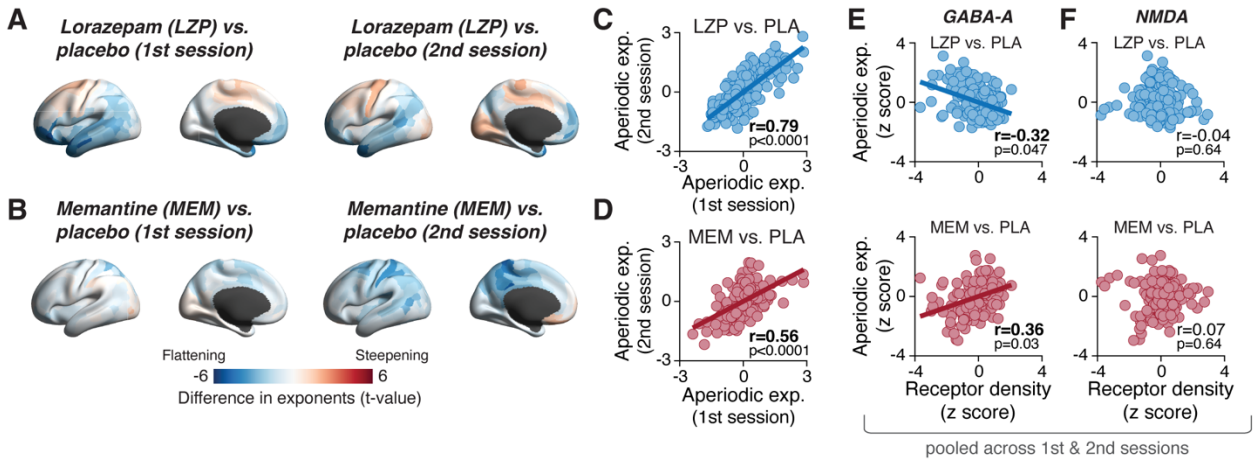

Figure 3: Reproducible large-scale patterns of drug effects on exponent of aperiodic activity. (A,B) Maps of drug effects on the aperiodic exponent (group-level, non-thresholded t-maps) for the first (left) or second (right) repetition of each drug condition across different sessions. (A), lorazepam (LZP); (B), memantine (MEM). **(C,D)** Spatial similarity of drug effects in the first versus second administration of each drug condition, a measure of test-retest reliability. (C), LZP; (D), MEM. **(E,F)** Spatial similarity of maps of drug effects on aperiodic exponent and maps of GABA-A (E) or NMDA (F) receptor densities (top/blue: LZP; bottom/red: MEM). Throughout, r-values are Spearman's correlation coefficients, p-values were assessed using spatial autocorrelation-preserving permutation tests , and lines are linear fits for significant correlations.

These drug effect maps again exhibited stable and reproducible patterns, which reflected the distribution of synaptic properties (Fig. 3C-F). The pharmacological study entailed two MEG sessions for each pharmacological condition (separated by 1 to 5 weeks). The spatial patterns of both the effects of both drugs were largely consistent across these two condition repeats for the aperiodic exponent (Fig. 3C,D) as well as on most of the other parameters (Fig. S2 G, H). Likewise, the maps of drug effects on exponent (but not the other parameters) exhibited significant spatial similarity to the map of GABA-A receptor densities (Fig. 3E), but not the map of NMDA receptor densities (Fig. 3F), with opposite signs for lorazepam and memantine effects (Fig. 3E).

These results establish the reproducibility and significance of the large-scale spatial patterns of changes in cortical dynamics induced by the two drugs. They also reveal a striking similarity in the spatial patterns of the average lorazepam effect and average psychosis signatures (e.g., compare Fig. 3A and Fig. 2A), an impression that we quantify systematically below (see section *Relating changes of neural dynamics induced by psychosis or pharmacological manipulations*).

Weak local effects of psychosis or pharmacology

Our analyses of the cortex-wide spatial patterns of changes in cortical dynamics induced by early-stage psychosis or pharmacological manipulations was motivated from the emerging understanding of the characteristic patterns of receptor expression in the healthy brain (*42*) as well as of circuit aberrations in schizophrenia (*3*). The observations that the psychosis signatures and drug effects in cortical dynamics exhibited stable and diagnostic spatial patterns across cortex further corroborated our focus on the spatial patterns. Control analyses complemented the pattern analyses by conventional mass-univariate analyses of the local changes in the parameters (Fig. 4 and Fig. S4). To boost

statistical sensitivity, we aggregated each dynamics parameter across areas before comparing between clinical groups or pharmacological conditions. We aggregated at two levels of granularity: (i) across all parcels belonging to each of 22 groups of areas (*48*) (psychosis signatures on aperiodic exponent: Fig. 4A; drug effects on aperiodic exponent: Fig. 4H; see Fig. S4 for all other parameters); and (ii) across the complete set of 180 areas, yielding a single number per parameter (psychosis signatures: Fig. 4 B-G; drug effects: Fig. 4 I-N). Few comparisons were significant (Fig. 4 and Fig. S4). Especially the clinical datasets which yielded only one single significant effect (in the paracentral lobular and mid cingulate cortex (*48*) for the area under the aperiodic curve). Bayes factors provided support for the null hypothesis (i.e., BF_{10}<1/3 (*69*)) for most comparisons in the clinical dataset (HC vs. CHR-P or FEP; AUC: BF_{10}<0.27; Hurst exponent: BF_{10}= 0.19 (CHR-P only); Alpha power: BF_{10}<0.25; Alpha frequency: BF_{10}<0.24).

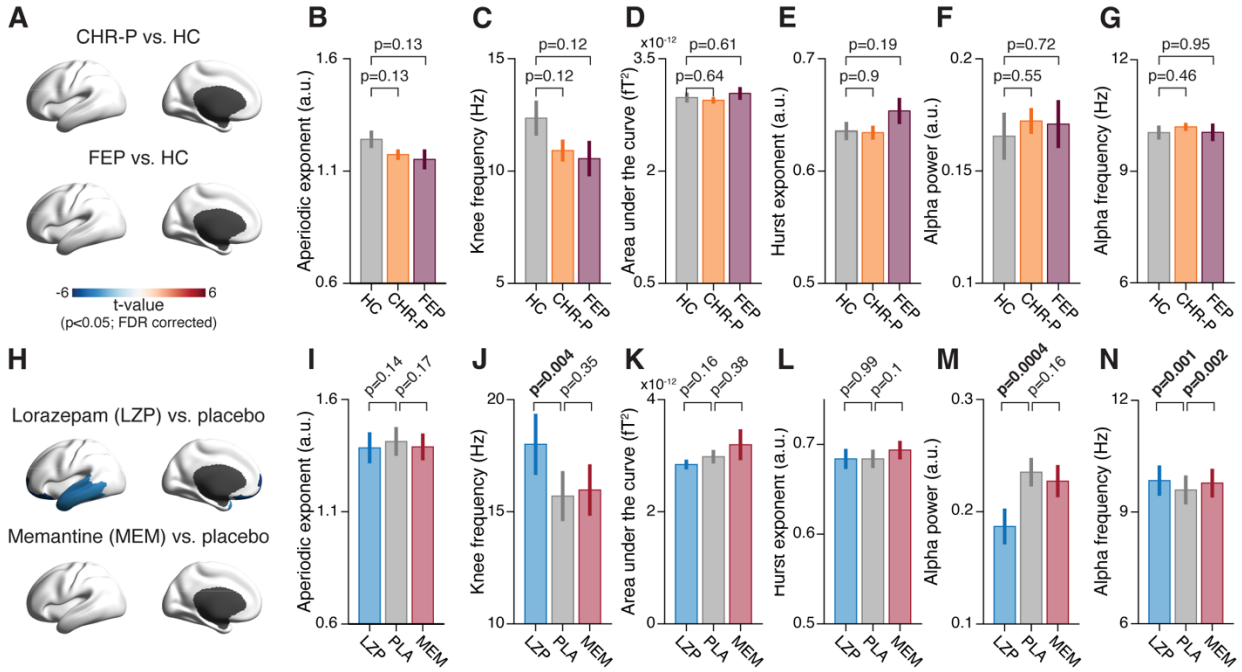

Figure 4: Weak local effects of psychosis or drugs on cortical dynamics. (A) Spatial patterns of differences in aperiodic exponents (CHR-P vs. HC or FEP vs. HC) from Fig. 2A, but after thresholding based on mass-univariate statistical tests per cortical area (t-tests, p<0.05, FDR correction). **(B-G)** Means and standard errors across all 180 parcels for healthy control (HC; grey), clinical high risk (CHR-P; orange) and first episode psychosis (FEP; purple) groups of the aperiodic exponent (B), knee frequency (C), area-under-the-curve (D), Hurst exponent (E), alpha power (F), and alpha peak frequency (G). **(H-N)** same as (A-G) for the pharmacological conditions; LZP: lorazepam (blue); PLA: placebo (grey); MEM: memantine (red). All p-values were assessed with two-sided t-tests.

In sum, the local effects of CHR-P or FEP, or of the pharmacological interventions, irrespective of their large-scale spatial patterns, were not sufficiently strong to be reliably detectable. We note that in the case of pharmacological manipulations, the strengths of these effects are under experimental control (drug dose), but in the case of psychosis they are given by the nature of the disorder (see Discussion). This implies that the spatial pattern analyses we focused on here were indeed essential to robustly identify alterations in the spontaneous brain dynamics due to psychosis, and their relation to neurotransmitter systems.

Relating changes of neural dynamics induced by psychosis or pharmacological manipulations

We went on to quantify the similarity between the large-scale spatial patterns of changes induced by psychosis (psychosis signature) and by the pharmacological interventions in healthy participants. We used two complementary approaches. The first approach used canonical correlation analysis (CCA), a multivariate statistical technique that determines the linear combinations of two sets of random variables (i.e., matrices) that maximizes the correlation between the two. Here, the random variables were the spatial maps of psychosis signatures or drug effects in the six cortical dynamics parameters defined in Fig. 1. We horizontally concatenated these spatial maps, yielding two matrices with 180 rows (areas) and six columns (parameters; Fig. 5A). The variables resulting from the linear transformations are called "canonical variables" (Fig. 5, B,C): sets of spatial maps (for psychosis signatures and drug effects), which were ordered by the fraction of co-variance explained by each pair of variables (Fig. 5C).

We performed two separate CCAs for the LZP and the MEM effects, respectively. In each case, we used a single psychosis signature pooled across the two clinical groups (CHR-P and FEP). We refer to these pooled data as "Early-stage psychosis (ESP)" for simplicity. Pooling the data across clinical groups was justified by the strong and significant similarity of the patterns for both groups shown in Fig. 2B (correlation of 0.85 for exponent) and Fig. S2F (correlations between 0.57 and 0.75 for the other parameters).

The first set of canonical variables accounted for a substantial fraction of the co-variance shared between the psychosis signature and drug effect: 48% for LZP (Fig. 4D) and 47% for MEM (Fig. 4F), each more than 10% larger than the co-variance explained by the next set of canonical variables. We, therefore, focused on the first canonical variables. These yielded a strong canonical correlation of $r(180)=0.69$ for both drug effects (Fig. 4D,F, inset). Note that only the magnitude, not the sign, of the canonical correlations were meaningful because canonical correlates are positive by construction.

The loadings of the canonical variables quantified the relative contribution of the six parameters of cortical dynamics to the canonical correlation. Under lorazepam, the loadings were the largest for the aperiodic exponent and knee frequency, each with equal sign for psychosis signature and LZP effect, (Fig. 4E), indicating that the spatial patterns of the changes of both parameters due to lorazepam and psychosis were positively correlated. This supports the visual impression that the maps of changes in exponent in both clinical groups (Fig. 2A) and under lorazepam (Fig. 3A) resembled one another. By contrast, under memantine, the aperiodic exponent had large loadings of opposite sign between drug effect and psychosis signature (Fig. 4G), indicating an anti-correlation between their respective spatial patterns, again supporting the visual impression from comparing Fig. 2A and 3B.

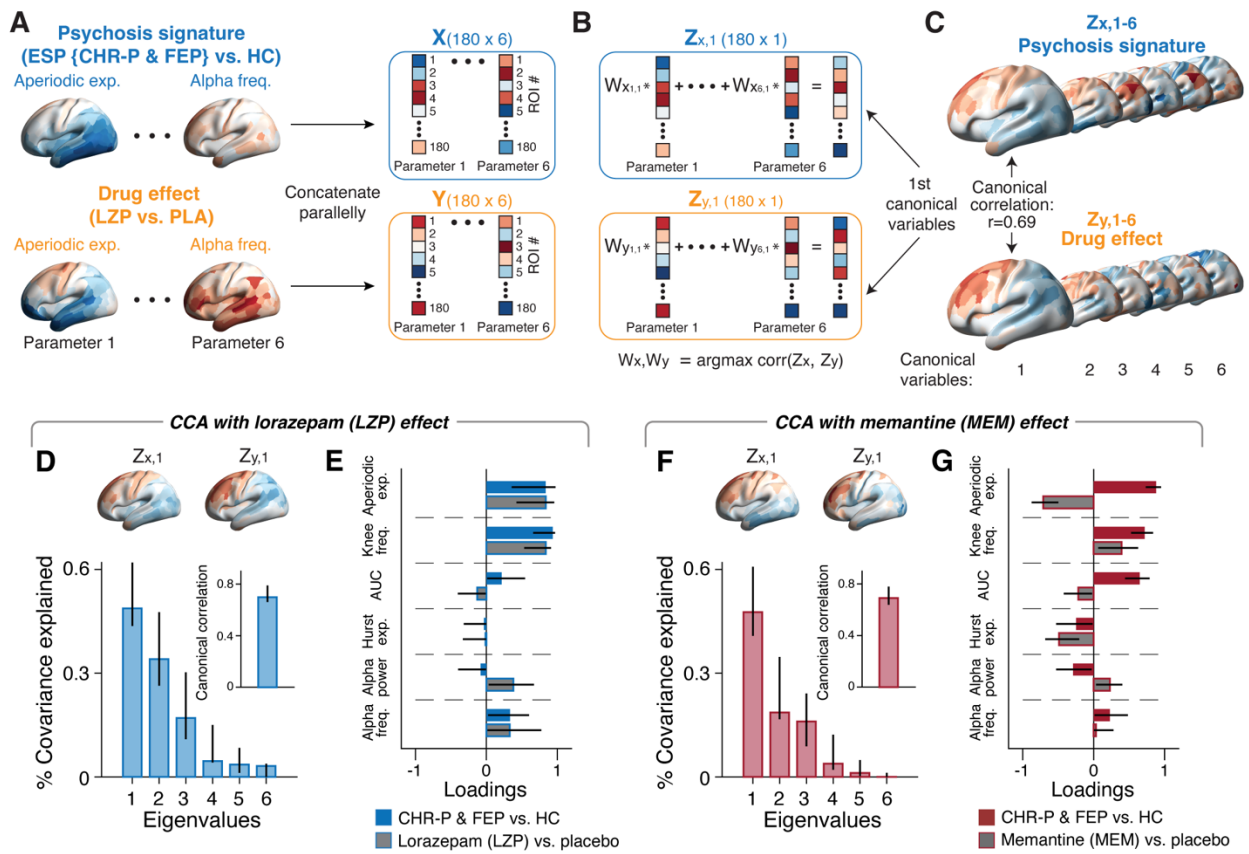

Figure 5: Exponent and knee frequency dominate similarity between psychosis signatures and drug effects. (A-C) Illustration of canonical correlation analysis (CCA) approach. **(A)** Maps of psychosis signatures (e.g., ESP vs. HC) or drug effects (e.g., lorazepam vs. placebo) on the six parameters (left) were concatenated parallelly to form two matrices (X, Y; respectively), each with 180 rows (areas) and 6 columns (parameters; right). **(B)** CC determined matrices (dimensionality: 6x6) of linear weights (W_x, W_y). Multiplication of these weight matrices with X and Y, respectively, ($Z_x = XW_x$ *and* $Z_y = YW_y$) yielded canonical variables (six column vectors of Z_x and Z_y) that maximized the spatial correlation. **(C)** Maps of canonical variables $Z_{x,i}$ and $Z_{y,i}$, i=1…6. **(D, F)** Spectra of eigenvalues quantifying the fraction of co-variance between X and Y explained by each pair of canonical variables. Insets: canonical correlation coefficients of the first canonical variables. Top: maps of the first canonical variable. **(H, I)** CCA loadings reflecting the relative contribution of each parameter to the canonical correlation. (D-E) CCA between psychosis signature (CHR-P & FEP vs. HC) and lorazepam effect (LZP vs. PLA), blue. (F-G) CCA between psychosis signature and memantine effect (MEM vs. PLA). Error bars are 95% bootstrap confidence interval.

Akin to the maps of the psychosis signatures (Fig. 2) and drug effects (Fig. 3), the maps of canonical variables were highly reproducible across independent data sets (Fig. S5). Consider the similarity of the two canonical variables between repeated sessions for a version of the LZP-CCA (Fig. S5 A). Correlations between the maps within each row are the corresponding canonical correlations, while the correlations between the canonical variable maps within each column quantify their consistency across the two clinical samples (drug effects pooled across repeats of each drug condition). We ran each CCA separately for the psychosis signature patterns in the CHR-P and FEP groups and separately for the drug effect maps in the two sessions of each drug condition. For each of the LZP -CCAs and MEM-CCAs, this yielded a total of four pairs of first canonical variables (Materials & Methods): two pairs of maps for the clinical groups times two pairs of maps for the session

repeats. These maps exhibited substantial spatial similarities (r(180)≥0.28), most (21/24) of which were statistically significant after spatial autocorrelation-preserving permutation tests (Fig. S5 E,F).

The loading patterns were, likewise, reasonably consistent across independent data sets, albeit less so than the maps of canonical variables. Fig. S5C,D show their similarity across the two clinical samples (drug effects pooled across repeats of each drug condition), with high and significant correlations for the LZP-CCA (not the MEM-CCA). Many correlations of the loading patterns across the different repeats of CCAs were statistically significant (13/24; 2 further marginally significant at p=0.06), but more consistently for LZP than for MEM (Fig. S5 G,H).

Taken together, the CCA approach established substantial large-scale pattern similarity between the psychosis signatures of the CHR-P and FEP-groups on the one hand and drug effects on the other hand. These similarities were consistent across two clinical groups and two separate experimental sessions in healthy participants several weeks apart. The approach also uncovered the relative contribution of the six dynamics parameters to this pattern similarity, highlighting the contributions of the exponent and knee frequencies of the aperiodic activity components.

Individual differences in similarity levels account for clinical symptoms

CCA is a principled approach to relating multivariate sets of spatial patterns that here shed first light on the spatial similarity relationships between psychosis signatures and drug effects as well as the dynamics parameters driving those similarities. However, its current application had two limitations: it required (i) a focus on the relationships captured by a subset (in our case the first) of the canonical variables, and (ii) averaging the psychosis signatures across the groups of participants. We reasoned that the latter limitation may be important with respect to psychosis, a condition known to exhibit considerable inter-individual variability, at the genetic and molecular levels (*61*) as well as at the level of circuit function (*3*). In other words, different patients diagnosed with, or at risk of developing psychosis might exhibit distinct spatial "fingerprints" (i.e., diagnostic spatial patterns) of neurotransmitter alterations.

We, therefore, devised a second approach that enabled us to also assess the inter-patient variability in the pattern similarities between their individual effects (compared to the group average HC maps) and the effects of the pharmacological interventions in healthy participants (Fig. 6). Here, we concatenated all parameters vertically, yielding a single column vector (u_{scz}), and for each drug effect (v_{LZP} and v_{MEM}). We computed $u_{individual}$ as the difference between each individual parameter map from the CHR-P and FEP groups and the corresponding group average parameter maps for the HC group, yielding individual psychosis signatures for each participant from the clinical groups. As a common reference, v_{LZP} and v_{MEM} were computed by pooling the data of all healthy participants from the pharmacological study (group-average drug effect). We then computed the similarity between individual psychosis signatures and the group average LZP or MEM effects (Fig. 6A).

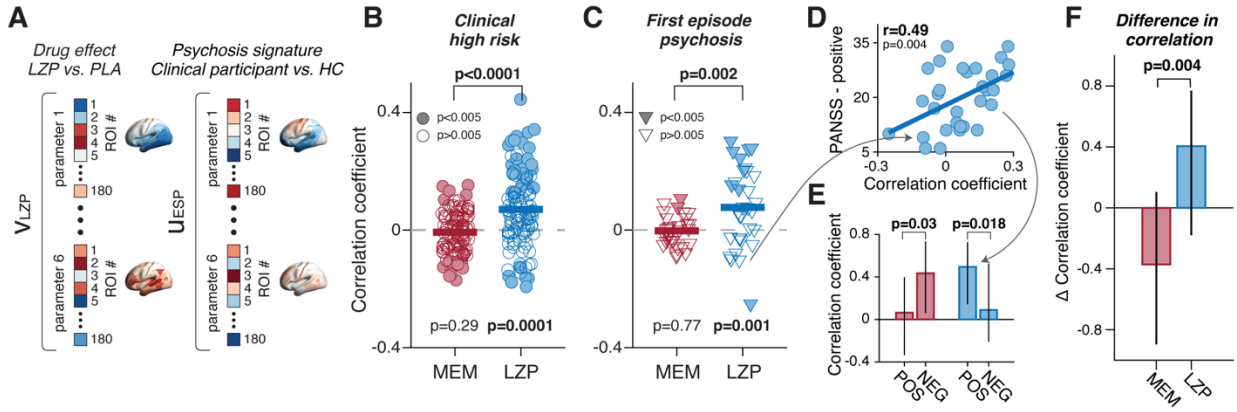

Figure 6: Individual differences of pattern similarities to drug effects relate to clinical symptoms. (A) Illustration of approach for individual difference analysis. Maps of the drug effect or psychosis signature (each of which were column vectors with 180 elements) on the complete set of six parameters were concatenated vertically to form "hyper-vectors" with 1080 elements (6 parameters x 180 areas). **(B)** Spatial similarity between group-average drug effects and individual psychosis signatures (CHR-P vs. HC average). Each dot represents the level of pattern similarity for a single patient and a given drug effect (LZP or MEM). Filled symbols, individual patients with statistically significant pattern similarity with a given drug effect. **(C)** same as (B) for individual psychosis signature of first episode psychosis patient (FEP vs. HC average). **(D)** Correlation between individual pattern similarity levels from panel (C) and a clinical summary score (so-called PANSS positive scores). The symptom score was obtained only from FEP patients. **(E)** Correlation between the individual spatial similarities from B and PANSS negative/positive scores, for memantine (red) and lorazepam (blue). **(E)** Comparison of the differences between correlations for positive and negative symptoms between drug conditions. The corresponding p-value tests for the significance of this comparison quantifies a double dissociation (factors: drug and symptom dimension). All p-values were assessed with two-sided permutation tests (corrected for spatial autocorrelation in (B)). Error bars are 95% bootstrap confidence interval.

As expected, this approach revealed substantial variability across both groups in terms of the similarity levels of individual psychosis signatures with the drug effects (Fig. 6B, C). For both LZP and MEM reference patterns, we found statistically significant similarities (correlations) for several individuals from both clinical groups of opposite signs (Fig. 6B, C; filled symbols above and below 0). For the MEM reference pattern, however, a comparable number of patients exhibited positive or negative correlations. When pooling the individual correlations across the CHR-P and FEP groups (based on their high similarity, Fig. 2C), the group average correlation coefficient that was indistinguishable from zero (r(1080)=-0.006; p=0.28; see Fig. 6B,C for separate tests for each clinical group). By contrast, the individual LZP similarities were mostly positive and yielding a significantly positive group average correlation, both pooled across CHR-P and FEP (r(1080)=0.07; p=0.002), as well as for each clinical group individually (Fig. 6B,C). The results indicate that individual psychosis signatures contained two components that were both spatially and neurochemically separable: one that was related to GABAergic inhibition and reasonably consistent across participants; and another, less consistent one, that was related to glutamatergic excitation via NMDA receptors.

The large variability in the expression of both components was related to individual clinical symptoms in the FEP group (Fig. 6 D-F). In the FEP group, clinical symptoms were assessed in terms of the Positive and Negative Symptoms Scale (PANSS; (*70*)). We correlated the individual similarities

for each drug pattern from Fig. 6C with either the aggregate scores of positive or negative symptoms (Materials & Methods). This revealed distinct symptom-correlates of the spatial similarities to the LZP and MEM effects: MEM similarities were positively correlated with the strength negative symptoms ($r(32)=0.45$, $p=0.007$) while LZP similarities were positively correlated with the expression positive symptoms ($r(32)=0.5$, $p=0.004$). The differences in correlation with positive and negative scores for MEM and LZP, respectively, was highly significant effect ($p=0.004$; Fig. 6F), demonstrating the specificity of these effects. In other words, FEP patients whose spatial patterns of alteration in cortical dynamics exhibited larger similarity to the changes by a boost of GABA-A transmission exhibited more severe positive symptoms, and patients with stronger similarity to changes induced by NMDA-R blockade exhibited more severe negative symptoms.

Discussion

The cerebral cortex constantly generates a rich repertoire of dynamical activity patterns, such as band-limited oscillations and aperiodic activity, which have been suggested as potential biomarkers for neuropsychiatric disorders (*11*, *23*, *24*, *28*, *30*, *71*). Recent work on the large-scale distribution of cortical microcircuit properties, such as cytoarchitectural type or receptor gene expression, identified substantial spatial heterogeneity in these parameters across cortical areas and cortical hierarchy as one overarching organizing principle (*17*, *42*). Here, we integrate these different bodies of work by leveraging the high spatio-temporal resolution and cortex-wide spatial coverage afforded by MEG source imaging (*33*) and combining the latter with state-of-the-art anatomical atlases (*48*) and pattern analyses.

We characterized large-scale cortical patterns of changes in several parameters of cortical dynamics in early-stage psychosis (psychosis signatures) and related those to the patterns of receptor densities as well as to the patterns of changes in the same dynamics parameters induced by pharmacological manipulations of GABA-A or NMDA receptors (lorazepam versus memantine) in healthy individuals. We defined the correlations between the psychosis signatures and the maps of GABA-A or NMDA manipulation effects in the healthy brain as the strength in the psychosis signatures of the "GABA-A component" or of the "NMDA component", respectively. For both clinical groups, we found a robust similarity between the group average psychosis signatures and the cortical distribution of GABA-A receptor densities, but no such relationship to NMDA receptor densities. Notably, in first-episode psychosis patients, we also observed a double dissociation in the correlation between individual symptoms and the strengths of the GABA-A component versus the NMDA component: The expression of the GABA-A (lorazepam) component was related to the strength of their positive (not negative) symptoms, while, the expression of the NMDA (memantine) component was related to the negative (not positive) symptoms. The observations that (i) the psychosis signatures were unrelated to NMDA receptor densities, (ii) less consistently expressed the pharmacologically defined "NMDA component" across different clinical participants, and (iii) that these "NMDA component" expressions were unrelated to positive symptoms may all be surprising in light of the so-called "ketamine model" of psychosis (*72–75*). Even so, the large inter-individual variability in the expression of that NMDA component we observed was systematically related to (negative) clinical symptomatology.

Neurotransmitter basis of psychosis signatures and symptoms

Taken together, our results support the idea that both neurotransmitter systems are involved in the pathophysiology of psychotic disorders (*76*), but contribute in distinct ways to positive and negative symptoms. Considerable evidence implicates GABAergic cortical inhibition (*8*) as well as NMDA receptors (*11*, *12*, *23*, *77*) in psychotic disorders, in particular early-stage psychosis (*78*). The observation of a lack of relationship between the *patient-average* pattern of psychosis signature on cortical dynamics to either the NMDA receptor density levels or to the effect of NMDA-receptor manipulation in healthy participants, may appear as inconsistent with a strong involvement of NMDA receptors. One possible explanation for this lack of correlation for our analyses of resting-state activity is that the alterations in circuit dynamics due to NMDA hypofunction in psychosis are more strongly and consistently expressed during effortful cognitive processes that recruit synaptic reverberation via NMDA-receptors (*12*, *14*, *77*)(but see (*78*)). This possibility should be tested in future work applying a similar approach to MEG obtained during performance of tasks involving working memory or evidence accumulation for decision-making.

Ketamine, an NMDA receptor antagonist with a mechanism of action resembling the one of memantine (*79*) has strong effects on the aperiodic exponent at high (*80*), but not low (*81*) dosage. At subanesthetic levels, it can produce symptoms in healthy participants that resemble symptoms of psychosis (*72–75*). Memantine effects on cortical dynamics (specifically, aperiodic exponent) also increases with dosage (*36*). We used memantine instead of ketamine and a low dosage because (i) memantine and ketamine have analogous mechanisms of action on NMDA receptors (*82*), (ii) the oral administration of memantine matches the one of lorazepam, improving the blinding in our within-participants intervention, and (iii) low dosage help to minimize non-specific secondary effects (*82*).

The inter-individual differences in similarity levels to NMDA- versus GABA-A neurotransmitter manipulations have implications for individualized approaches in psychiatry research and clinical practice. Our approach affords mapping the MEG signature of each individual patient on two axes of similarity (GABA-A and NMDA effects), in an objective and quantitative manner. The fact that these axes are obtained by comparison with controlled manipulations of two well-defined receptor types that have been implicated in the pathogenesis of psychosis implies the resulting values are mechanistically grounded. Our finding that these inter-individual differences also explained substantial fractions of inter-individual variability in distinct symptom classes means that the resulting values are also clinically meaningful. We, therefore, propose that our approach provides a useful basis for the stratification of patient cohorts in future research of psychosis or related neuropsychiatric disorders.

Local effects versus spatial patterns

We found only weak local differences in cortical dynamics parameters under either pharmacological manipulation of GABA-A and NMDA receptors or in clinical groups compared to healthy controls. The strengths of pharmacological effects will scale with the drug doses, which were low in our study, to minimize secondary and side effects and maximize specificity of effects for the receptors with highest affinity. However, the local expression strengths of the psychosis signatures are unlikely to change substantially between different patient samples. This highlights the importance

of our approach focusing on spatial pattern similarity, and specifically the similarity of the *difference patterns* (patients versus controls) for picking up locally subtle, but spatially highly consistent, reproducible, and clinically relevant features of large-scale cortical dynamics. The observations that the large-scale patterns of these psychosis signatures and drug effects were (i) highly reproducible across independent datasets and (ii) reflected an important synaptic feature of brain organization, the cortex-wide distribution of GABA-A receptor densities, establish that these patterns are genuine and meaningful.

Our approach was inspired by insights from multivariate pattern analyses of mental representations in neuroimaging (*83*, *84*). Conventional mass-univariate approaches were designed to detect differences in the activity of individual sources (e.g., fMRI voxels) between conditions. Such local differences, while robust for coarsely defined conditions (e.g., high versus low cognitive load), are often too subtle for discriminating between conditions differing only in specific stimulus or cognitive variables (*83*, *84*). Detection of small effects at the level of single sources is limited by the multiple-comparisons problem associated with mass-univariate statistical tests (*84*). By combining the information contained in many such small, but systematic, local effects, multivariate pattern analyses boost sensitivity(*85*, *86*). Spatial pattern correlations similar to ours, just operating at the level of within-area voxel patterns, are at the heart of state-of-the-art representational similarity analyses (*87*) . While guided by the same methodological insights, our current approach is designed for a different purpose: identifying and explicitly relating large-scale patterns of changes in cortical dynamics induced by pharmacological interventions or brain disorders.

Relationship to previous work on cortical dynamics

Several previous studies in schizophrenia have investigated the EEG or MEG markers that were part of our six-parameter assay, which mixed results (*35–41*, *67*, *88*, *89*) These studies have commonly focused on a single parameter of cortical population activity (e.g., aperiodic exponent), or a small subset of them. None of these previous studies has comprehensively quantified the cortex-wide patterns of psychosis-related alternations of multiple dynamic parameters in source space, as we did here. This pattern analysis was critical for identifying the relationship between the neurophysiological psychosis signatures to neurotransmitter systems and symptoms in the current work.

A large body of work has demonstrated psychosis-related aberrations of neuronal responses in the gamma-band (*24*, *55*), which are, in turn, generated by excitatory-inhibitory synaptic interactions within cortical microcircuits (*34*, *62*, *63*, *90*). We here focused on alpha- rather than gamma-band oscillations for the quantification of periodic components of local cortical dynamics. This choice was pragmatic, because our approach relied on across-area patterns, and alpha peaks were more consistently detected across cortical areas in the resting-state data analyzed here. Under conditions of strong external (stimulus and/or task) drive of local cortical circuits, gamma-band responses will be more prominent (*34*), and future applications of our approach to such data may also utilize gamma-band oscillations. That said, the alpha-band oscillations used here are likely to provide relevant information complementary to the information caried by parameters describing the aperiodic activity components, for example due to a contribution of thalamocortical interactions to the generation of cortical alpha-band oscillations (*91*).

We replicated the observation from previous work (*29*, *45*, *92*, *93*), that the spatial patterns of cortical dynamics parameters followed the anatomical hierarchy (*42*) which, in turn, has been identified as an important organizing principle that accounts for a large fraction of variation in gene-expression and microcircuit architecture across the cortex (*17*, *42*). We extended this finding in two important ways. First, we show that this relationship is preserved in early-stage psychosis as well as under pharmacological manipulations of NMDA and GABA-A receptors. Second, and importantly, we also show that the psychosis signatures were only weakly associated with anatomical hierarchy but strongly associated with GABA-A receptor density levels as well as the maps of pharmacological manipulation effects. This points to the presence of other principles of large-scale brain organization beyond anatomical hierarchy (*94*, *95*), which may be important for understanding the pathophysiology of psychotic disorders.

Signatures versus causal mechanisms of psychosis

Does the multi-parametric psychosis signature that we identified directly *generate* the symptoms of psychosis? We consider it unlikely that emergent features of neural mass activity, such as oscillations (*34*) or long-range temporal correlations (*30*) are directly used in the neural computations underlying behavior (*96*). The same will hold for the relationship between changes of such MEG markers on the one hand and disorders of cognition on the other hand. However, we think that at least a subset of the parameters we assessed here are, in turn, directly produced by the microscopic features of cortical circuits that also give rise to psychosis, such as the strength of recurrent excitation and/or inhibition in the network, an assumption supported by the here-established link to the neurotransmitter systems involved intracortical recurrent excitation and inhibition. In other words, changes of these circuit properties are likely to be a common cause of both, MEG markers and clinical symptoms. This highlights the importance of our theory-guided selection of the parameters of the current assay: features of neural mass action that are more remote from the intracortical circuit mechanisms generating psychosis (e.g., phase-locked components of stimulus responses; (*34*)) may be less useful for identifying psychosis signatures that relate to large-scale cortical neurotransmitter distribution and function. An important avenue for further research will be to convert the current multi-parameter maps into maps of the underlying (microscopic) circuit parameters, the alterations of which directly generate the symptoms of psychosis by means of biophysical model fitting (*31*).

Regardless of causality our results indicate that the large-scale neurophysiological signatures of early-stage psychosis we identified here (in part) reflect alterations in GABA-A or NMDA receptor functions and relate to individual symptomatology. Our results corroborate the notion that the pathophysiology of psychosis is fundamentally distributed across the brain and establish a foundation for a mechanistically informed stratification of early-stage psychosis cohorts as well as biomarker development.

Materials &Methods

We analyzed resting-state MEG data sets collected in two separate studies: (i) a study (*53*) comparing CHR-P participants, FEPs versus healthy controls; and (ii) a pharmacological study(*54*) in young and healthy participants with double-blind and placebo-controlled manipulations of GABA-A or NMDA receptors, respectively.

Participants and informed consent

Clinical dataset

Three groups of participants were recruited to the study. One group included participants who met CHR-P criteria (N=117, mean age: 22 y, range: 16-24 y, 83 females), based on the Comprehensive Assessment of At-Risk Mental State interview (CAARMS) (*97*), and the Cognitive-Perspective Basic Symptoms (COGDIS/COPPER) item of the Schizophrenia Proneness Instrument (SPI-A) (*98*). Exclusion criteria included diagnosis of Axis I psychotic disorders, including affective psychosis, as evaluated by the Structured Clinical Interview for the Diagnostic and Statistical Manual of Mental Disorders-IV (SCID). In addition, an FEP-group (N=32, mean age: 24 y, range: 18-34 y, 12 females) was recruited, for which clinical symptoms were assessed in terms of the Positive and Negative Symptoms Scale (PANSS; (*70*)).

The control group for both above clinical groups was a sample of age- and gender- matched healthy controls (HC; N=45, mean age = 23 y, range: 18-32 y, 31 females), who were screened for psychopathology using the SCID or the MINI-SCIS interview. The HC group was matched by age to the two other group (HC vs. FEP and CHR-P combined: p=0.48, two-sided permutation test), but not by years of education (HC: 16.8 y; CHR-P and FEP combined: 15.1 y; p=0.002, two-sided permutation test). There was a similar percentage of females in the HC and in the combined clinical sample (68.8% and 63%, respectively; p=0.47; Chi-square test). The three groups of participants were recruited as part of the Youth Mental Health Risk and Resilience (YouR) study (see (*53*) for more information about subjects' recruitment, exclusion criteria and experimental procedures), which was approved by the NHS Research Ethical Committee Glasgow. All participants provided written informed consent and received remuneration of 36 £. We excluded 3 participants (all from the CHR-P group) due to excessive artifacts in MEG signals.

Pharmacological dataset

We recruited 23 healthy participants (mean age: 28 y, range: 21-40 y; 9 females) to the study. Exclusion criteria included: impaired vision or hearing, illegal drug use, regular medication intake, consumption of more than 15 units of alcohol per week, known hypersensitivity to Memantine or Lorazepam, past or current psychiatric or neurological diagnosis, cardiovascular, liver, kidney or metabolic diseases, pregnancy, and non-removable metallic parts (e.g., insulin pump, retainer). We excluded one participant after detecting excessive metal artifacts in the MEG signal, and two participants dropped out before completing all experimental sessions. Participants received remuneration of 15€ for the training session, 100€ for each MEG session, 150€ as a completion bonus, 10€ for MRI session, and a performance-dependent bonus of a maximum of 150€. The study was

approved by the ethics committee of the Hamburg Medical Association, and all participants provided written informed consent.

Experimental design

Clinical dataset

The three groups of participants (CHR-P, FEP and matched controls) completed one MEG session (~ 3.5 h long) followed by one MRS/MRI session (~2.5 h). Among other tasks in the MEG (*53*, *99*), participants completed a 5 min block of resting state recording with eyes open (fixation of a central cross on an otherwise gray screen). Participants were instructed to keep fixation at a plus sign in the center of a gray screen and keep a blank state of mind as well as possible, (i.e., do not think of anything in particular and if a thought comes up, do not follow up on it).

Pharmacological dataset

Participants completed one training session (outside the MEG) followed by six MEG sessions, interleaved by at least one week. Each MEG session started with the intake of a pill (Lorazepam, Memantine or placebo; see 'Pharmacological manipulation' subsection), followed by a 150 min waiting period before MEG recording. In the MEG, participants performed several different tasks, lasting approximately 2.5 h. This included a 10 min block of resting state recording with eyes open (fixation of a central cross on an otherwise gray screen). This resting state recoding took place at the end of the session, around 4.5 h after drug intake. During the block, participants seated quietly with their eyes open, and asked to maintain fixation at a centrally presented black cross against a grey background throughout the block.

We orally administered lorazepam or memantine, in a double blind, placebo-controlled and a cross-over design. Each drug was given twice, in two different experimental sessions, in addition to two placebo sessions. Lorazepam is a GABA-A receptor agonist that boosts GABAergic neurotransmitters. Memantine is a NMDA receptor antagonist that decreases glutamatergic neurotransmitter. We choose sub-clinically dosage for the drugs: 1 mg for lorazepam (common clinical daily use between 0.5 and 2mg) and 15 mg for memantine (common clinical dose: 20 mg). Peak plasma concentration for lorazepam is 2-3 h, and 3 to 8 h for memantine. Thus, we administered the drugs 3 h before MEG session started (2.5 h waiting period plus 30 min preparation time before MEG recording), to maximize plasma concentration levels. To allow plasma concentration level to return to normal, experimental sessions were interleaved by at least one week (plasma half-life of lorazepam is ~13 h, and of memantine is 60-70 h; Table 2).

Subject ID	Sess 1	Sess 2	Sess 3	Sess 4	Sess 5	Sess 6
S01	MEM	LZP (5)	LZP (1)	PLA (2)	MEM (1)	PLA (5)
S02	MEM	LZP (5)	MEM (1)	PLA (2)	LZP (8)	PLA (1)
S03	LZP	MEM (1)	PLA (1)	LZP (1)	MEM (1)	PLA (1)
S04	PLA	LZP (5)	LZP (1)	MEM (1)	PLA (1)	MEM (1)
S05	PLA	LZP (1)	LZP (1)	PLA (1)	PLA (3)	PLA (1)
S06	LZP	MEM (1)	PLA (1)	MEM (1)	LZP (1)	PLA (1)
S07	MEM	LZP (4)	LZP (1)	PLA (1)	PLA (1)	MEM (1)
S08	LZP	PLA (7)	PLA (1)	MEM (5)	LZP (1)	MEM (1)
S09	LZP	PLA (5)	PLA (1)	MEM (1)	MEM (1)	LZP (1)
S10	MEM	LZP (5)	PLA (1)	LZP (1)	MEM (1)	PLA (1)
S11	LZP	MEM (6)	MEM (1)	PLA (1)	PLA (1)	LZP (1)
S12	PLA	LZP (5)	MEM (1)	PLA (1)	MEM (1)	LZP (1)
S13	MEM	PLA (1)	LZP (1)	PLA (1)	MEM (3)	LZP (1)
S14	PLA	MEM (1)	LZP (2)	PLA (1)	LZP (2)	MEM (1)
S15	LZP	MEM (1)	PLA (2)	LZP (1)	PLA (3)	MEM (1)
S16	MEM	resting state data missing	PLA (2)	LZP (1)	MEM (3)	LZP (1)
S17	MEM	LZP (1)	LZP (6)	PLA (1)	MEM (1)	PLA (2)
S18	MEM	PLA (1)	LZP (1)	MEM (1)	LZP (1)	PLA (2)
S19	PLA	MEM (1)	PLA (1)	LZP (1)	LZP (3)	MEM (1)
S20	PLA	MEM (3)	MEM (1)	PLA (1)	LZP (1)	LZP (1)

Table 2: Time course of pharmacological design. Each row shows the order of pharmacological conditions per subjects. Numbers in parenthesis are times (in weeks) from last session. PLA: placebo, LZP: lorazepam, MEM: memantine.

Data acquisition

Clinical data

MEG: MEG data was collected at the Center for Cognitive Neuroscience at University of Glasgow, using 248 channels 4D-BTI system (4D-Neuroimaging, San Diego), at a sampling rate of 1017.25Hz. Online low-pass filter was applied at 400Hz.

MRI: T1- Weighted data was obtained from 178 out of 191 participants included in the final analyses reported here, using a 3T Siemens Magnetom Trio MRI scanner at the Center for Cognitive Neuroscience at University of Glasgow with the following parameters: 192 slices, voxel size = 1x1x1 mm^3, FoV= 256x256x176 mm^3, TR=2250 ms, TE=2.6 ms, flip angle = 9°.

Pharmacological data

MEG: MEG data was collected at the Department of Neurophysiology at University Medical Center Hamburg-Eppendorf using a CTF MEG system with 275 gradiometers, and a sampling rate of 1200Hz. Participants were seated in a dark and magnetically shielded room and were asked to

minimize head movements. We monitored and recorded head positions continuously, using three fiducial coils, placed on participants' ear canals and nasal bridge. Additionally, we recorded ECG, and vertical and horizontal EOG using Ag-AgCl bipolar electrodes with a sampling rate of 1200Hz. Eye movements were recorded using EyeLink 1000 system, with a sampling rate of 1000Hz. We calibrated gaze positions at the beginning of the block.

MRI: T1-weighted images were obtained from all participants using a 3T Siemens Magnetom Trio MRI scanner (Siemens Medical Systems, Erlangen, Germany) and the following parameters: voxel size = 1x1x1 mm^3, TR=2300 ms, TE=2.98 ms, FoV= 256 mm, slice thickness = 1mm, TI= 1100 ms, flip angle = 9°.

MEG data analysis

We analyzed both datasets (pharmacological and clinical) using the same procedures, with several adjustments due to differences in the acquisition protocols. Unless stated otherwise, the following refers to both datasets. We analyzed MEG data using customized code from Fieldtrip toolbox(*100*) in MATLAB (MathWorks), and MNE(*101*) and pymeg (https://github.com/DonnerLab/pymeg) toolboxes in Python. We preprocessed MRI scans using FreeSurfer.

Preprocessing. Preprocessing of MEG data included three steps. The first step detected MEG artifacts to be rejected from the signal before applying independent component analysis (ICA; second step), to avoid extreme values affecting the ICA. The third step rejected data segments containing previously identified artifacts and removed ICA components from the remaining continuous data. Each step applied different high-pass filters with cutoffs adapted the respective purpose. Hence, each step started from the raw unfiltered data.

The first step identified segments containing head movements, muscle contractions, squid jumps, or metal artifacts. Continuous MEG and external electrodes (ECG) were down-sampled to 400Hz, and band-pass filtered to remove powerline noise at 50 Hz, 100 Hz and 150 Hz (two pass Butterworth filter; band stop frequencies: ±1Hz around each frequency). We detected muscle artifacts by band-pass filtering MEG signals between 110Hz to 140 Hz and z-scoring; values exceeding z=10 were labeled as muscle artifacts. Head movements (only for pharmacological dataset; continuous monitoring of head movements was not done in the clinical dataset) were detected as deviation of any coil more than 6mm from the template head position. Squid jumps were detected by fitting a line to the log power spectrum of individual artificial trials (7 s long) and detected outliers of its intercept. Finally, metal artifacts (e.g., cars passing near the building), were detected as samples exceeding a threshold of ± 5 pT.

In a second step, the raw MEG data was high-pass filtered at 1 Hz, and segments containing squid jumps, head movements and metal artifacts were rejected, to avoid extreme values during ICA. We then applied ICA using the infomax algorithm as implemented in MATLAB) and manually identified components containing eye movements (i.e., blinks and saccades) and heart beats.

In a third step, we resampled the raw data and removed power line noise, using the same parameters described above for the first step, high-pass filtered the data at 0.1 Hz (Butterworth filter) and removed previously identified ICA components or rejected data segments previously identified as

containing artifacts (muscle contractions, head movements, metal artifacts and squid jumps), respectively. We did not reject segments containing eye movement-related activity (blinks or saccades), but rather removed ICA components containing these artefacts. This was done to match the pre-processing steps between the two datasets, where the clinical dataset did not include any monitoring of eye-movements (e.g., neither EOG nor eye-tracking data).

In total, our procedure led to the rejection of 13% of data segments in the clinical dataset, and 26% of data segments in the pharmacological dataset, resulting in time series with duration of 262 sec ± 36 sec (mean and s.d across subjects) or 437 sec ± 56 sec (mean and s.d across subjects), respectively.

Source reconstruction. We used linearly constrained minimum variance (LCMV) beamforming to project broadband sensor-level signals into the cortical source space. We constructed a three-layer head model (inner skull, outer skull and skin) for each subject based on their individual MRI scan. In cases where an MRI scan was missing, we used the FreeSurfer fsaverage to reconstruct a template head model. We aligned the head model to MEG data by computing a transformation matrix, using the mean coils positions across the resting state block (for pharmacological dataset), or a fixed coils positions measured at the beginning of the block (for clinical dataset) and the corresponding locations of fiducial coils on the individual head model. We then used the individual MRI scan and FreeSurfer to reconstruct cortical surfaces and parcellate the cortex into 360 parcels, using the anatomical atlas from Glasser and colleagues (*48*). Based on the head model, we generated a forward model ("leadfields") for the computation of LCMV filters, that was confined to the cortical sheet (4098 vertices per hemisphere, recursively subdivided octahedron). For each vertex, a set of LCMV filters (one per cardinal orientation) were computed by combining the leadfield matrices of that vertex with a covariance matrix of the sensor-level signal. For each vertex, we chose the source orientation with the maximum source power using LCMV filters. We projected the time series through the LCMV filters into source space and collapsed the data across all vertices within each parcel. This resulted in 360 time series, one for each parcel, of source-level broadband data.

Quantification of local cortical circuit dynamics. We estimated power spectral density (PSD) by dividing the time series of each parcel into 10sec epochs, with 50% overlap, transforming each epoch into the frequency domain using the Fourier transform, and averaging the absolute values of Fourier coefficients across all epochs. This resulted in PSDs with a frequency resolution of 0.1 Hz. We smoothed the PSD at 50Hz, 100Hz and 150Hz using linear interpolation (±2 Hz around each frequency) since activity at those frequencies was filtered during preprocessing. We fitted the FOOOF model (*58*) to each PSD in a range between 1-65 Hz, to avoid the noise floor at higher frequencies (*102*), and included a knee parameter, based on a visual inspection of the PSDs. If the algorithm failed to fit the model or returned a negative knee frequency, we re-fitted the model without the knee parameter. Additional fitting parameters were as follows: peak threshold: 2 standard deviations, peak limit: [2 16] Hz. We extracted from the model the aperiodic exponent, knee frequency (if fitted, otherwise a NaN was assigned), alpha power and its peak frequency. Alpha power is computed as the difference in power between the fitted periodic and aperiodic components, at its peak frequency reported in arbitrary units. We noticed that in some cases multiple peaks within the frequency range from 7 to 13 Hz were detected by the algorithm. To identify alpha peak more accurately, we constrained the range of searching by first fitting the model to the mean PSD across V1 and early visual cortex (V2-V4), where alpha activity is the strongest and extracted a single

alpha peak frequency and its bandwidth, after visually verifying it is indeed in the alpha range. We used this frequency and its bandwidth (± 2 Hz) to constrain the range of searching for alpha peaks in all other parcels. If still more than one peak was identified within this range, we chose the one with the highest power. In rare cases, no alpha peak could be detected from the visual cortex. In such events, we selected the peak with the highest power within the traditional alpha range of 7-13 Hz. If no peaks were detected whatsoever, we treated those as missing values (i.e., NaNs) for all further analysis. We computed the area under the curve from the aperiodic fit of the PSD, by summing the power between 1-65 Hz. The Hurst exponent of spontaneous fluctuations of amplitude envelopes in the alpha-band oscillations was computed as in (*30*). In brief, we used Detrended Fluctuation Analysis (DFA), as implemented in NBT toolbox (Neurophysiological Biomarker Toolbox: https://github.com/NBT-Analytics/NBTpublic), with the following parameters: filter range: 8-13Hz (order 100 FIR filter), calculating range: 1-120 s (50% overlap) and fitting range: 3-50 s. Importantly, the six dynamics parameters extracted here were not correlated by construction. Such trivial correlations exist, for example, for the exponent and intercept of the aperiodic component. Our parameter selection ensured that any (across-area) correlations between parameters identified in the data were meaningful and interpretable in terms of underlying mechanism or shared organizational principles (such as anatomical hierarchy).

Receptor density maps

We used the publicly available volumetric PET images from (*47*) . We used the group averaged PET images of two neurotransmitter receptors: GABA-A and NMDA. PET images were registered into the MNI template and then parceled into 360 parcels according to the above-mentioned parcellation (*48*), and then z-scored across parcels.

Canonical correlation analysis (CCA)

We used CCA to relate the psychosis signature on the cortical patterns of the six dynamics parameters to the matching drug effect on them. In the clinical dataset, we first z-scored the cortical spatial pattern of each of the six parameters, computed the mean across both clinical groups (i.e., pooled across CHR-P & FEP), and finally calculated the psychosis signature by subtracting from the mean clinical subjects the mean across healthy controls. Similarly, in the pharmacological dataset, we z-scored each parameter for each subject and drug condition, and then calculated the drug effect as the mean across subjects of the difference between each drug condition and the placebo condition. We then horizontally concatenated the group-average spatial patterns of all six parameters into two 180x6 matrices, which we denoted X for the psychosis signature and Y for the drug effect. We performed two separate CCA's for the lorazepam and memantine effects, respectively, so below Y refers indiscriminately to lorazepam or memantine effects, since the computation was identical for both effects.

CCA decomposed the relationship between the two multivariate datasets (i.e., the pair of matrices X and Y) into orthogonal sets of latent variables according to:

$$Z_x = XW_x,\ Z_y = XW_y, \tag{1}$$

where W_x and W_y were 6x6 matrices of linear weights, which X and Y were projected onto, resulting in 180x6 matrices Z_x and Z_y, the columns of which corresponded to the six latent (so-called "canonical") variables. The weights were chosen so as to maximize the correlations between each pair of canonical variables (i.e., corresponding columns of $Z_{x,}, Z_y$). These pairs of columns of Z_x and Z_Y were ordered by the magnitude of their respective correlations, such that the first pair had the largest correlation, and each subsequent pair had progressively smaller correlations, while being orthogonal to all other pairs. The weight matrices (W_x, W_y) satisfying these constraints were found by first applying a QR decomposition to X and Y:

$$X = Q_x R_x, Y = Q_y R_y, \tag{2}$$

where Q were 180x6 orthogonal matrices (columns were orthogonal unit vectors) of dimensionality, and R were 6x6 upper triangular matrices. The term $Q_x^T Q_y$ was subjected to singular value decomposition (SVD):

$$Q_x^T Q_y = USV^T, \tag{3}$$

where U and V were 6x6 orthogonal matrices, and S was a 6x6 diagonal matrix containing the canonical correlation coefficients in ascending order, such that $diag(S) = R$, where R was a vector of canonical correlation coefficients. The weight matrices were computed as:

$$W_x = R_x^{-1} U \text{ and } W_y = R_y^{-1} V. \tag{4}$$

The amount of co-variance explained by each set of canonical variables equalled R^2.

To quantify the relative contribution of each dynamics parameter to the canonical correlation for the first canonical variables (first columns of Z_x and Z_y), we computed the so-called "loadings" as the Pearson's correlation coefficients between these canonical variables and the original data (psychosis signature or drug effect) matrices. For each CCA (i.e., the LZP and the MEM analysis), this yielded a pair of 1x6 vectors, with one entry per dynamics parameter, for the contributions of parameters in drug effect and in psychosis signature, which were tested further for their reliability as described below.

To demonstrate the reproducibility of the CCA results, we repeated the analysis for each clinical group (i.e., CHR-P and FEP) and for each pair of the repeated sessions (S) of a pharmacological condition (e.g.., LZP S1 and LZP S2). This resulted in a total of 4 pairs for each drug condition: session S1- CHR-P, S2-CHR-P, S1-FEP and S2-FEP. For each combination, we computed the canonical variables matrices (e.g., $Z_{x(CHR,S1)}$, $Z_{y(CHR,S1)}$) and corresponding loading vectors, and quantified the similarity in the resulting (spatial or parameter) patterns across sessions and clinical groups by calculating the correlation between pairs of canonical variables (e.g., $Z_{x(CHR,S1)}, Z_{x(CHR,S2)}$) or between pairs of corresponding loading vectors, across all combinations. This was done separately for variables or loadings associated with psychosis signatures and drug effects.

Individual correlations of spatial patterns of effects

We tested the similarity between the effect of memantine or lorazepam on the spatial patterns of cortical dynamics parameters to the individual effect of patients. Parameters were z-scored as described in the section above, and the drug effect was computed in the same way. The individual psychosis signature, however, was computed as the difference between each patient and the mean across all subjects in the healthy control group. We then concatenated all parameters vertically into a single column vector for each patient ($u_{scz,i}$; $i = 1 \dots N$ patients), and for each drug effect (v_{LZP} and v_{MEM}). The vectors u and v had the same length of 6 (parameters) times 180 (parcels). To assess the spatial similarity between group average maps of drug effect and individual maps of psychosis signature (map for each patient versus average map for HC group), we computed the correlation coefficient between each patient map and each drug effect map (lorazepam or memantine) as $R_{LZP,i} = corr\left(u_{scz,i}, v_{LZP}\right); i = 1 \dots N$ (same for memantine).

Pattern classification

We trained multivariate pattern classifiers to discriminate between clinical groups (CHR or FEP vs. HC). We used support vector machines for all results reported in the main paper but achieved similar performance for another non-linear classifier (Random Forest) and slightly worse performance for a simple linear classifier (logistic regression). To ensure balanced classes, we first randomly sampled the larger group (CHR, for CHR vs. HC; HC, for FEP vs. HC). Next, the multivariate patterns of parameters (180 areas times 6 parameters; or a subset of the latter) of each individual participant were submitted to principal component analysis for dimensionality reduction. The top principal components together explaining 95% of the total variance in the data were used (typically around 20 components). We used an SVM classifier (using the Matlab function *fitcsvm*) with the 'rbf' kernel, for which we optimized two hyperparameters: BoxConstraint and KernelScale. We used the parameters maximizing classification accuracy to train and test the model using leave-one-out cross validation. We quantified the model performance as the mean classification accuracy across all folds. We repeated the above procedure 200 times, each time randomly sub-sampling the larger group. The classification accuracies reported in Table 1 were the mean accuracies across all repeats. To rigorously quantify the classifier ability to separate between the two classes, we also computed the receiver-operator-characteristic curve (ROC), by taking the continuous classifier outputs (i.e., probabilities of the predicted samples to be CHR or FEP), and then computed the area under the ROC curve (AUC). AUC=1 indicates a perfect separation, while AUC=0.5 indicates no separation between classes. We tested the statistical significance of classification accuracy using permutation testing: we randomly shuffled the label of the classes 500 times, for each shuffle again trained and tested the model using leave-one-out cross validation and computed the mean classification accuracy across all folds. We compiled the resulting accuracy values in a null distribution concatenated across all repeats. P-values were obtained as the probabilities of observing the accuracy from the true (non-shuffled) data under this null distribution.

Statistical analyses

We computed the correlations between cortical patterns maps (e.g., psychosis signature or drug effect on dynamics parameters, receptor densities, cortical hierarchy) using Spearman's rank correlation. To estimate the statistical significance of correlations across parcels we used spatial autocorrelation-preserving permutation tests. We generated null models using the spin rotation method (*103*, *104*) where the cortical surface is projected into a sphere and then randomly rotated, generating permuted cortical surfaces with preserved spatial autocorrelations. We used the spherical projection of the FreeSurfer fsaverage surface for the atlas (https://github.com/rudyvdbrink/Surface_projection) to assign each parcel with the coordinates of the vertex that is closest to the center of mass of the parcel. We then randomly rotated the coordinates, and reassigned each original parcel with the value of the closest rotated parcels. We repeated this procedure 10000 times. For parcels of which the medial wall was the closest, we assigned the value of the next closest parcel. Note that we implemented the sphere rotation on the parcel-level surface, to avoid repeated values within a single permutation which often occur when re-parceling vertex-resolution surfaces (*105*). The same procedure was applied to assess the statistical significance of CCA (Fig. 4) and of each correlation coefficient from Fig. 5. We applied the same rotation angle for all parameters within a single permutation (but randomly across permutations) before vertically or horizontally concatenating them. We computed the confidence interval using bootstrapping: we first sampled the data with replacement 10,000 times, and each time computed the relevant statistic (e.g., correlation coefficient, canonical correlation). We then calculated the lowest 2.5 and highest 97.5 percentiles of the resulting distribution, which we considered as the confidence interval.

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Competing interests: All authors declare they have no competing interests

Data and materials availability: The complete preprocessed MEG data from the pharmacological dataset and the full set of dynamics parameters computed from the clinical dataset (i.e., 6 maps per participant) will be made available in a permanent publicly accessible repository of the University of Hamburg upon acceptance. All code to reproduce the reported results and figures will also be made available in that permanent publicly accessible repository of the University of Hamburg upon acceptance. All data are available in the main text or the supplementary materials.

Supplementary Materials for

Large-Scale Maps of Altered Cortical Dynamics in Early-Stage Psychosis Are Related to GABAergic and Glutamatergic Neurotransmission

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This PDF file includes:

Figs. S1 to S5

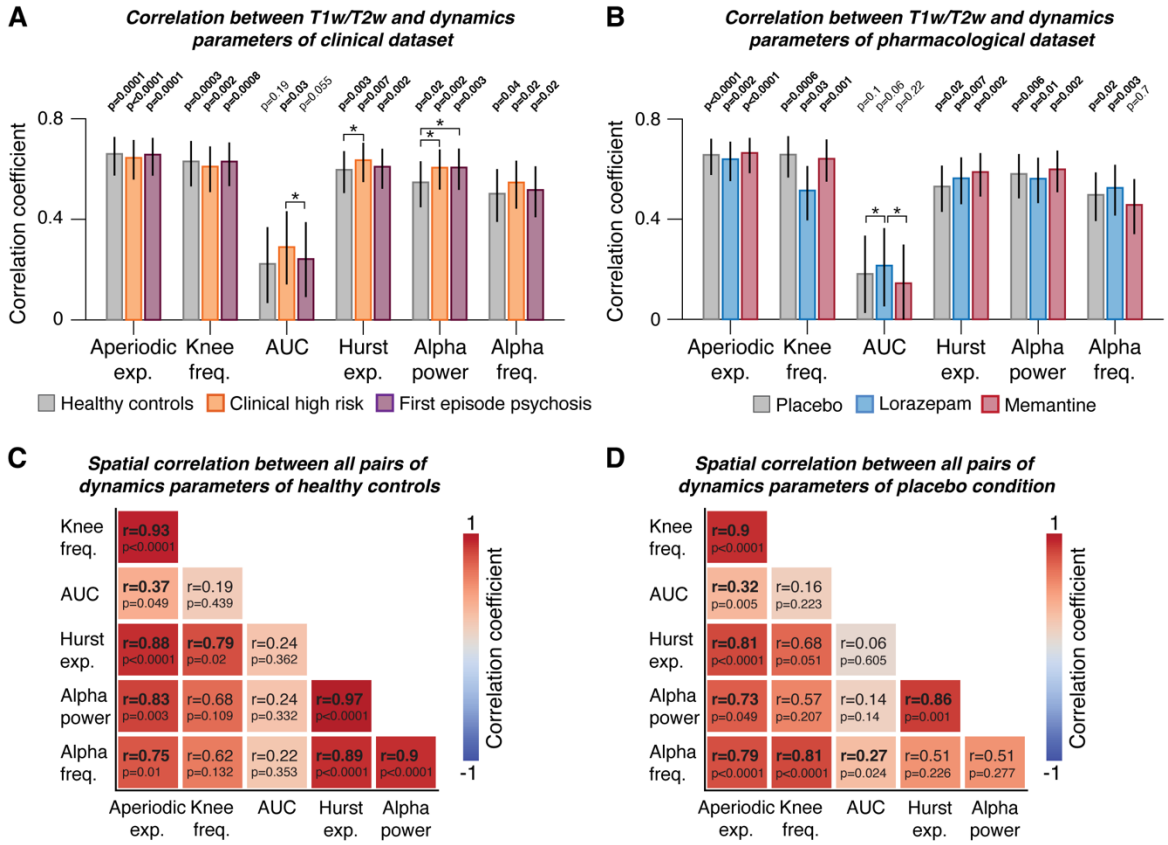

Figure S1: Quantification of the spatial correlation structure of spontaneous cortical dynamics.

(A, B) Anatomical hierarchy correlates with several dynamics parameters. Across-area correlations between dynamics parameters and T1w/T2w maps for clinical data (A, healthy control and both clinical groups) and pharmacological data (B, placebo and both drug conditions). Asterisks: significant difference between correlation coefficients healthy controls vs. each clinical group, or between placebo and each drug condition. Error bars are 95% bootstrap confidence interval. **(D, E)** Matrices of the across-area correlations between all pairs of parameters within each sample. In all panels, the statistical significance of all Spearman correlation coefficients was tested using spatial autocorrelation-preserving permutation tests.

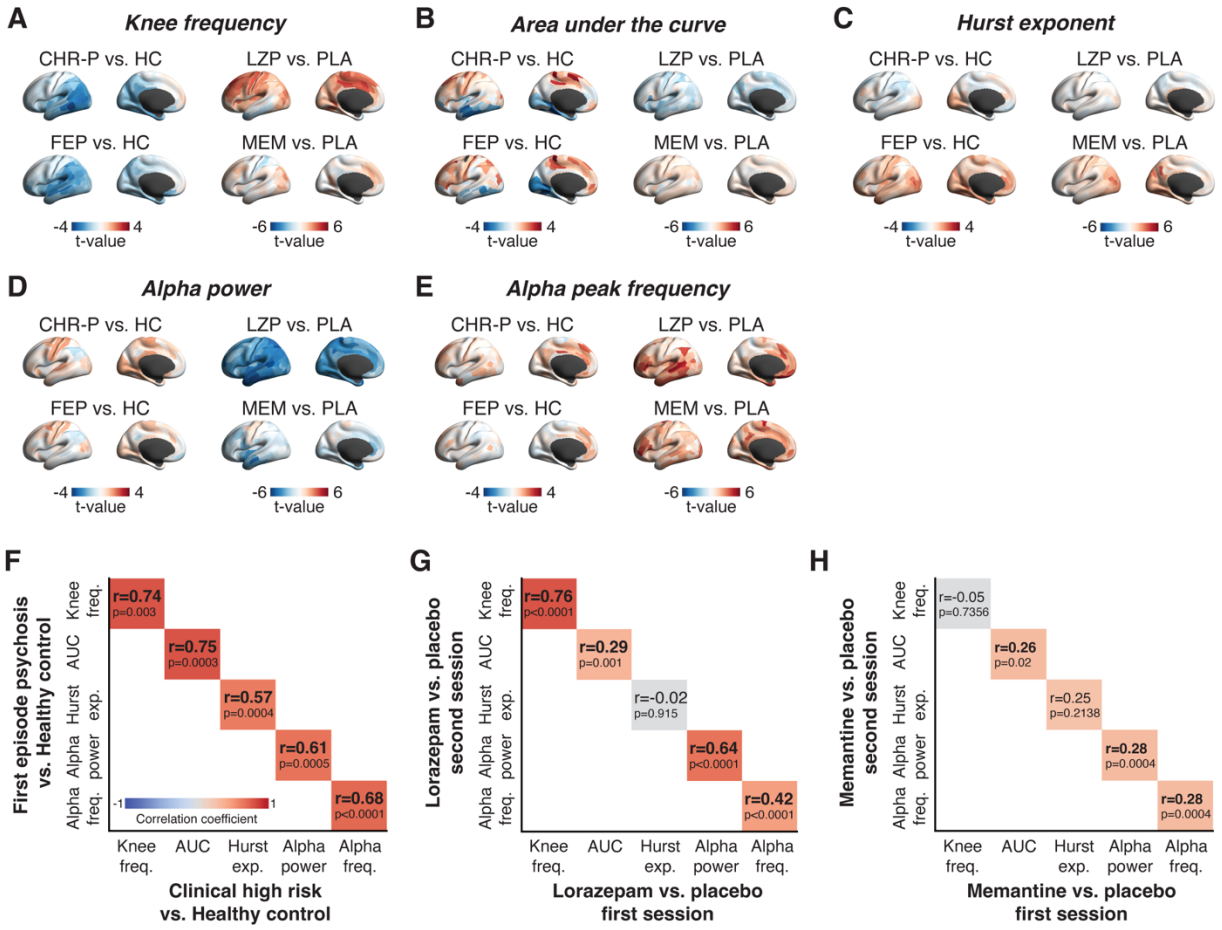

Figure S2: Heterogenous and reliable maps of psychosis signatures and drug effects in cortical dynamics.

(A-E) Maps of drug effects or psychosis signatures on five dynamics parameters (LZP: lorazepam; MEM: memantine; CHR-P: clinical high risk; FEP: first episode psychosis; HC: healthy control). Results are presented as group level non-thresholded t-values. **(A)** Knee frequency, **(B)** AUC, **(C)** Hurst exponent, **(D)** Alpha power and **(E)** Alpha peak frequency. **(F)** Spatial correlations between the psychosis signature in the clinical high risk and first episode psychosis groups. **(G, H)** Spatial correlations between drug effects in the first and second repeat of the pharmacological condition, separated by 1-5 weeks. (G) Lorazepam, (F) memantine. All correlations are Spearman's correlation coefficients and all p-values were estimated using spatial autocorrelation-preserving permutation tests.

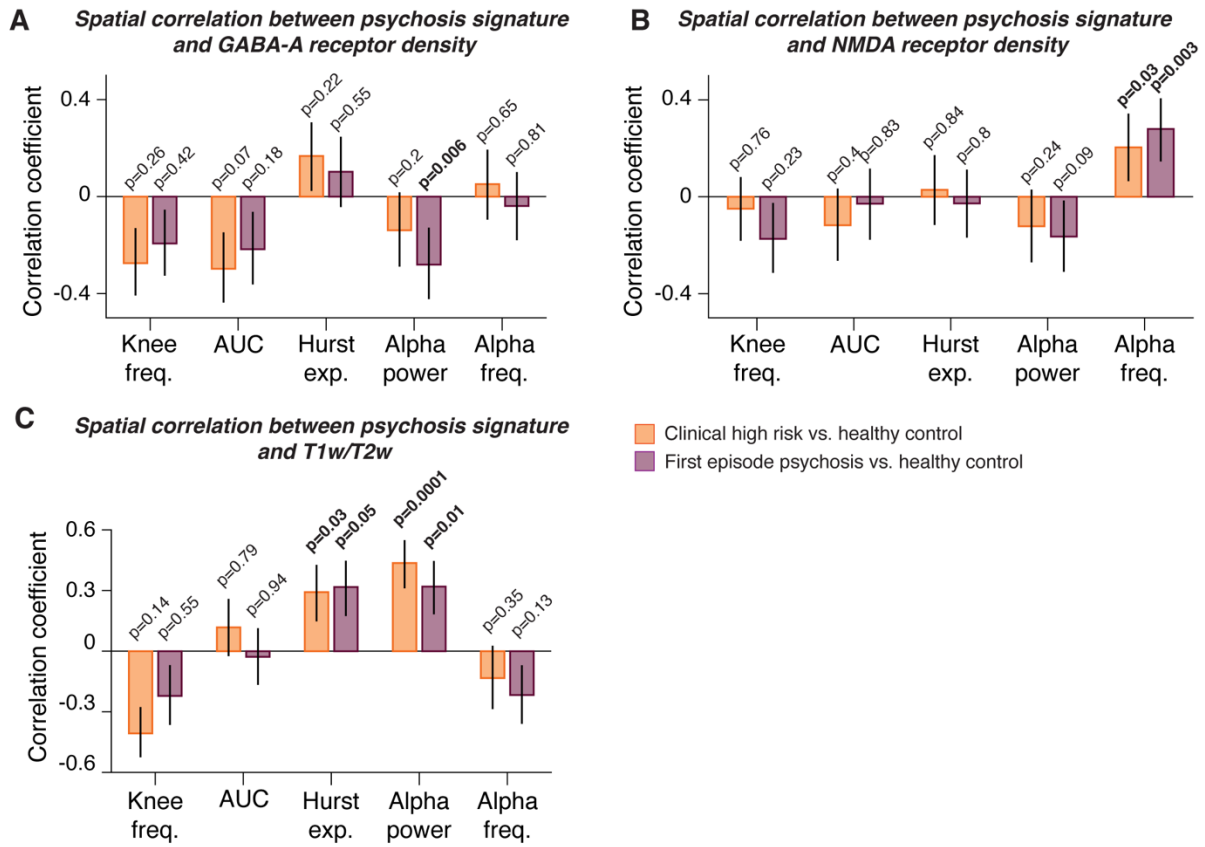

Figure S3: Similarity between maps of psychosis signatures on dynamics parameters and maps of GABA-A or NMDA receptor density levels, or T1w/T2w maps.
(A, B) Spatial correlations between the psychosis signature on dynamics parameters and GABA-A (A) or NMDA (B) receptor densities. **(C)** Spatial correlations between psychosis signature and T1w/T2w maps. Error bars are 95% bootstrap confidence interval. All correlations are Spearman's correlation coefficients and all p-values were estimated using spatial autocorrelation-preserving permutation tests.

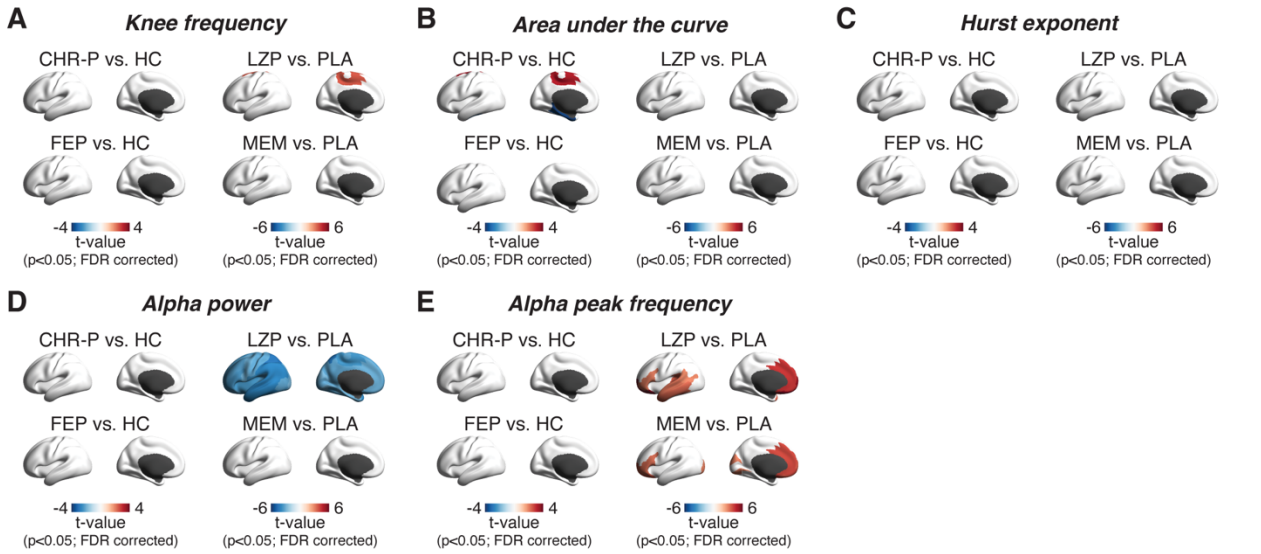

Figure S4: Weak psychosis signatures or drug effects in local cortical dynamics.
Replicas of the maps of psychosis (CHR-P vs. HC or FEP vs. HC; left) or drug effects (lorazepam vs. placebo or memantine vs. placebo; right) for different parameters from Figure S2, but after applying statistical significance threshold based on mass-univariate tests for each area (t-tests; ($p<0.05$, FDR correction). **(A)** knee frequency, **(B)** AUC, **(C)** Hurst exponent, **(D)** alpha power, and **(E)** alpha peak frequency. The widespread reduction in alpha power under LZP in panel D is a well-documented phenomenon (105-107). CHR-P: clinical high risk; FEP: first episode psychosis; HC: healthy controls; LZP: lorazepam; MEM: memantine.

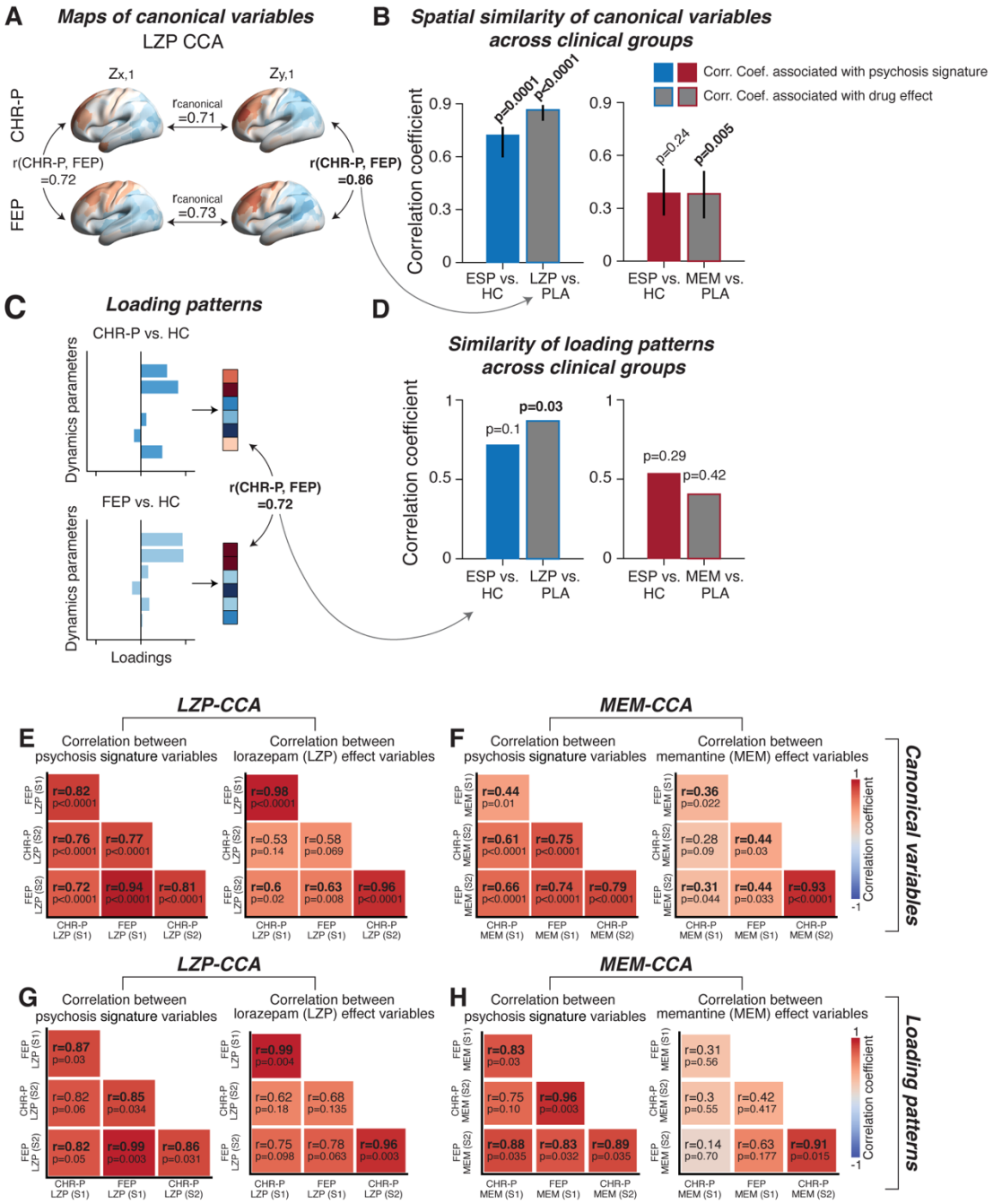

Figure S5: Reproducibility of CCA across clinical groups.
(A) Maps of the first canonical variables of the CCA between the psychosis signature (up: CHR-P vs. HC; bottom: FEP vs. HC) and lorazepam effect (LZP vs. PLA). The maps were computed separately for the CHR-P and FEP groups. Horizontal arrows: canonical correlation. Vertical arrow: spatial similarities of corresponding canonical variables across groups. **(B)** Spatial similarity of first canonical variables across the two clinical groups. ESP: Early-stage psychosis. **(C)** CCA loadings of the first canonical variable between the psychosis signature and lorazepam effect, computed separately for the CHR-P and FEP groups. Horizontal arrow: correlation between loadings of the two clinical groups. **(D)** Similarities between loadings across the two clinical groups. Blue/red bars: similarities across canonical variables or loadings of the psychosis signature (i.e., $Z_{x,1}$), for CCA with lorazepam/memantine, respectively. Gray bars: similarities across canonical variables or

loadings of the drug effect (i.e., $Z_{y,1}$). P-values were obtained using permutation tests (corrected for spatial autocorrelation). **(E-H)** Complete results from all reproducibility analyses. **(E,F)** Correlation matrices between all pairs of canonical variables, separated by drug (E: lorazepam; F: memantine), and canonical variable (left: psychosis signature; right: drug effect). All correlations are Spearman's correlation and p-values were estimated using spatial autocorrelation-preserving permutation tests. **(G,H)** same as (E,F) but for the CCA loading patterns.