Human Attentional Networks

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Aufmerksamkeits-Netzwerke des Menschen

Originalarbeit

Zusammenfassung

In den letzten Jahren gelang es, die Dimension Aufmerksamkeit als eine Art Organsystem mit spezifischer Anatomie sowie eigenen Schaltschemata und Funktionen zu definieren. Aufmerksamkeit kann in Form von drei untereinander verbundenen neuronalen Netzwerken im menschlichen Gehirn betrachtet werden. Diese Netzwerke bewerkstelligen spezifische Funktionen wie die Entwicklung und Aufrechterhaltung von Wachsamkeit, die Orientierung hin zum sensorischen Input und die exekutive Kontrolle. Störungen dieser Netzwerke bzw. ihrer Neuromodulatoren geht einher mit spezifischen neurologischen und psychiatrischen Defiziten. Um die Anatomie, die Schaltschemata, die Pathologie und die Entwicklung der Aufmerksamkeitsnetzwerke genauer zu studieren haben wir mittels fMRI, ERP, genetischen und Rechenmodellen behaviorale, Entwicklungs- und Patientenuntersuchungen durchgeführt. Der Aufmerksamkeitsnetzwerk-Test (ANT) wurde entwickelt um die Effektivität der drei neuronalen Netzwerke messen zu können und könnte unter Umständen als Test zur Endophänotypisierung für genetische Studien genutzt werden. Der folgende Überblick fasst die Untersuchungen unserer Arbeitsgruppe hinsichtlich normaler und psychopathologischer ANT-Testergebnisse zusammen.

Abstract

In recent years it has been possible to treat attention as an organ system with its own anatomy, circuitry and set of functions. We view attention in terms of three interrelated neural networks in the human brain. These networks carry out the specific functions of developing and maintaining the alert state, orienting to sensory input, and executive control. Damage to these networks or their chemical neuromodulators can produce specific neurological and psychiatric deficits. We have conducted behavioral, developmental, and patient studies using functional magnetic resonance imaging (fMRI), event related potentials (ERP), genetics, and computational modeling to investigate the anatomy, circuitry, pathology, and development of attentional networks. The Attentional Network Test (ANT) is developed to measure the efficiency of each of the attention networks. The ANT can also serve as an endophenotype for genetic studies on attentional networks. This paper reviews our work with the ANT in studies of normal performance and various forms of psychopathology.

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Attention as an organ system

James [1] defined attention as the taking possession of the mind in clear and vivid form of one out of what seem several simultaneous objects or trains of thought. However, the nature of attention remains elusive after more than one hundred years of active research and hundreds of publications on the subject. This is hardly surprising given that this subjective definition does not provide hints that might lead to an understanding about the operation, development, or pathology of attention.

It is now possible to view attention as an organ system with its own anatomy and circuitry. An organ system is defined as differentiated structures made up of various cell and tissues and adapted for the performance of some specific function and grouped with other structures into a system. We have defined the attentional system in functional and anatomical terms [2].

Attentional functions

Recent theories have conceptualized attention as comprising three separate functional components [3]. The attentional component of alerting subsumes the capacity to increase vigilance to an impending stimulus. While intrinsic alertness is defined as the cognitive control of wakefulness and arousal, phasic alertness represents the ability to increase response readiness of the target subsequent to an external warning stimulus in reaction time tasks.

The orienting function involves the component of attention that supports the selection of specific information among numerous sensory input. Orienting can be reflexive, as when a sudden target event directs attention to its location or it can be more voluntary as when a person searches the visual field looking for some target. Orienting often involves head and/or eye movements toward the target which is called overt orienting. Orienting that does not involve head and/or eye movement is referred to as covert orienting.

Executive control of attention involves more complex mental operations engaged during monitoring and resolving conflict between computations. Executive control is most needed in situations that involve planning or decision making, error detection, novel or not well-learned responses, conditions judged difficult or dangerous, and in overcoming habitual actions.

Attentional networks

These attentional functions are mediated by anatomically distinct neural networks. Alerting has been associated with thalamic, frontal, and parietal regions and is influenced by the cortical distribution of the brain's norepinephrine (NE) system that arises from the midbrain nucleus locus coeruleus [4, 5]. Blocking the NE system blocks the normal effect of warning signals [5]. The NE system has also been implicated in the maintaining of an alert state [6].

The orienting system for visual events has been associated such brain areas as the superior parietal lobe, temporal parietal junction and the frontal eye fields. Cholinergic systems arising in the basal forebrain may play an important role in modulating orienting. Injections of scopolamine into lateral intraparietal area (LIP) in nonhuman primates have been shown to have a specific effect (increase in reaction time and decrease in performance accuracy) on covert orienting [7] suggesting the relation of this network to Acetylcholine (ACh) and the site of this effect is not in the basal forebrain, but in the parietal lobe.

Finally, the executive control of attention involves the anterior cingulate cortex and lateral prefrontal cortical regions and is modulated by dopamine [8]. A number of neuroimaging studies have shown activation of the dorsal anterior cingulate in tasks requiring people to respond to one dimension of a stimulus rather than a strong conflicting dimension [9 – 11]. The anterior cingulate and lateral frontal cortex are target areas of the ventral tegmental dopamine system. All of the dopamine receptors are expressed in layer five of the cingulate [12].

The attentional network test (ANT)

The ANT

The Attentional Network Test (ANT) was developed to measure the efficiency of each of the attention networks [13]. The test requires subjects to press a left key for a left pointing central arrow and a right key for a right pointing central arrow. There are two flanker arrows on both left and right side of the central target. The flankers are either congruent (pointing to the same direction as the target) or incongruent (pointing to the opposite direction). Therefore, the executive control of attention can be measured by subtracting the mean reaction time (RT) of the congruent condition from the mean RT of the incongruent condition. We use subtraction of reactions times in the ANT as a measure of the efficiency of the networks.

In order to measure the alerting and orienting, four cue conditions are introduced before the appearance of the target and the target can be either above or below the central fixation point. The no cue condition is the baseline. The center cue appears on the fixation point with alerting involved only. The double cue condition has two cues at the two possible target locations with alerting involved but not orienting. The spatial cue appears on the target location with both alerting and orienting involved. The difference between no cue condition and double cue condition provides the index of the efficiency of alerting network. The difference between spatial orienting cue and center cue provides index of the efficiency of orienting network.

Interpreting the ANT scores

The ANT provides three numbers that indicate the efficiency of the networks that perform the alerting, orienting and conflict resolution functions. The full range of reaction time and accuracy data needs to be considered when interpreting the efficiency differences of these networks between groups. Consideration of the RT and error rate in each condition is essential to interpret the attentional scores and ascertain possible differences in strategies between groups.

Larger alerting numbers generally arise when one group has difficulty in maintaining alertness without a cue. For example, younger subjects have more difficulty when no cue warns them of a trial. However, in some cases larger numbers may reflect more efficient use of cues or even increased effort. As such, large RT differences between no cue and double cue may not indicate less efficient performance, but rather that subjects benefit more from the double cue condition.

For the orienting condition we generally assume that larger orienting times arise because of a difficulty in disengaging from the center cue, where no target appears. Disengagement difficulties would implicate a deficit of the type found in parietal patients. It is also possible that increased effort may facilitate more efficient use of the peripheral cue, in which case larger number could indicate improved orienting.

In general, the greater the difference between incongruent and congruent RTs, the greater the difficulty in resolving conflict. Thus, interpretation of the conflict condition is straightforward if error rates of the two groups are in the same direction. However, interpretation of this condition becomes more complex if one group shows large RT differences while the other group shows large differences in error rates. In this case, different conflict scores could reflect different strategies of approaching the task instead of differences in the ability to resolve conflict. A more conservative individual (or group) who opts for being accuracy will mainly make slower responses in the incongruent situation in which the probability of committing an error is higher. This approach results in an increased conflict RT score.

Characterizing the attentional networks

Behavioral testing

Results indicate that the ANT produces reliable estimates of alerting (47 ms), orienting (51 ms) and executive control (84 ms), and further suggest that the efficiencies of these three networks are uncorrelated [13]. In a larger study using the ANT [14], we found a significant correlation between the orienting and conflict scores. Moreover, with small changes to the paradigm, additional interactions between the network scores have been observed [15,16]. It would be surprising if the networks did not interact and influence each other in various tasks, since there are certainly connections between them. When cognitive resources are limited and rapid reactions have to be made, the processes of these networks overlap and the interactions occur.

Development

We have also adapted the ANT to study the development of attentional networks during childhood. In the child version of the ANT, five colorful fish replaced the arrows [17]. We ask the children to help us make the middle fish happy by pressing a button corresponding to the direction in which it is swimming. Visual and auditory feedbacks are provided for successful responses. On each trial, the flanker fish are swimming in either the same (congruent) or the opposite (incongruent) direction as the central fish. Similar to the adult version, different types of cues are presented before the fish, so that the efficiency of the three attentional networks can be assayed using the same subtractions as described above. Reaction time and accuracy improve at each age interval, and increases in efficiency were found for two of the three attention networks. While the alerting network developed up to and beyond age ten, and executive attention increased in efficiency and stabilized after age seven, orienting scores did not change in the age range studied.

fMRI and ERP studies

The development of functional neuroimaging techniques for human has been invaluable in the study of attention and other cognitive functions. These technological advances enabled us to use the ANT as an activation task in a series of neuroimaging studies that attempted to localize anatomical areas involved in attentional processes and explore the anatomical and temporal dynamics of the executive attention network. We conducted integrated functional magnetic resonance imaging (fMRI) and event-related potential (ERP) studies of the ANT to investigate the time course and anatomical specificity of stimulus-response conflict resolution. Overall the results suggest that the ANT does activate three mostly separate networks related to components of attention.

Psychiatric disorders and attention

The ANT has proved to be convenient and effective in evaluating attentional abnormalities associated with stroke and other brain injuries and to test a variety of clinical populations, including patients with borderline personality disorder, ADHD, and schizophrenia. Findings from these studies may prove useful in designing better interventions and determining the effectiveness of pharmacological and behavioral interventions. The ANT may also offer a model for conducting studies for several classes of psychotropic medications that are currently being developed.

Attention Deficit Hyperactivity Disorder (ADHD)

Many theories of ADHD have suggested a deficit in executive functions. However, in early work using a spatial orienting task the most compelling deficit appeared to be a difficulty in maintaining the alert state in the absence of a warning signal [18]. This difficulty might arise from right hemisphere damage which has also been reported to be a feature in many studies of ADHD. More recent studies of the full ANT have also shown problems with alerting, mostly due to the inability to hold the alert state when no warning signal was used. In one study [19], the full ANT was used to attempt to discriminate the inattentive subtype from normals and the combined subtype. The alerting network best distinguished the different forms of ADHD.

Schizophrenia

Although many studies have shown attentional abnormalities in schizophrenic patients, it is not clear whether this is a global deficit or relates to specific attentional networks. We used the ANT to test the efficiency of the three attentional networks in schizophrenic patients and normal controls. Schizophrenic patients showed a large and highly significant deficit in the executive network and a smaller but significant deficit in the orienting network, as well as in overall RT and accuracy. There was no deficit in the alerting network. These results suggest some specificity in the attentional networks impacted by the disorder. However, there is no evidence showing that the efficiencies of these three networks are related to any of the demographic factors or symptoms measured.

Borderline Personality Disorder
Borderline personality disorder is characterized by liability of affect and difficulty in interpersonal relations, with frequent incidences of suicide, self-mutilation, and violence. These difficulties may be related to disruptions of the executive attention network. Specific deficits in executive attention were found in executive attention in borderline patients compared to normal controls, and although not significant, greater than what was found in other control groups matched on the temperamental variables of negative affect and effortful control [20].

Individual differences

Considerable evidence points to disruptions of executive attention in several neuropsychiatric disorders. Given that the risk of many neuropsychiatric disorders is influenced by genetic factors, we also explored several potential genetic factors that may influence performance on the ANT.

Heritability of attentional networks
To test the heritability of the attentional networks, we first examined the heritability of each component by correlating efficiency scores in normal monozygotic (MZ) and dizygotic (DZ) twin populations [21]. The efficiency of the executive attention network demonstrated high heritability, while the alerting network showed modest heritability, and orienting showed no evidence of heritability. These results demonstrate that genetic variation may contribute to individual differences in attentional function among normal subjects.

Genetic analysis
We followed up the ANT heritability study by using the ANT as an endophenotype in a population-based human gene association study [22]. In this study, genetic variation in a series of dopaminergic candidate genes were correlated with efficiency of the executive attention network. The monamine oxidase-a (MAOA) and dopamine D4 receptor genes (DRD4) showed significant association with the efficiency of executive attention.

Mapping genetic variation onto brain activity
Subsequent imaging-genetic studies on a smaller genetically defined cohort showed that specific variants of the MAOA and DRD4 genes contribute to individual differences in activation of the anterior cingulate gyrus, insular cortex, and cerebellum [23]. Combining genetic and fMRI in this way is a new and promising avenue to explore and provide anatomical constraints on the role of candidate genes known to contribute to neuropsychiatric disorders.

Computational Modeling

Computational modeling of the brain has the potential to provide important links between neuroimaging findings and behavioral data. We are developing computational models, at both subsymbolic and symbolic levels, to simulate the three attentional networks and account for the ANT results. Results have shown that the model is capable of reproducing the behavioral data [24]. Such a model is innovative and substantive, because it is both neuroanatomically realistic and psychologically plausible, thereby offering the real possibility to link and cross-validate findings at different levels. This model is comprehensive enough to simultaneously examine multiple attentional networks and their interaction. It is able to make novel and testable predictions about normal operations and development of attention, as well as both qualitative and quantitative predictions about problems with attention, such as ADHD and schizophrenia.

Summary

One of the most important present and future contribution of cognitive neuroscience is in understanding of the sources of voluntary control of thoughts, feelings and actions. The attentional networks of the human brain are at the basis of these control systems. In this paper we defined the attention based upon anatomical and functional terms and treated attention as an organ system. We introduced the ANT as a tool to measure attentional networks. We then summarized studies conducted on independency and efficiency, development, and individual differences of attentional networks using behavioral testing, genetic analysis, and functional neuroimaging (ERP and fMRI) with normal and psychiatric populations. Several new directions centered on attentional networks are apparent from these studies. First, extend the fMRI-genetic studies by mapping genetic variation in relation to electrical recording of normal subjects. Second, conduct additional fMRI-genetic studies on candidate genes known to contribute to the risk of schizophrenia and other disorders using selected subjects. Third, combine diffusion tensor imaging (DTI) and fMRI to investigate the functional connectivity of attentional networks.

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