Functional connectivity resilience in meningioma and glioma: growth biology shapes compensation and its limits

Brain tumors disrupt neural connectivity, but the nature of this disruption depends on tumor growth biology. Here, we analyze pre-operative structural connectivity (SC), functional connectivity (FC), and generalized effective connectivity (GEC) in 14 meningioma patients, 10 glioma patients, and 10 matched controls to characterize how extra-axial and intra-axial tumors differentially affect brain networks. We introduce FC resilience, the relative preservation of functional connectivity in structurally damaged regions, and find that meningioma patients exhibit significantly higher FC resilience than glioma patients, with SC-dominant damage and preserved neural activity in damaged regions. Glioma patients show balanced SC-FC damage and degraded neural activity, consistent with infiltrative destruction of both white matter and neural substrate. Connectivity damage is not localized to the tumor vicinity and is non-randomly distributed across functional networks, with distinct propagation patterns: glioma SC damage clusters along white matter pathways, while meningioma SC damage preferentially targets Limbic and Default networks. Network topology analysis reveals that more segregated functional and effective connectivity, particularly higher modularity, predicts FC resilience in meningioma patients but not in glioma patients, while structural connectivity topology shows no predictive value. Non-equilibrium dynamics, quantified via the Fluctuation-Dissipation Theorem, are elevated in damaged regions of meningioma patients, serving as a dynamical marker of structural damage rather than an independent compensatory mechanism. Clinically, higher FC resilience in glioma patients is associated with worse cognitive outcomes, suggesting that preserved FC without an intact neural substrate does not reflect genuine functional preservation. These findings demonstrate that the interpretation of functional connectivity resilience depends fundamentally on tumor type and its underlying growth biology.

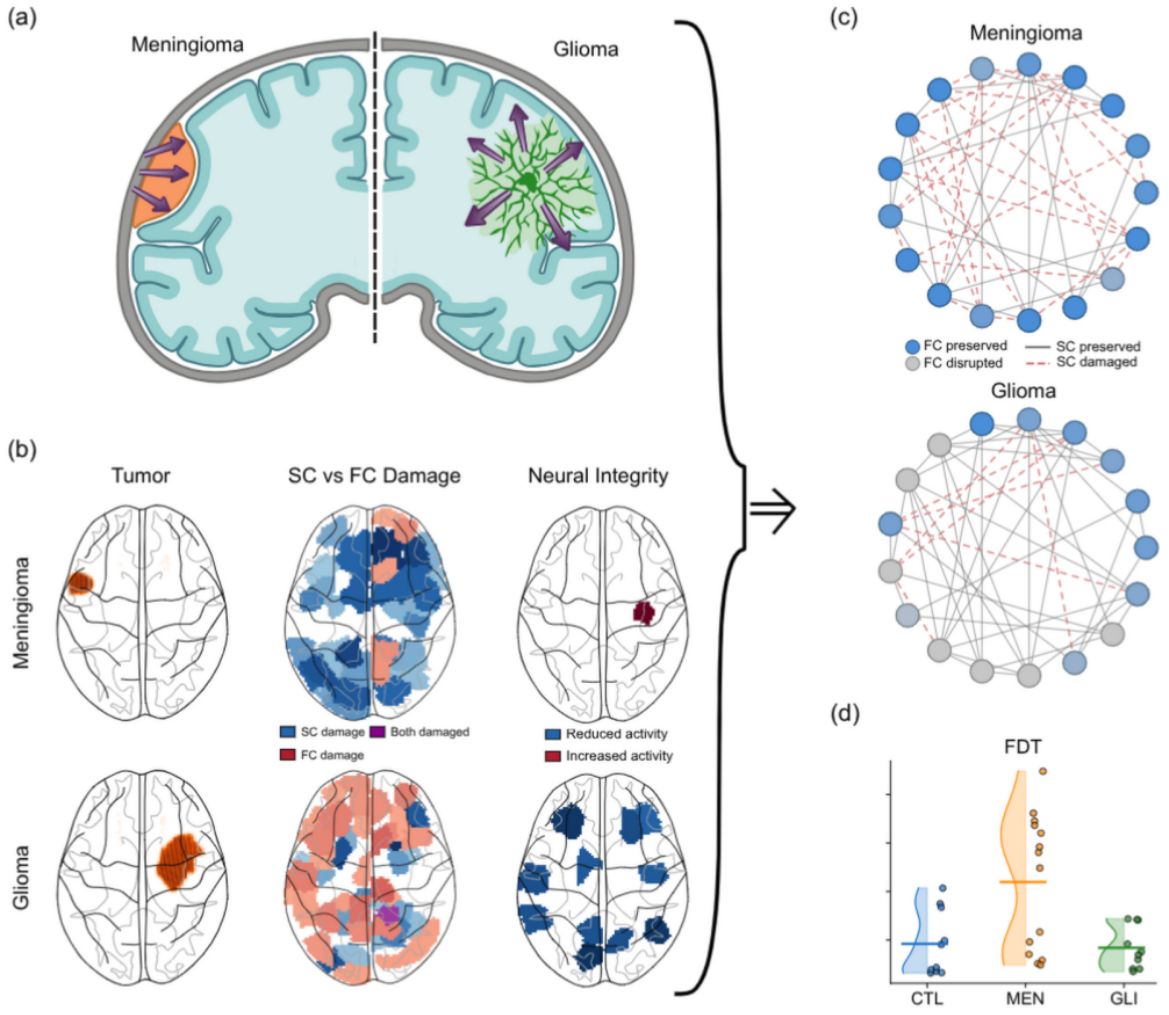

Figure 1. Meningiomas and gliomas produce distinct patterns of structural and functional connectivity damage. **(a)** Schematic illustration of the two tumor types: meningiomas (left, orange) grow extra-axially and primarily compress adjacent brain tissue, whereas gliomas (right, green) grow intra-axially and infiltrate brain tissue directly. **(b)** Axial glass-brain views of representative patients (top: meningioma; bottom: glioma). *Tumor location* (left): tumor mask in MNI space. *SC–FC mismatch* (middle): regions colored by the type of connectivity damage—blue where SC is damaged but FC is preserved, red where FC is damaged but SC is preserved, and purple where both are affected. Darker shades indicate greater severity. The meningioma patient shows predominantly blue regions, indicating structural damage with functional preservation, while the glioma patient shows a more balanced mix of blue, red, and purple, reflecting damage across both modalities. *Neural integrity* (right): regions with abnormal low-frequency BOLD power relative to controls, where blue indicates reduced, and red indicates increased neural activity. The glioma patient shows widespread activity reductions, whereas the meningioma patient remains near normal levels. **(c)** Network-level summary mapped onto the Yeo 17-network parcellation for visualization purposes. Node color reflects FC status within each network, ranging from blue (preserved) to gray (disrupted). Edges represent between-network SC, shown as solid gray when preserved and dashed red when damaged. The meningioma patient shows many damaged SC connections but preserved FC across all networks, while the glioma patient shows widespread FC disruption alongside SC damage. **(d)** Non-equilibrium dynamics quantified as FDT violation from the Hopf bifurcation model applied to structural connectivity. Meningioma patients show elevated values relative to controls and glioma patients.

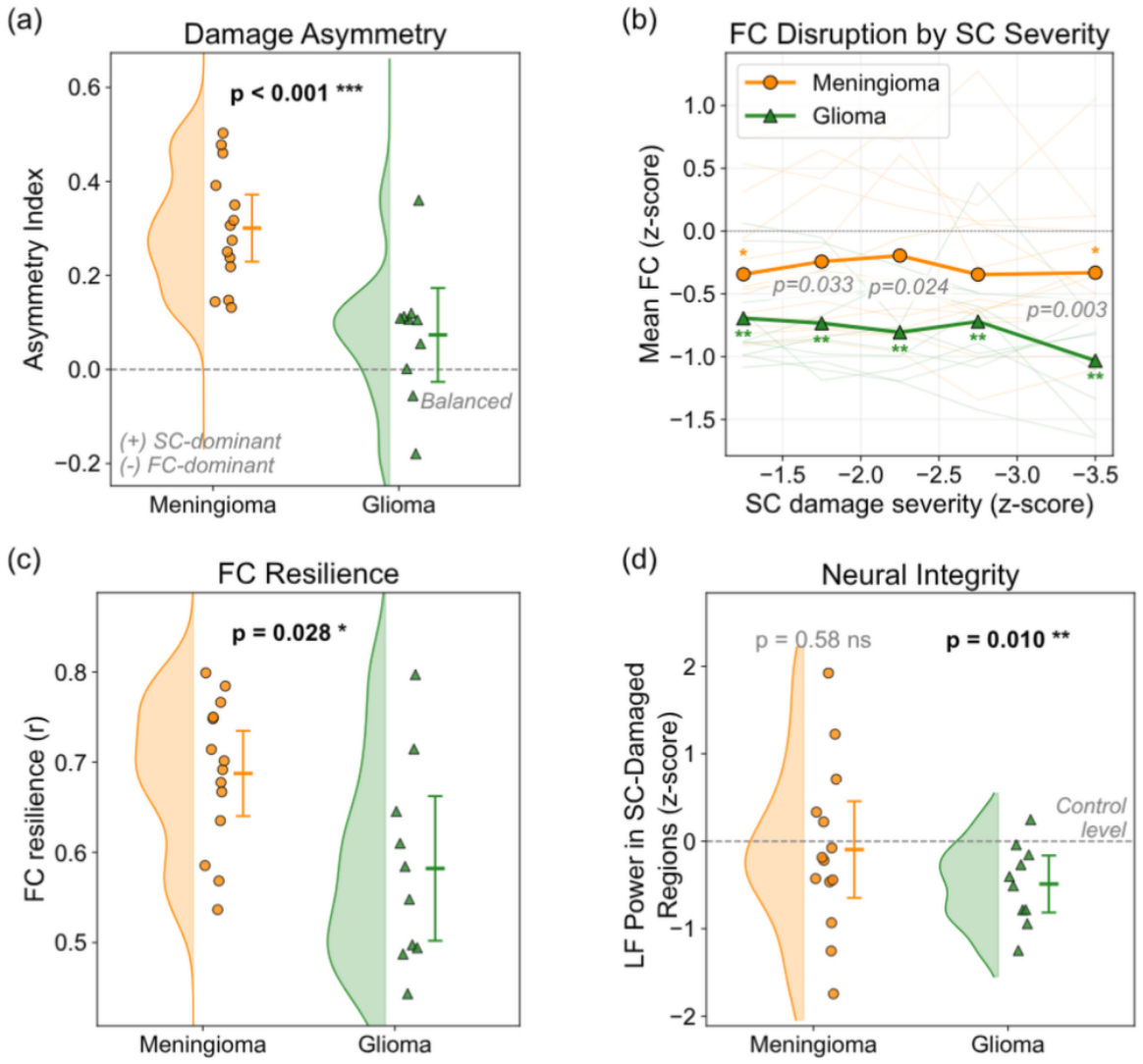

Figure 2. Quantification of structural and functional connectivity damage across tumor types. **(a)** Damage asymmetry index per patient, quantifying the relative dominance of SC versus FC damage. Positive values indicate SC-dominant damage; meningiomas show a significant positive bias while gliomas cluster near zero, reflecting balanced SC–FC disruption. **(b)** FC disruption binned by SC damage severity (both z-scored relative to controls). Faint lines show individual patient trajectories; markers indicate group means. Meningioma patients maintain relatively stable FC across all damage levels, while glioma patients show progressively greater FC disruption. **(c)** FC resilience per patient (computed in SC-damaged regions only), defined as the relative preservation of FC given the degree of SC damage. Meningioma patients show significantly higher FC resilience than glioma patients. **(d)** Neural integrity per patient (averaged across SC-damaged regions), measured as low-frequency BOLD power (0.01–0.1 Hz, z-scored relative to controls). Glioma patients show significantly reduced neural activity, whereas meningioma patients remain near control levels.