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An Introduction to Developmental Cognitive Neuroscience Along With Its Progress and Potential

Dr. Prahalad Kumar Meena
Assistant Professor,
Department of Zoology,
Government College Karauli Rajasthan

ABSTRACT:
The aim of cognitive and neuroscientific research is to comprehend how the mind and brain function. In the past, cognitive explanations and neural findings were so far apart that they frequently seemed to have only academic value to one another. As a means of bridging the divide between neuroscience and cognitive science, symbol processing models based on digital computers have proved unproductive since they did not correspond to what was understood about neural systems at the level of signal processing. But there is also a growing consensus among scientists that it is time for research from previously disparate domains to successfully integrate. In cognitive neuroscience, research is neither being conducted entirely from the bottom up or from the top down. It is actually a coevolutionary strategy, characterized by interaction between research domains, where research at one level serves as limits, corrections, and inspiration for research at other levels. In this paper, we focus on the progress and potential of neuroscience.
KEYWORDS-*cognitive neuroscience, brain function, integration, coevolutionary approach, research domains, progress*

I. INTRODUCTION

The study of the biological mechanisms and elements that underpin cognition is the subject of cognitive neuroscience, which focuses in particular on the neuronal connections in the brain that are important for mental processes [1]. It covers the issues of how neural networks in the brain influence or regulate cognitive functions. The fields of behavioral neuroscience, cognitive psychology, physiological psychology, and affective neuroscience all overlap with cognitive neuroscience, a component of both neuroscience and psychology. Cognitive neuroscience is based on theories from cognitive science as well as data from neurobiology, computational modeling, and other fields [2].

Important brain regions are involved in this area. Since the fundamental goal is to build an understanding of cognition from a neurological perspective, together with the various lobes of the cerebral cortex, neurons play the most important function [3]. Experimental techniques from psychophysics and cognitive psychology, functional neuroimaging, electrophysiology, cognitive genomics, and behavioral genetics are some of the techniques used in cognitive neuroscience.

An important area of cognitive neuroscience is research on people who have cognitive impairments brought on by brain injuries. The damage in brains with lesions offers a comparable place to start when compared to brains that are healthy and completely functional. These injuries alter the neuronal networks in the brain, causing it to malfunction when performing fundamental cognitive functions like memory or learning. People with learning difficulties and other brain injuries can be compared to how neural circuits in healthy people function in order to make conclusions about the neural underpinnings of the impaired cognitive processes. Brain regions like Wernicke's area, the left half of the temporal lobe, and Brocca's area near to the frontal lobe are some examples of areas that have learning problems [4].

The discipline of developmental cognitive neuroscience also studies and investigates cognitive capacities based on brain development. This demonstrates how the brain changes over time, identifying distinctions and speculating about potential causes for those differences [5].

Cognitive neuroscience, which has been a cornerstone approach in understanding the relationship between the brain and behavior, has traditionally relied on studying brain-behavior correspondence [6]. Over the years, functional neuroimaging techniques have expanded their scope beyond studying the adult brain and have ventured into exploring maturational brain changes and cognitive abilities in children, giving rise to the field of developmental cognitive neuroscience (DCN) [7].In recent times, cognitive neuroscience and DCN have undergone a shift in focus. Previously, the emphasis was on dissecting detailed psychological processes and their corresponding brain activations. However, the current trend revolves around establishing connections between complex behavioral patterns and distributed brain networks. This shift often involves the integration of various analytic strategies, including those borrowed from other fields such as machine learning. These advancements in cognitive neuroscience have introduced novel concepts and technologies that hold great promise for understanding intricate human brain functions and applying these findings to practical and beneficial applications.Nevertheless, this evolution in the scope of cognitive neuroscience also brings forth new challenges and potential obstacles that can impede progress. It is crucial to address these challenges in order to fully capitalize on the field's potential and ensure continued advancements in our understanding of the brain and its relation to behavior.

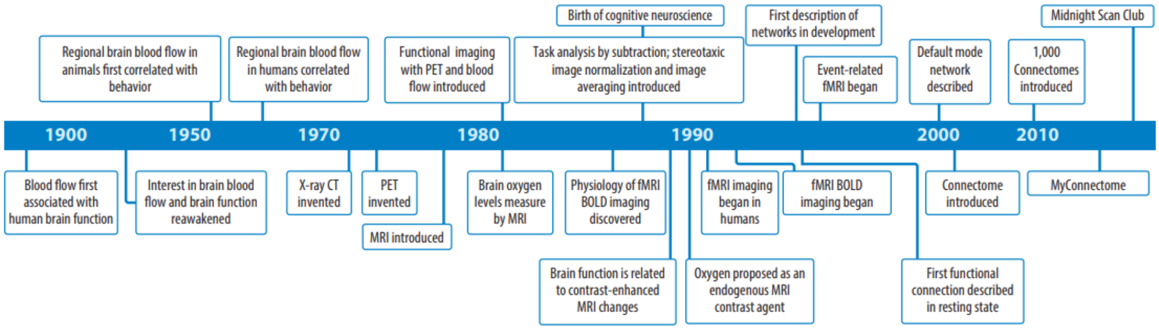

Figure 1. Timeline of developments in brain mapping and network neuroscience. Abbreviations: BOLD, blood oxygenation level–dependent; CT, computerized tomography; fMRI, functional magnetic resonance imaging; MRI, magnetic resonance imaging; PET, positron emission topography. Figure adapted with permission from Raichle (2009).

Cognitive psychology and computational neuroscience are examples of theoretical approaches.

Neuroscience and psychology have given rise to the interdisciplinary field of cognitive neuroscience. These disciplines have gone through a number of stages that altered how scholars conducted their studies and helped the field become completely established [8].

While the goal of cognitive neuroscience is to characterize the neurological underpinnings of the mind, traditionally, the field has advanced by examining how a particular region of the brain supports a particular mental skill. Early attempts to partition the brain, meanwhile, ran into difficulties. The phrenologist movement was abandoned because it was unable to support its claims with evidence from science. Brain mapping, which started with Hitzig and Fritsch's experiments and eventually developed through techniques like positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), also led to the rejection of the aggregate field view, which held that all regions of the brain participated in all behavior [9]. The development of cognitive neuroscience as a field saw important turning points in the development of gestalt theory, neuropsychology, and the cognitive revolution, bringing together concepts and methods that allowed researchers to establish greater connections between behavior and its neurological underpinnings.

As it relates to scientific study, there are at least three alternative interpretations of the word "levels" that are in use today. These interpretations include levels of analysis, levels of organization, and levels of processing.

Different sorts of inquiries that might be answered about a phenomenon are conceptually divided into levels of analysis. Munakata (2) developed a framework that defined three levels based on the idea of levels in computer science. (i) The level of computation for abstract problem analysis, which breaks the task down into its component parts (for instance, figuring out the three-dimensional structure of a moving object from successive views); (ii) The level of the algorithm, which specifies a formal procedure to complete the task by producing the right output for a given input; and (iii) the level of physical implementation [10]. According to Researcher (3), it is possible to analyses high-level computing problems without knowing the details of the algorithm used to carry out the computation. In a similar vein, he believed that it was possible to solve the second level's algorithmic difficulty without necessarily understanding how it was implemented physically.
The notion of independence has led some researchers to claim that cognitive neuroscience is not relevant.

The independence that Marr stressed, though, only applied to the formal characteristics of algorithms, not to the process by which they can be discovered. According to computational theory, algorithms can be executed on various hardware, therefore in that sense alone, they are implementation-independent. The formal point is simple: since an algorithm is formal, it does not require any particular physical components, such as vacuum tubes or $ca^{2+.}$ However, it is crucial to note that the merely formal argument cannot address the problem of how to find the algorithm utilized by a specific machine or how to arrive at the task analysis that is neurobiologically appropriate[11]. It certainly cannot inform us that the identification of the algorithms crucial to cognitive processes will be possible without a thorough knowledge of the neurological system. Furthermore, the speed, size, efficiency, and elegance of various implementations vary greatly. Once we understand how the brain functions, we can use the formal independence of algorithm from architecture to create additional machines, but it is not a tool for discovery while we do not yet understand how the brain functions. Understanding brain architecture can also be a crucial starting point and a priceless motivator for creating reliable and potent algorithms—algorithms that could perhaps explain how the brain actually performs its functions.

NEURAL CHANGES DURING LEARNING

Brain organization and function undergo changes during the learning process, and understanding these changes in comparison to developmental differences is a fascinating area of study. Thanks to the advancements in non-invasive tools like functional magnetic resonance imaging (fMRI) [12,13], we now have the means to investigate these brain-behavior questions in developing humans, which was not possible just a decade ago.Using fMRI, we can safely monitor alterations in cortical activation as individuals engage in extensive learning. This allows us to track the changes that occur within the same individual over time. Additionally, we can compare these changes with the patterns observed in younger and older children, providing insights into the developmental differences in brain activation during learning. These advancements in fMRI technology have opened up new avenues for investigating the dynamic relationship between brain function and learning processes, shedding light on the neural mechanisms underlying cognitive development.

One of the pioneering studies utilizing fMRI [14] demonstrated rapid learning effects in primary motor areas by tracking cortical changes over an extended period. Within a single session, changes in cortical activity were observed during motor sequence learning, and these changes continued to increase over weeks of training. The cortical activity became less diffuse and more focused over time. Interestingly, these findings align with results from developmental fMRI studies, which have shown that children exhibit more diffuse cortical activity compared to adolescents and adults during the performance of behavioral tasks, even when performance levels are similar across groups [15–20].

It is important to note that the differences in brain activity between age groups cannot be solely attributed to experience. Even in the absence of normal stimulation, brain maturation involves changes in neuronal connections and synaptic pruning [21]. Therefore, these findings suggest the need to explore the contributions of both maturational and experiential factors. For instance, one approach could involve comparing brain activity in mature systems with brain activity in immature systems before and after extended experience, aiming to investigate whether the immature brain engages in similar neural processes as the mature brain after extensive practice. Currently, fMRI is being utilized to trace learning-related changes in cortical areas and investigate the effects of behavioral and cognitive interventions on developmental disorders such as dyslexia and obsessive-compulsive disorder.

In addition to functional changes, learning and development also lead to neuroanatomical modifications, including alterations in the strength and number of neuronal connections and the myelination of fibers. During early development, the brain undergoes significant reorganization, generating more neuronal processes and connections than will ultimately be retained [22,23]. Learning plays a crucial role in a competition process where certain synapses are eliminated or pruned based on activity, while others are stabilized and strengthened [24,25].

Developmental studies have challenged previous assumptions about neural organization and learning. Traditionally, it was believed that the effects of visual experience were transmitted from the eye to the thalamus and then to the primary visual cortex (V1), as observed in changes to ocular dominance columns following monocular deprivation. However, recent research has demonstrated that physiological changes occur more rapidly in V1 than in the thalamus [26]. Furthermore, protein synthesis in V1 is necessary for rapid plasticity, while anatomical changes in thalamo-cortical afferents are not [27]. These findings suggest that cortical circuitry likely underlies the swift plasticity in response to visual experience or the lack thereof, while thalamo-cortical changes may contribute to the stability of these alterations.

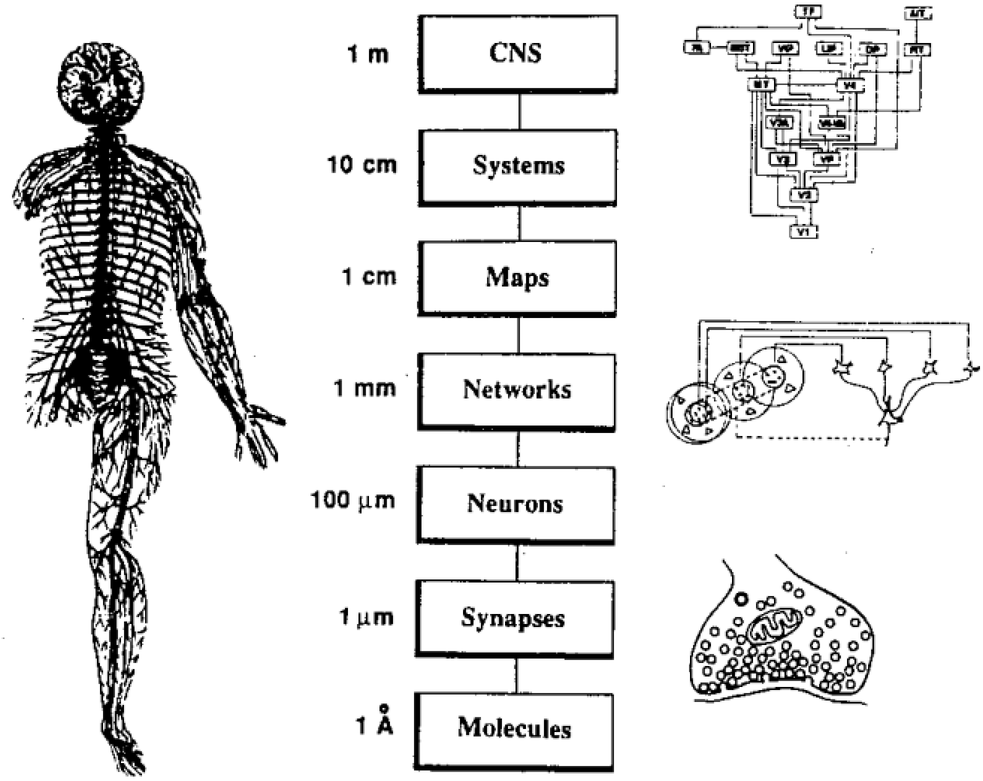

Fig. 2. Structural levels of organization in the nervous system.

LEVELS OF ORGANIZATION TO ANALYSIS MAP ONTO THE NERVOUS SYSTEM

At several scales, there is organized structure, including in molecules, synapses, neurons, networks, layers, and systems (Fig 2). Therefore, the variety of structural organization means that there are various levels of execution, each with a corresponding task description. However, this diversity will be mirrored in a plurality of algorithms that characterize how the tasks are done if there are as many different forms of task description as there are levels of structural organization. As a result, both the implementation level and the notion of the algorithmic level are grossly simplified. The structure of the nervous system, including its molecules, synapses, neurons, networks, layers, maps, and systems, is conceptually separable yet physically immovable. Different levels may be connected to psychological processes. While attention may depend on a variety of mechanisms, some of which can be found at the level of local neural networks and others at the level of larger neural systems that reside in many different locations in the brain, some perceptual states, such as the "raw" pain of a toothache, may be low-level effects [28].

process levelsThis idea could be explained as follows: The degree of information processing increases with increasing distance from cells reacting to sensory input. As a result, the level given depends on the synaptic distance from the outside regions. On this metric, cells in the lateral geniculate nucleus (LGN), which respond to directed bars of light, are at a higher level than retinal ganglion cells, which in turn are at a higher level than cells in the primary visual area of the neocortex.

As soon as the sensory data enters the cerebral cortex, it spreads out by cortico-cortical projections into numerous parallel processing streams. There are 24 visual regions in the primate visual system, and many (perhaps all) forward projections are accompanied by a back projection. Primary visual cortex also makes large amounts of feedback projections to the LGN. Given these reciprocal projections, it may appear that there is no actual hierarchy in the processing levels, but this is debatable because it is possible to organize the information flow by looking at the layer of cortex into which fibers are projected. Feedback projections typically end in the top and lower layers of the cortex, while forward projections typically end in the middle levels [29]. However, we still don't fully comprehend how these feedback pathways work. The idea of sequential processing needs to be altered if higher areas can influence how information moves through lower areas.

Not all sensory areas follow the hierarchical organization found in early sensory sections. However, processing appears to occur in webs of densely interconnected networks, as suggested by the structure of association regions and the prefrontal cortex, which supports a more "democratic" organization. An alternative to having a single control center is a system with distributed control, which could result in decisions to act as well as the implementation of plans and decisions. Both new experimental methods and new conceptual developments will be needed to deal with dispersed control systems. Perhaps through researching models of interconnected networks of neurons, new suitable metaphors for this kind of processing will become apparent.

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Research on how form, motion, and color information are processed in the visual system provides another illustration of the connection between the brain and cognition. There should be circumstances in which these specializations are disclosed if distinct components of the system are designed for specific duties, such as motion or color [31]. Consider a scenario in which the "color system" excels in distinguishing colors but struggles with other tasks, such as determining shape, depth, and motion, whereas the "shape system" is more sensitive to brightness differences than color variations. Shape detection ought to be hampered when borders are only indicated by color differences—all variations in brightness are experimentally eliminated [32]. Research in psychophysics has confirmed that this is the case. In random-dot stereograms, perceived depth collapses, shape-from-shading cues are difficult to decipher, and the perceived motion of equiluminant contours is deteriorated. Research in anatomy and physiology has started to find a potential explanation for these findings. The distinct processing streams in the cerebral cortex that were stated before contain visual data about various object characteristics. The primary channel used to convey color information, in instance, differs from those used to convey motion and depth information. Despite the imperfection of the separation, equiluminant stimuli give physiologists a visual "scalpel" for locating the correlates of perceptual coherence across various visual areas.

The knowledge gained from studying color perception may be useful for researching other cognitive areas. According to what we currently understand, just a small portion of the neurons in the visual system react in a way that is consistent with our perceptual report of color [33]. For various components of color perception, the retina and deep in the visual system are the distinct parts of the brain where connections between physiological conditions and perceptual states can be found. When the information is stored in a sizable population of interacting neurons, new experimental techniques will be required to investigate these connections.

TECHNIQUES USED AND RESEARCH STRATEGIES

While the issue of colour vision has been researched for hundreds of years, the molecular underpinnings of other perceptual and cognitive states are far less well understood. Fortunately, new methods are becoming available for noninvasively assessing human brain activity, such as regional blood flow analysis with positron emission tomography (PET) and magnetic resonance imaging (MRI). With the use of these techniques, it is possible to identify the general pattern of what is occurring in the brain at different times and locations; later, as techniques with more resolution are developed, they can be concentrated on the pertinent regions to investigate how the processing is carried out[34].

Graphing the various techniques in relation to the temporal and geographical resolution is a helpful way to gain an understanding of the various approaches. This enables us to pinpoint locations where methods to reach organisational levels at such spatio-temperal resolutions do not yet exist and to contrast their advantages and disadvantages. The processing of neural networks within cortical layers and columns over a variety of time scales, from milliseconds to hours, is one area where it is clear that we are lacking detailed information. Additionally, there is a critical need for experimental methods that focus on the dendritic and synaptic levels of the cerebral cortex [35].

Without these facts, it will be impossible to create accurate models of how cortical circuits process information. In addition to behavioural information about psychological abilities and experimental information about the characteristics of neurons, models that explain how patterns of activity in neurons represent surfaces, optical flow, and objects, how networks grow and learn to store and retrieve information, and how networks carry out sensorimotor and other types of integration are also needed. The ideal relationship between modelling and experimental research is one in which each informs, corrects, and inspires the other.

It is important to distinguish between realistic models, which are genuinely and strongly predictive of some aspect of nervous system dynamics or anatomy, and simplifying models, which, while less predicative, show that the nervous system could be governed by specific principles. This is true even though many different kinds of things are presented as models for various aspects of the nervous system. While honouring extremely general neurobiological restrictions like the number of processing units and task completion time, connectionist network models, which are simplifying models, are often motivated by cognitive phenomena and are governed primarily by computational constraints. They should therefore be viewed more appropriately as examples of what might be feasible and, occasionally, what is not. Contrarily, biological restrictions such as the physiological and anatomical characteristics of particular cell types serve as the primary motivation for realistic simulations of real neural networks. Simplifying models and realistic neural models are both founded on the mathematics of nonlinear dynamical systems in high-dimensional spaces, despite their distinct beginnings and sources of prevailing constraints. Therefore, connectionist and neural models have the potential to coevolve towards an integrated, coherent account of information processing in the mind-brain because of the shared conceptual and technical tools used in these models, which should provide bridges between two rich sources of experimental evidence.

The ultimate objective of a consolidated account does not necessitate that it be one model that covers all organisational levels. Instead, a chain of models connecting adjacent layers will likely make up the integration. When a higher level theory or phenomenon is used to explain a lower level, it does not imply that the higher level theory or phenomenon is no longer valid. As is the case in chemistry, physics, genetics, and embryology, explanations will coexist at all levels.

FUTURE DIRECTIONS

The field of developmental cognitive neuroscience has made significant progress, yet there is still untapped potential for further advancements. As we conclude, it is essential to reflect on key issues that we consider crucial in the pursuit of understanding the relationship between brain development and cognitive abilities.

Interactions and integration

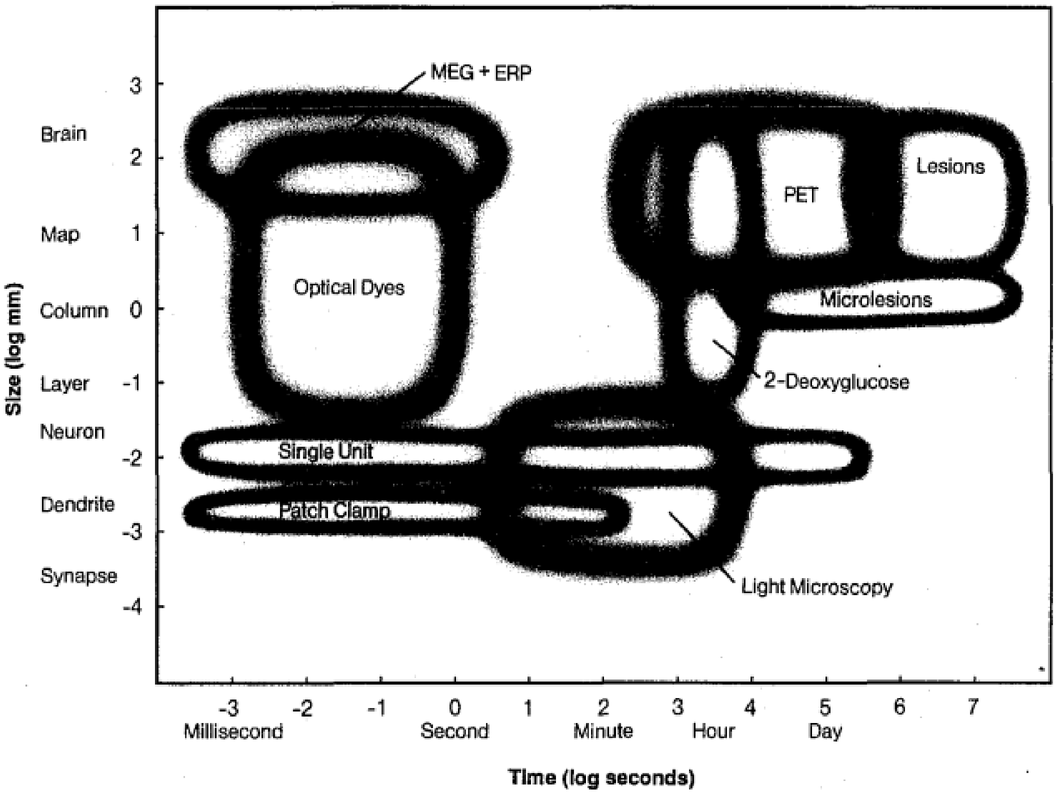
In future research, it is anticipated that there will be a shift away from dichotomous perspectives, such as nature versus nurture, domain-specific versus domain-general systems, and cognition versus emotion. Instead, there will be an emphasis on studying the developing system holistically, considering the interconnectedness of various processes. This includes examining the interactions among different neurotransmitters, as well as the interplay between chemical, physiological, and structural changes in the brain, and how these factors influence behavior and psychological development. For a comprehensive understanding of the relationship between brain development and cognitive development, it is important to incorporate the role of hormones and stress within the broader context.

Complementarity

In the field of developmental cognitive neuroscience, the integration of complementary methods will play a growing role as new tools emerge and our understanding of the relationships among various levels of developmental processes progresses. An example of this is the combination of functional magnetic resonance imaging (fMRI) with electroencephalography (EEG). This approach allows researchers to leverage the spatial resolution of fMRI to pinpoint the precise brain regions where activity changes occur, while simultaneously harnessing the temporal resolution of EEG to capture neural changes associated with rapidly unfolding cognitive processes [72]. By integrating these methods, researchers can gain a more comprehensive understanding of the dynamic interplay between brain activity and cognitive changes.

II. CONCLUSIONS

It would be useful if we could comprehend cognition's nature without comprehending the nature of the brain. Unfortunately, in the absence of neurobiological limitations, it is challenging, if not impossible, to theorize successfully on these issues. The main reason is that computational space is quite large and therefore there are numerous potential approaches to the issue of how a cognitive activity may be carried out. Because they place important limits on computational models, neurobiological data are an effective way to focus the search. Importantly, the data are also highly suggestive in terms of clues as to what might actually be happening and what computing techniques evolution might have just discovered. The specific categories of function at the cognitive levels are also still up for debate, and understanding the nature of higher level organisation may depend on our understanding of lower level function categories. Accordingly, basic neurobiology is essential in the quest to uncover the theories that account for how we carry out such functions as seeing, thinking, and being conscious, despite the fact that the brain is an empirically demanding organ.



[Fig. 3. Schematic illustration of the ranges of spatial and temporal resolution of various experimental techniques for studying the function of the brain].

On the other hand, it is ill-conceived to think that once we fully comprehend every single neuron's genesis, connection, and response characteristics, cognition will become a clear-cut science. Even if we were able to replicate every synapses in our entire nervous system, we still wouldn't fully comprehend how it functions. The simulation may not offer anything on the network and system qualities that are the key to cognitive effects, making it just as mysterious as how the brain now functions. It might be challenging to comprehend the capabilities of even simulations of small network models. Therefore, it is crucial to engage in genuine theorising about the nature of neurocomputation.

Major questions still need to be addressed. Though some issues with vision, learning, attention, and sensorimotor control are improving, it will be more difficult to accomplish this for psychological processes that are more complicated, like thinking and language. However, once we comprehend some fundamental concepts relating to how the brain works, we might be able to reformulate the current issues and find new approaches to solve them. The results are sure to surprise us no matter what happens.

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