Review

Characterizing Attention with Predictive Network Models

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Recent work shows that models based on functional connectivity in large-scale brain networks can predict individuals' attentional abilities. As some of the first generalizable neuromarkers of cognitive function, these models also inform our basic understanding of attention, providing empirical evidence that: (i) attention is a network property of brain computation; (ii) the functional architecture that underlies attention can be measured while people are not engaged in any explicit task; and (iii) this architecture supports a general attentional ability that is common to several laboratory-based tasks and is impaired in attention deficit hyperactivity disorder (ADHD). Looking ahead, connectivity-based predictive models of attention and other cognitive abilities and behaviors may potentially improve the assessment, diagnosis, and treatment of clinical dysfunction.

Trends

Valuable research has described the attention system of the human brain using mostly group-level analyses of neuroimaging data.

fMRI research is moving towards single-subject-level analyses, which afford significant scientific and practical benefits such as personalized assessment, diagnosis, or prediction.

Recent work shows that models based on functional brain networks can predict how well individual people pay attention.

Predictive models provide empirical evidence that attention is a network property of the brain and that the functional architecture that underlies attention can be measured while people are not engaged in any explicit task.

Looking ahead, connectivity-based predictive models of attention and other cognitive abilities may improve the assessment, diagnosis, and treatment of clinical dysfunction.

What Is Attention and How Do We Measure It?

Perhaps no cognitive capacity is more crucial to navigating daily life than the ability to pay attention. Although we all know what it feels like to pay attention, the concept is notoriously difficult to define. More than a century ago in what has perhaps become one of the most oft-quoted lines in psychology, William James explained attention as 'the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought' [1]. Seventy years later Anne Treisman questioned the utility of such folk-psychological definitions, arguing that conceptualizations of attention as "the focalization of consciousness" or "the increased clearness of a particular idea" . . . .[had] proved sterile for empirical research and ended in a series of inconclusive controversies'. She instead suggested that studying attention as information processing could 'open the way to a more exact linking of behavioural concepts with underlying physiological mechanisms' [2].

Treisman's words proved prescient: psychological research on attention, guided by this approach, has boomed in the past half-century. However, despite the resulting advances in our understanding of attentional processes and neural mechanisms, we still do not have a clear understanding of what kind of process attention is in the mind and brain, or whether it is a single process at all [3]. One reason for this lack of clarity, Chun, Golomb, and Turk-Browne recently observed, is that 'Attention has become a catch-all term for how the brain controls its own information processing' [3]. To advance understanding, they argue, researchers should work to understand the common and distinct mechanisms that support different forms of attention [3].

While the broad scope of what researchers mean when they say 'attention' has made the topic unwieldy to study [3], the absence of a standardized way to measure attention may have further hindered basic research and translational applications. Unlike for other abilities, such as memory and intelligence, researchers and clinicians lack a straightforward way to summarize a

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person's overall attentional function. Although complex processes often cannot be reduced to a single number, summary indices like capacity for working memory and *gF* for fluid intelligence are useful for quantifying individual differences and changes in abilities over time. A comparable measure of attention – an objective, standardized summary score – would benefit both research and clinical practice by facilitating comparisons across and within individuals, evaluations of treatments and interventions, and predictions of real-world behavior and clinical symptoms.

Here we propose that attention can be understood as an emergent property of large-scale brain networks, based on a novel framework for measuring attentional abilities with fMRI. We review empirical work showing that, although the functional organization of the brain is generally consistent across individuals, every person has a unique pattern of **functional connectivity** (see Glossary) that lies atop a common blueprint and distinguishes them from the group. These distinct connectivity patterns can be used to predict how well individual people pay attention. Predictions can be made from connectivity patterns observed as people perform attention tasks, but also from patterns observed as they are not engaged in any explicit task at all. In other words, we can measure attention using **resting-state fMRI** data alone, meaning that the neural architecture that supports attention function is reflected in the brain's intrinsic functional organization. Viewing attention as a network property of brain activity, not unlike how one might characterize the efficiency of a computer or air-traffic network, reveals insights about the nature and underlying structure of attention. Looking beyond attention, models that make individualized predictions from brain networks may have clinical benefits in translational settings and offer a new kind of solution to challenges in cognitive, clinical, and developmental neuroscience.

Attention: From Brain Areas to Brain Networks

It is hard to imagine meeting the demands of daily life without the ability to focus. Impairments in attention, which are common to clinical populations as diverse as ADHD [4], depression [5], schizophrenia [6], bipolar disorder [7], post-traumatic stress disorder [8], and traumatic brain injury [9], predict a wide range of negative outcomes, from poorer educational achievement to worse employment and job performance, peer acceptance, and family relationships [10].

Although the ability to attend varies widely even in the healthy population [11], until recently cognitive neuroscience studies of attention devoted little focus to individual differences. That is, since the early 1990s fMRI studies of human attention have focused on identifying regions of the brain where activity and/or functional connectivity is, on average, modulated by specific attentional demands. This work has been vital in identifying the basic neural architecture of attention and, from a cognitive psychological standpoint, clarifying subcomponents of attention by demonstrating that distinct processes are related to distinct patterns of brain activity. Some findings support distinctions posited by cognitive psychology, such as that between goal-directed and stimulus-driven attention [12], whereas others highlight the importance of dimensions that had been, by comparison, relatively unexplored, such as internal versus external attentional focus [13]. Despite the success of cognitive neuroscience in describing the brain bases of different forms of attention, the focus on group-level rather than single-subject-level analyses has resulted in neuroanatomical models that, on the whole, do not account for the individual differences in attention that permeate our everyday experience.

One of the earliest and most influential models of attention divided attention into three subsystems based on behavioral and neural evidence: (i) alerting, or preparing and maintaining alertness and vigilance; (ii) orienting, or directing overt or covert attention to a stimulus; and (iii) target detection/executive control, or noticing and selecting stimuli for conscious processing [14,15]. One line of behavioral evidence that alerting, orienting, and executive control are independent components of attention comes from the Attention Network Task (ANT), which

Glossary

Correlational versus predictive studies: fMRI studies of individual differences often claim that a brain-based measure 'predicts' a behavioral measure when the two are simply correlated across individuals. Following Gabrieli *et al.*, we reserve the term 'prediction' for cross-validated models; that is, models that generalize to novel individuals [86]. Although it is beyond the scope of this article, another sense in which models can be predictive is that they use baseline data from an individual to predict his or her future behavior [86]; for example, using functional connectivity to predict performance on perceptual tasks [30].

External validity: a model is externally valid when it generalizes to novel datasets; that is, when predictions are robust across the specific group of participants or data collection site. For models of traits, behavior, or symptoms to be clinically useful, they must demonstrate external validity.

Functional brain connectivity: functional connectivity is measured by correlating the BOLD signal time course, measured with fMRI, in two spatially distinct regions of the brain. Activity in regions that are strongly functionally connected fluctuates in synchrony whereas activity in regions that are weakly functionally connected changes out of sync. Functional connectivity does not necessarily imply structural connectivity; rather, functional connections are thought to reflect regions engaged in common or related processing during task performance or rest.

Functional connectivity matrix: an $m \times m$ matrix, where m is the number of nodes (brain regions) in the network. Cells represent functional connections. Cell (i,j) of the matrix represents the temporal correlation between the activity in brain region i and the activity in brain region j. Non-directional connectivity matrices are symmetrical about the diagonal. The diagonal, the correlation of a region with itself, is equal to 1.

Internal validity: a model is internally valid when it generalizes to novel individuals within a single dataset. Although leave-one-subject-out cross-validation (i.e., *k*-fold