Review Article

Structural, Functional and Cognitive Differences Between Female and Male Brains: A Neuroscientific Review

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Abstract

This review aims to systematically examine the structural, functional, and cognitive differences between male and female brains through neuroscientific findings. The process of sexual differentiation begins prenatally under hormonal influences and continues to be shaped by environmental stimuli after birth. Based on an extensive literature review, the study discusses neuroanatomical structures (e.g., corpus callosum, hippocampus, amygdalae), neural connectivity patterns, and cognitive performance variations. It also explores the influence of hormones on neurodevelopmental processes and the relationship between sex-based cognitive tendencies and individual differences. The findings indicate that gender-based distinctions should be interpreted within the framework of functional complementarity and neurodiversity, rather than superiority. Differences between male and female brains arise from a complex interplay of biological and environmental factors. These distinctions should be viewed as part of a broader spectrum of neurodiversity.

Keywords: Sex Differences, Neuroscience, Brain Structure, Hormonal Influence, Cognitive Performance.

Introduction

In recent years, sex-based differences in the brain have become an increasingly prominent focus in neuroscience research. Comparing the structural and functional features of male and female brains provides valuable insights not only into biological sex but also into diverse domains such as cognitive performance, emotional regulation, social interaction patterns, and susceptibility to psychopathology[4,5,25]. Exposure to varying levels of androgens during the prenatal period affects neurodevelopmental pathways in the brain, shaping cognitive and behavioral patterns later in life[13]. In the postnatal period, however, social learning, educational stimuli, and cultural norms play a key role in guiding cognitive development on top of this biological foundation[7]. According to the literature, women generally outperform men in domains such as verbal expression, empathy, and emotional recognition, whereas men tend to excel in spatial abilities and goal-directed tasks[11,30].

This review aims to examine the differences between female and male brains not only from a biological perspective but also within the framework of cognitive, behavioral, and environmental interactions. Alongside structural and physiological differences, the functional outcomes and real-life implications of these sex-related distinctions are comprehensively discussed.

The origins of sex-related differences in brain development are largely shaped by hormonal effects during the prenatal period. Gonadal hormones, particularly testosterone and estrogen, exert organizational influences on the nervous system throughout embryonic and fetal stages, contributing to the establishment of sex-specific neural pathways[9,13,21]. During the first 6 to 8 weeks of embryological development, the brain is not yet differentiated by sex. From the eighth week onward, testosterone secreted by the testes in male fetuses plays a decisive role in neuronal migration, synaptic connectivity, and neural plasticity[26].

The effects of testosterone are especially prominent in brain regions such as the left hemisphere language centers and the limbic system, which may lead to sex differences in cognitive abilities. Conditions such as Congenital Adrenal Hyperplasia (CAH), characterized by increased prenatal testosterone exposure, provide unique examples of hormonal influences. Females with this syndrome often display more male-typical behavioral patterns, supporting the impact of prenatal hormonal environments on cognitive and behavioral outcomes[13,16].

On the other hand, estrogen also plays a critical regulatory role in brain development. Particularly in the hippocampus, estrogen has been shown to enhance neuroplasticity, increase synaptic connectivity, and modulate stress-related neural circuits, thereby offering neuroprotective benefits[28,20]. These effects are thought to contribute to females' generally superior performance in tasks involving emotional memory, empathy, and emotional regulation.

In this context, sex differences in the brain should not be viewed solely as a consequence of biological sex. Rather, they reflect the

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enduring influence of prenatal hormonal environments that shape the neural architecture of the brain. These organizational differences, in turn, interact with environmental and social experiences throughout life, shaping cognitive and behavioral patterns in a dynamic and context-dependent manner[24].

Materials and Methods

There is no need for ethics committee approval.

Result

Although male and female brains share overall organizational similarities, substantial and systematic differences have been identified at the level of specific neuroanatomical structures. These differences have been consistently supported by neuroimaging techniques and postmortem brain studies, particularly in relation to measures such as volume, neuronal density, and connectivity[6,22,29].

On average, male brains are approximately 10–12% larger in volume than female brains[16]. However, this volumetric difference does not necessarily confer cognitive superiority. Indeed, women have been shown to exhibit higher connectivity density and functional efficiency in certain brain regions. For instance, the corpus callosum tends to be proportionally thicker in females, which may enhance interhemispheric communication and potentially contribute to superior performance in multitasking and emotional processing tasks[31,15].

Limbic system structures also exhibit sex-based differences. While females tend to have more symmetrical amygdala volumes that are functionally linked to emotional memory, males often show right-dominant amygdala activation, which has been associated with spatial orientation, risk-taking, and competitive behaviors[27]. Furthermore, the hippocampus demonstrates sex-specific patterns: while males generally show larger hippocampal volumes, females display higher neuroplasticity, which may contribute to superior performance in tasks related to memory and emotional regulation[19,3].

In terms of neuronal density, studies have shown that the male neocortex contains approximately 16% more neurons than that of females[22]. Nevertheless, this numerical advantage does not necessarily translate into functional superiority. On the contrary, it has been suggested that females achieve comparable or even superior cognitive performance through more compact and efficient neural networks, indicating a compensatory functional balance[10,17].

Differences in cognitive performance between males and females are shaped at the intersection of neurobiological and environmental factors. Neurodevelopmental processes, the effects of sex hormones, and structural brain variations may contribute to certain tendencies in how individuals process information and approach problem-solving tasks[14].

According to the literature, women generally perform better in domains such as verbal fluency, emotional recognition, and empathy, whereas men tend to outperform women in tasks requiring spatial processing, navigation, and systematic problem-solving[11,30]. These cognitive differences are thought to be underpinned by neuroanatomical variations. For example, greater involvement of prefrontal and limbic regions in females has been associated with faster responses in emotional processing and social cognition tasks[31,3].

In contrast, males often display superior performance in spatial tasks that involve mental rotation, manipulation of three-dimensional objects, and goal-directed motor coordination, which may be linked to greater right hemisphere activation and lateralization[1,16].

However, it is crucial to acknowledge that these cognitive tendencies exhibit considerable variability across individuals. Hyde's Gender Similarities Hypothesis emphasizes that sex differences are often overstated and that individual differences may be far more influential in determining cognitive abilities[14]. Therefore, these observed tendencies should not be interpreted as fixed or deterministic outcomes but should instead be considered within a flexible and context-sensitive framework.

Moreover, social learning processes, cultural norms, and educational inequalities also play a significant role in shaping these cognitive differences. Gender-based expectations can subtly influence how individuals utilize their cognitive potential[7]. As such, cognitive sex differences should be approached through a multidimensional lens that considers the complex interplay between biological, environmental, and sociocultural factors[18].

Discussion

The differences between male and female brains emerge through complex, multilayered interactions ranging from prenatal biological processes to environmental and sociocultural factors. This review has provided a systematic synthesis of the existing literature by addressing sex-related brain differences from neurodevelopmental, structural, and cognitive perspectives. The findings reveal sex-based morphological and functional distinctions in key brain regions such as the corpus callosum, hippocampus, amygdala, and prefrontal cortex. Additionally, they demonstrate relative cognitive advantages across sexes; with women generally excelling in verbal memory, emotional recognition, and empathy, while men tend to outperform in spatial processing, problem-solving, and goal-directed tasks.

However, these differences must be interpreted with caution and viewed through the lens of neurodiversity and functional complementarity, rather than being regarded as fixed or deterministic traits. The prevailing tendency to overemphasize sex differences overlooks the dynamic and experience-dependent nature of the brain. Neuroscientific evidence increasingly suggests that such differences are modifiable and shaped by environmental influences across the lifespan[14,18,23].

This review has aimed to examine the neuroscientific differences between female and male brains in accordance with the current literature, focusing on various dimensions such as hormonal influences, structural brain characteristics, and cognitive performance differences. However, several limitations should be acknowledged in the interpretation of the findings.

First, a number of the studies included in this review were conducted using animal models or relatively small sample

sizes, raising concerns about the generalizability of the results to human populations[2,29]. Second, many studies did not sufficiently control for confounding variables such as age, educational background, cultural context, and gender roles. This limitation complicates efforts to disentangle biological factors from sociocultural influences on cognitive and behavioral differences[12].

Moreover, while much of the existing literature has described sex differences at a behavioral level, the underlying neurobiological mechanisms have not been fully elucidated. Although this review has attempted to address this gap by providing critical comparisons, the limited availability of neuroimaging data means that some interpretations remain at a theoretical level rather than being fully empirically substantiated.

Finally, as this study is based on a secondary analysis of previously published literature, it does not include original experimental data. The conclusions drawn herein should therefore not be interpreted as establishing direct causal relationships. Furthermore, this review was limited to peer-reviewed and accessible academic sources; gray literature and recent preprint publications were excluded from the scope, which may have narrowed the comprehensiveness of the work.

Conclusion

Avoiding biological determinism is essential when interpreting sex-based brain differences. Neuroscientific data should be integrated with social learning theories and environmental factors to establish a holistic and ethical scientific perspective[8]. Understanding cognitive development within the broader framework of social and cultural influences will yield more balanced and nuanced interpretations.

Patient informed consent

There is no need for patient informed consent

Ethics committee approval

There is no need for ethics committee approval.

Conflict of interest

There is no conflict of interest to declare.

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Author contribution subject and rate:

- Sibel Yamac Tamkafa (80%): Design the research, data collection and analyses and wrote the whole manuscript.
- Rıdvan Ekmekçi (20%): Design the research

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