A systematic data-driven approach to analyze sensor-level EEG connectivity: Identifying robust and reliable network components using surface Laplacian with spectral-spatial PCA

Columbia Psychiatry

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Ezra Smith [1], Tarik Bel-Bahar [1], Jürgen Kayser [1,2]

[1] New York State Psychiatric Institute, New York, NY, USA; [2] Department of Psychiatry, Vagelos College of Physicians and Surgeons, Columbia University, New York, USA

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BACKGROUND

- Phase-synchronous resting-state networks (RSNs) can be uniquely assessed with electrophysiological assays
- Whereas most prior work identified 1-2 posterior alpha (8~13 Hz) and 1 midfrontal theta (4~8 Hz) RSNs [1], multivariate approaches suggests the existence of additional RSNs [2]
- Conventional analysis approaches likely preclude a comprehensive spectral-spatial characterization of phase-based RSNs in the human EEG at rest
- Here, we combine *current source density (CSD)* and *principal components analysis (PCA)* to systematically summarize phase-locked *functional connectivity (FC)* and to identify EEG-based RSN components at sensor level (CSD-fcPCA)

METHODS

- Resting EEG (71 sites, 10-10 placement) obtained from 35 healthy adults twice (1-week retest, eyes open/closed [EO/EC], 4 min each) from four study sites [3]
- 2-s epochs (75% overlap) transformed into reference-free scalp CSDs (surface Laplacian) [7] to mitigate volume conduction and improve spatial resolution
- FC calculated using debiased-weighted Phase-Lag Index (dwPLI) [4] between 2,485 unique electrode pairs for each subject, session, and condition
- FC data restricted to 3-16 Hz theta/alpha frequency range (Morlet wavelet frequency bins interpolated to 42 logarithmically-spaced bins)
- FC data were submitted to a 2-step covariance-based PCA-Varimax procedure (**step 1, spectral**: input matrix = 695,800 cases × 42 variables [frequencies]; **step 2, spatial**: for each back-projected spectral FC component, re-arranged input matrix = 11,760 cases × 2,485 variables [FC electrode pairs])
- Robustness of FC components from steps 1 and 2 was evaluated for group data (split-half internal consistency, 1-week retest reliability), subsamples, and individual participants
- Tucker congruence coefficients (ϕ) assessed FC component similarity (larger numbers indicate more similarity, and $\phi \geq .95$ considered component equality) [5]

RESULTS

- Spectral (step 1) PCA solution extracted 6 components with frequency peaks in canonical theta (at 4.2, 5.1, 6.3 Hz) and alpha (8.0, 10.2, 13.0 Hz) bands (**Fig. 1**)
- Spectral FC components were highly consistent for single recordings (**Fig. 2**), and highly similar to factor loadings from aggregate data (ϕs ≥ .81)
- The ensuing spatial (step 2) PCA solutions identified ***1 theta*** and ***7 alpha*** FC components (**Fig. 3**) that aligned with prior work and together explained 37.1% total FC variance
- Spectral-spatial FC components were characterized by unambiguous frequency peaks and distinct FC topographies
- EO/EC effects were seen for posterior 8-Hz and all 13-Hz alpha FC components
- FC components had good-to-excellent internal consistency (odd/even epochs, eyes open/closed) and test-retest reliability (0.8 > ICC < .95)
- Spectral-spatial FC components from aggregate data were highly consistent with those from random samples of 10 recordings (**Fig. 4A**) but more variable with those from single recordings (**Fig. 4B**)

CONCLUSIONS

- Our 2-step spectral-spatial CSD-fcPCA identified seven reliable FC components within the canonical alpha band and one midfrontal theta FC component
- These data-driven FC components demonstrated good-to-excellent internal consistency and 1-week retest reliability
- Component extraction was not driven by participants with unrepresentative FC strength, as random participant samples evidenced highly similar factor loadings
- Spectral (step 1) FC components were virtually identical across single-subjects
- Spatial (step 2) FC components from single-subjects had modest similarity with those at group-level, however, considerable between-subjects variability
- The spectral-spatial profiles of FC components aligned with RSNs identified with other neuroscientific approaches [6], but the precise functional significance of these RSNs remains to be determined

✓ **Three posterior alpha RSNs were similar to alpha components previously identified by frequency PCA [11] and are hypothesized to be important for attention and vision**

✓ **A sensorimotor 13-Hz RSN was identified that was compatible with the mu rhythm associated with intention and motor control [8]**

✓ **The frontal-parietal 13-Hz RSN aligns with work linking frontal-parietal FC at 10~13 Hz to visual working memory [9]**

✓ **The midline 8-Hz and midfrontal 10-Hz FC components, which have not been characterized previously, may be linked to activity of medial nodes of the default-mode network [6] and to the motivational significance of frontal alpha [10]**

References

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Highlights

- **Identification of phase-based resting-state networks (RSNs) in human EEG**
- **A novel CSD-fcPCA technique summarized an FC dataset into 8 RSNs**
- **These RSNs were internally consistent and retest reliable**
- **CSD-fcPCA revealed RSNs not detected by a conventional EEG-FC approach**
- **RSNs were functionally distinct and largely consistent with previous work**

Spectral solution (Step 1)

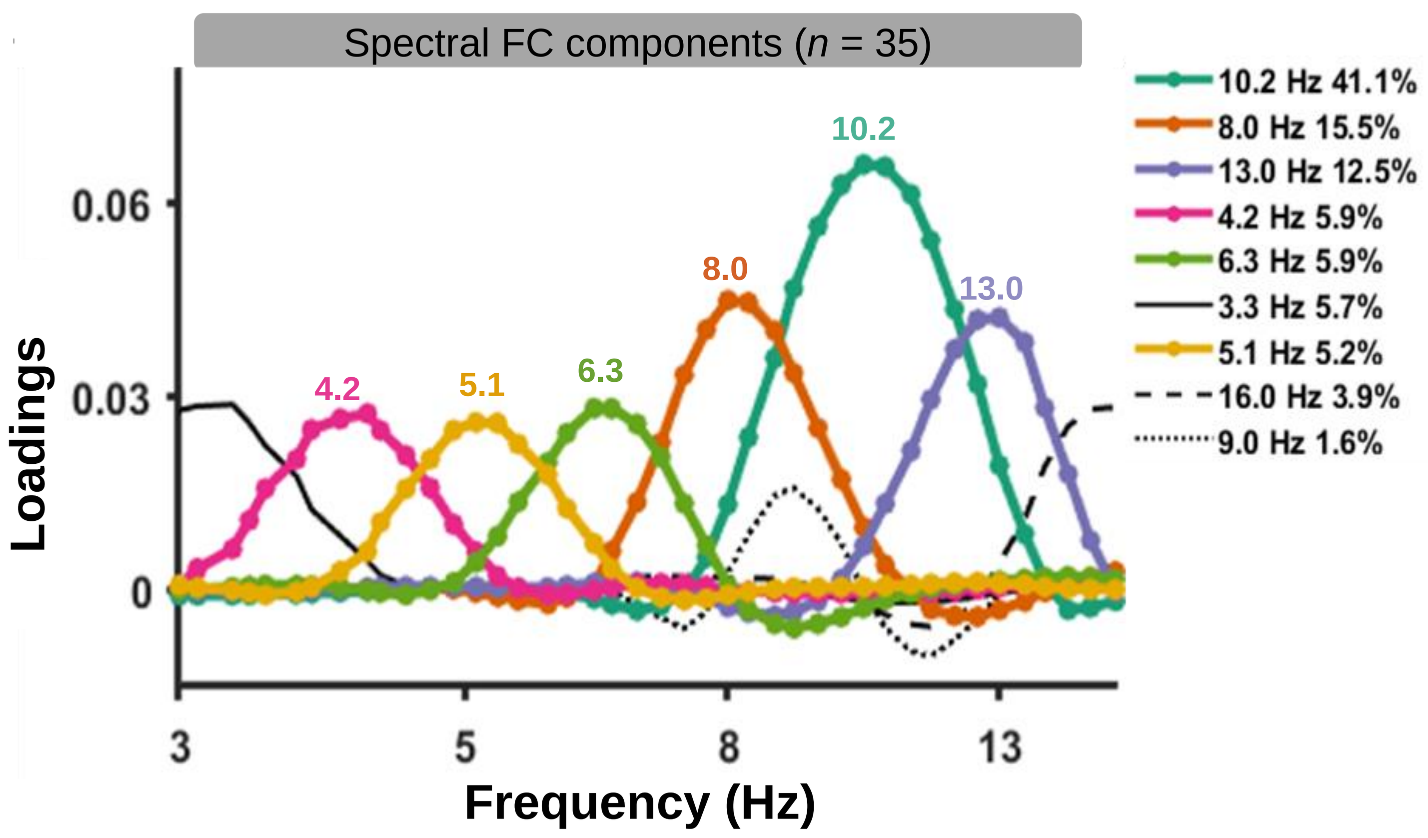


Fig. 1. CSD-fcPCA factor loadings of 9 spectral FC components (step 1, explained variance ≥ 1%). Six components (in color) were carried forward for subsequent analysis. Three components (in black) were not considered further because of peak loadings at the edge of the analysis window (3.3 and 16.0 Hz) or substantive adjacent negative loadings (9.0 Hz).

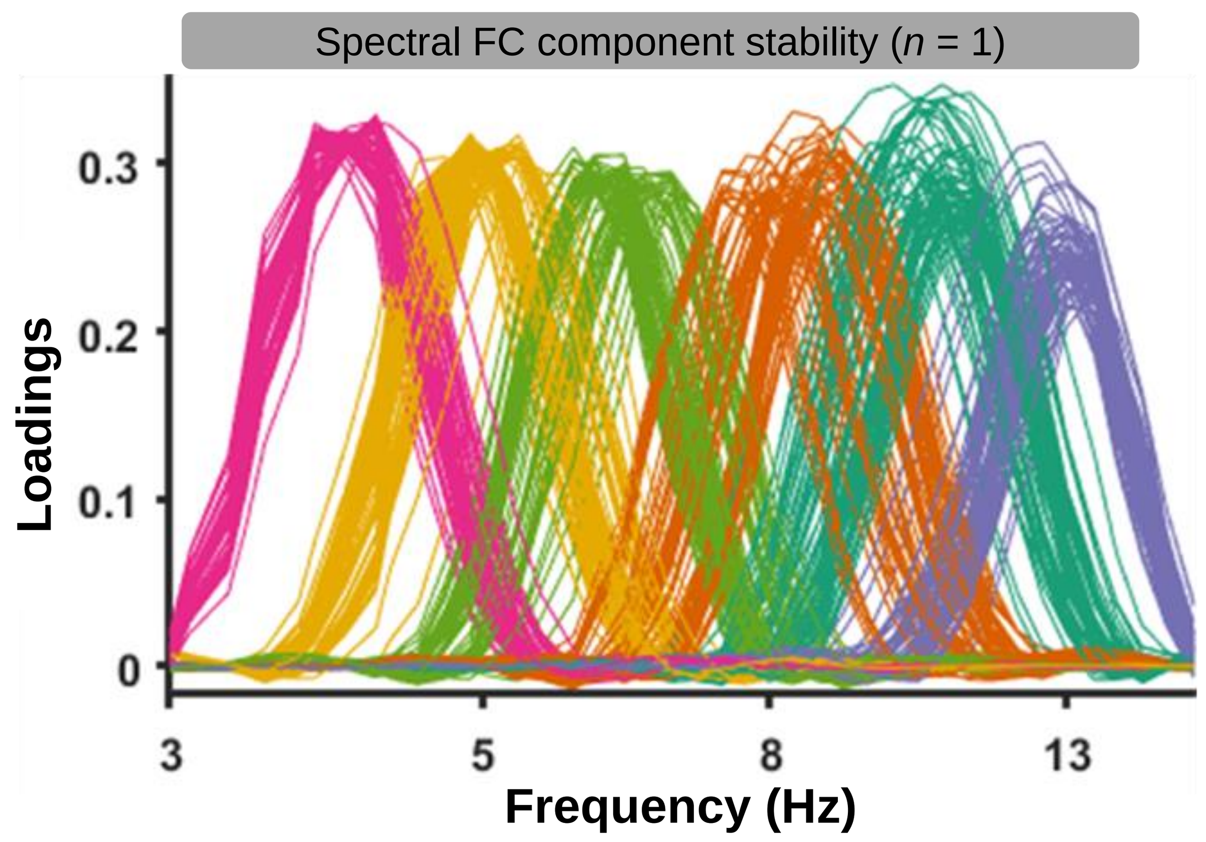
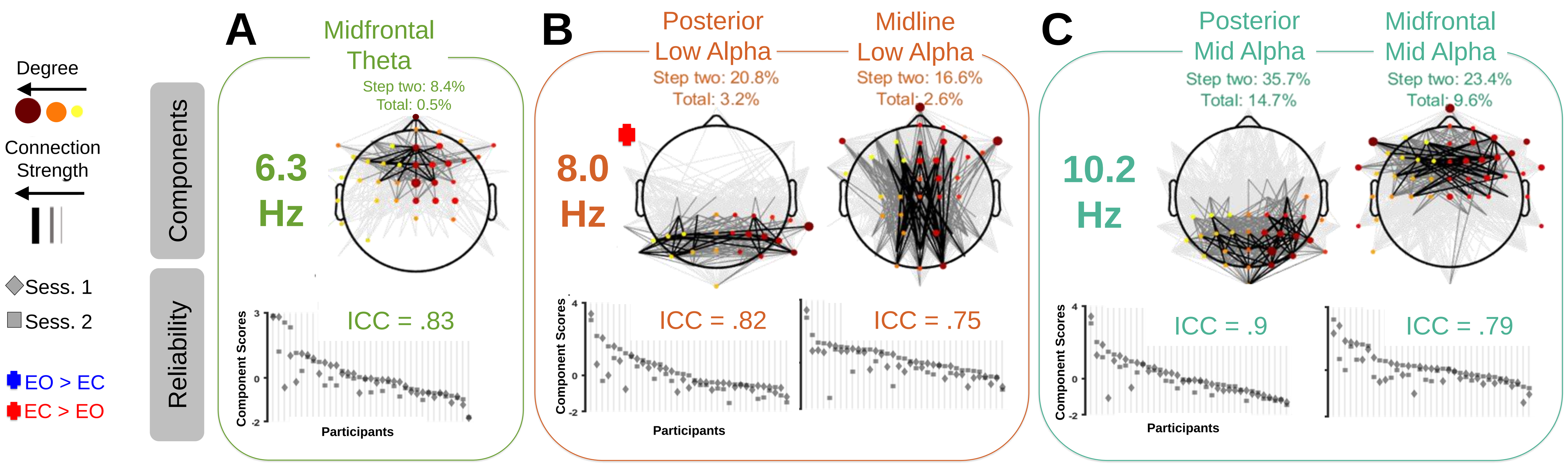
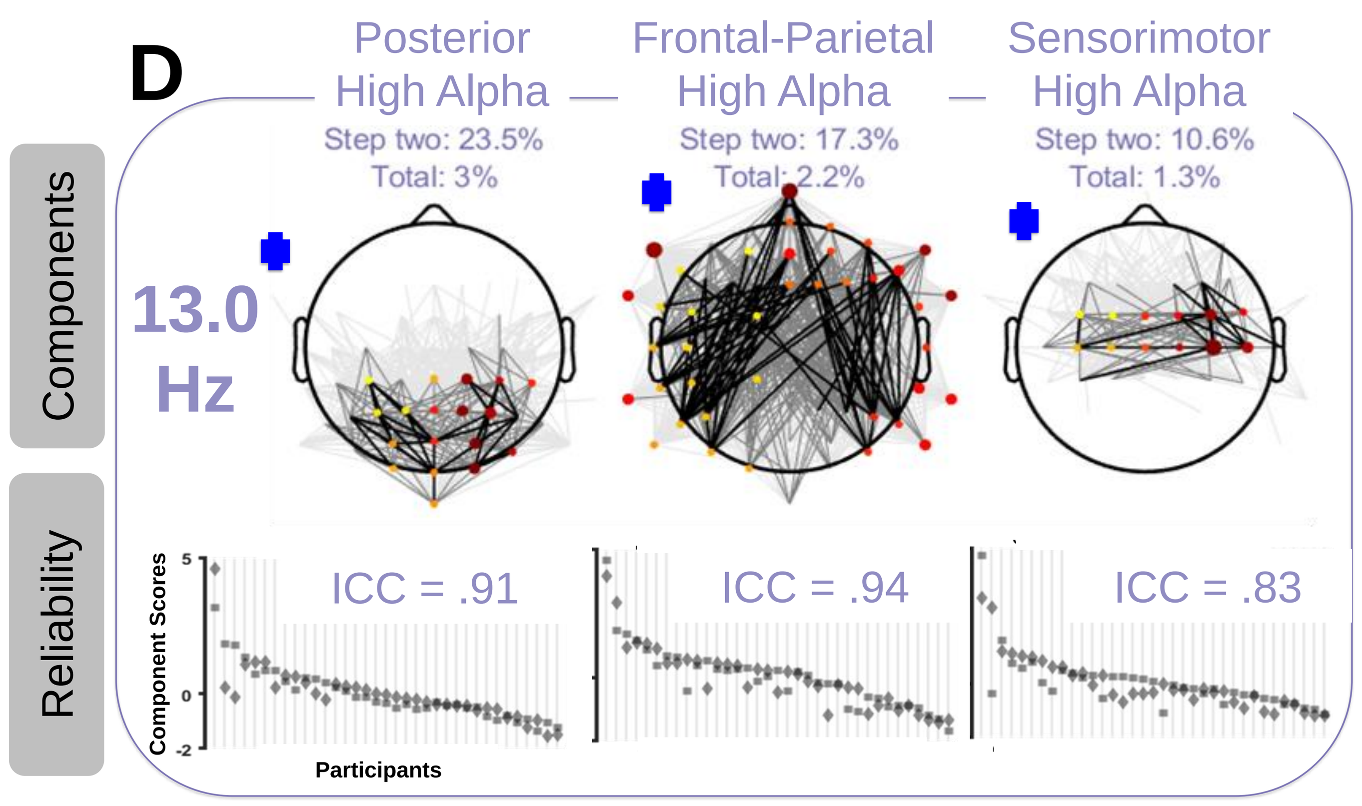


Fig. 2. Consistency of step-1 factor loadings across 70 individual recordings (n = 35, 2 sessions), which were highly comparable to those from aggregate data (ϕs ≥ .81), with most demonstrating fair similarity (.85 ≥ ϕs ≤ .95) or equality (ϕs > .95).

Spatial solutions (Step 2)





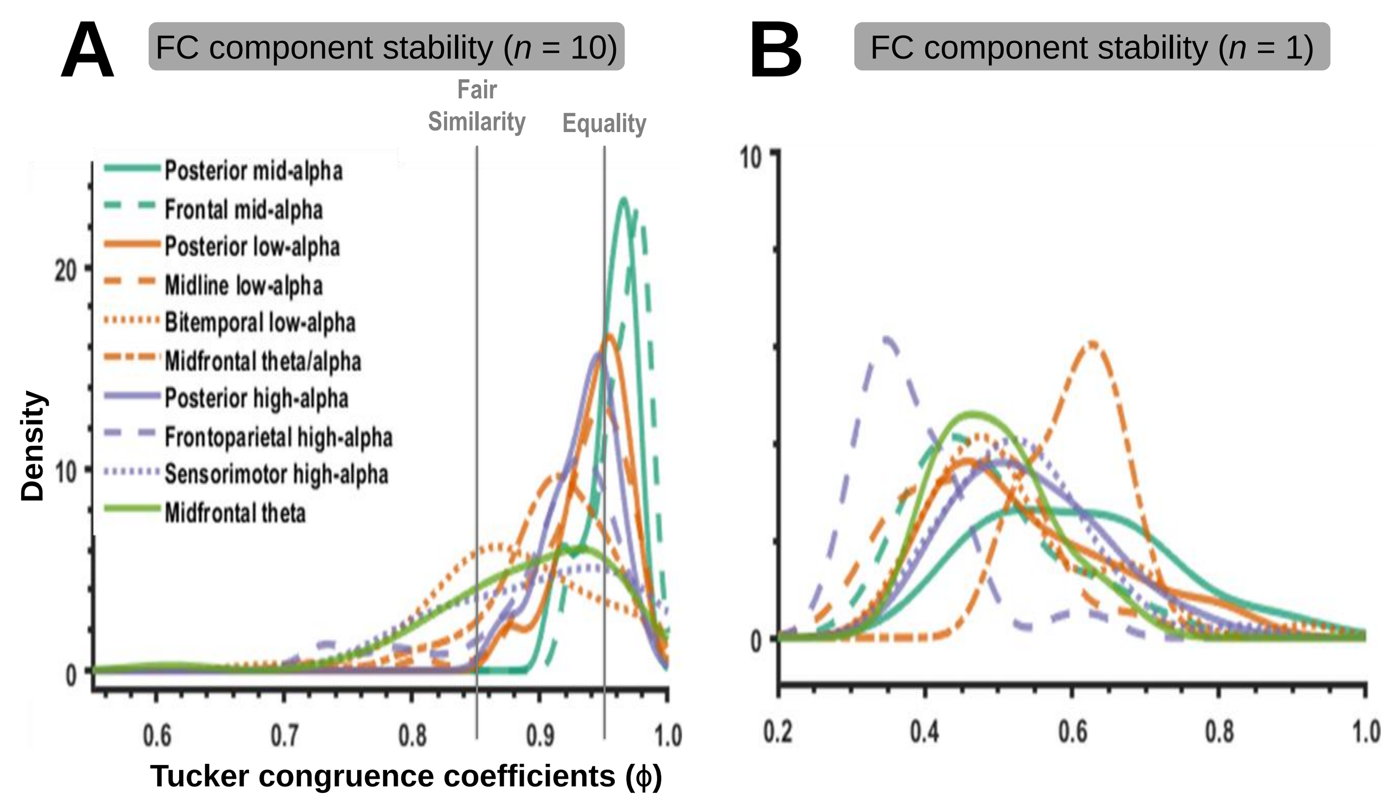


Fig. 3. CSD-fcPCA factor loadings of 8 spatial components (step 2). A: Low-variance (< 1% total) midfrontal theta retained for further analysis given its hypothesis-congruent topography. B: Posterior and midline low-alpha. C: Posterior and frontal mid-alpha. D: Posterior, frontal-parietal, and sensorimotor high-alpha. All components had good-to-excellent retest reliability per Intraclass Correlation (1,k). Variability between participants was much greater than within individual participants (i.e., between sessions; scatter plots at bottom of each panel).

Fig. 4. Consistency of step-2 factor loadings. A: Density of Tucker Congruence Coefficients for PCA solutions for 50 random subsamples of 10 recordings (from either session 1 or 2) revealing for most loadings at least *fair similarity* ($\phi \geq .85$) with corresponding spatial FC components of the aggregate dataset. B: As in A but for single recordings, which yielded less similarity with group-level components due to between-subjects variability.