A Brief Communication to Nature Neuroscience

Intrinsic Dynamic Brain Eigen-states Predict Fluid Intelligence

Oliver Y. Chén and Jenna Reinen

We demonstrate that intrinsic brain connectivity is linked to continuous behaviour metric. In particular, we show that one state, the first *eigen state* for fluid intelligence (gF), contains features that are the most predicative of gF.

Darwin argued that the variability is the greatest in structures that evolves the fastest. As the most variable organ in humans, the brain operates via functions that vary in space and time to adapt to the environment in which it resides. The brain is also a knowledge-acquiring system. In order to form knowledge, the brain must be able to stabilize knowledge. The brain, therefore, evolves to incorporate both variability and constancy, to acquire knowledge, and to stabilize knowledge. The product of this biological operation is the dynamic brain network: it varies over time, resulting in variability, and each network occurs repetitively, achieving constancy.

There has been a tremendous amount of effort to understand the dynamic network of the brain during the resting state (Calhoun et al, Hutchison et al, Allen et al, Chang and Glover, Fox et al). Consequently, much debate has arisen regarding whether discrete brain states represent true characteristic of brain function or are due to measurement error (Hutchison et al, Laumann et al, Wang et al, Shine et al). A potential resolution to solve this disagreement is to enquire into the relationship between discrete brain states, the product of intrinsic brain operations, and continuous behaviour measurement, the product of extrinsic brain operations. Here, we demonstrate that temporally resolved features are more predicative of fluid intelligence (gF), an important cognitive metric, than using static features. Critically, we find that one particular state, which we term the first *eigen state* for gF, contains features that are specifically related to gF. We introduce the concept of "eigen-states" with respect to a particular behaviour metric to distinguish different dynamic brain states based upon their predictability of that metric. Therefore, the first eigen state for gF is the one that is the most predicative of gF; the second eigen state is the second most predicative state for gF; and so on.

Since the discovery that brain regions supporting the similar functions during task also couple together at rest (Biswal, Krienen), there has been a broad attempt to relate the brain's intrinsic activity to cognition using resting state fMRI (rsMRI). Some approaches have linked intrinsic activity to more individual differences in more complex cognitive capacity. For instance, individuating "fingerprints", expressed as the collective matrix of connectivity edges computed from an individual's rsMRI data, is more similar across scans within an individual than across individuals, and is associated with fluid intelligence (Finn, Rosenberg). However, traditional approaches such as these treat neural activity as static over the course of a scan, when in fact the human brain is a dynamic organ. Recent studies have supported this, demonstrating that the brain may be separated into multiple "states" of connectivity (Allen, Hutchison), and is related to metrics of arousal (Wang), attention (Shine), and psychiatric illness (Reinen, in prep). Still, while a similar fingerprint property has also been identified across dynamic states (Reinen in prep), a more concrete link between cognitive capability and specific brain state expression has yet to be defined. Here, we considered the data from the Human Connectome Project, and applied a k-means clustering to define brain states. We found that intelligence (gF) was specifically related to the first *eigen state* for gF, that was differentiated in their enhanced within-network expression of default, frontal-parietal network (FPN), and attention. Given the high degree of interconnectivity of these regions, it is possible that an individual's ability to flexibly express states that engage diffuse hubs may respond optimally to a variety of cognitive demands. Further, it has been demonstrated that disruption in large neural networks such as the FPN and default networks (Baker, Reinen) are selectively compromised in static and dynamic analysis of rsMRI. Future studies should unpack the flexibility, stability, and temporal expression differences in these states as they relate to cognitive abilities.

In sum, our finding aligns with previous studies where the features (defined as the strength of edges in the network) that are the most predicative of gF are observed in the frontal parietal network (Spreng et al, Vincent et al, Badre and D'Esposito), and the default mode (Buckner et al); our result extends previous attempt to link intrinsic brain connectivity with disease and network, to link for the first time intrinsic brain connectivity with a cognitive metric.