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Exploring Sex-Specific Brain Complexity in Quran Memorizers: A Fractal Dimension Approach

Abdul Halim Sapuan[1], Zafri Azran Abdul Majid[1], Mohd Izzuddin Mohd Tamrin[2] and Mohd Zulfaezal Che Azemin[3]

[1]*Department of Diagnostic Imaging and Radiotherapy, Kulliyyah of Allied Health Sciences, International Islamic University Malaysia, Kampus Kuantan, Jalan Sultan Ahmad Shah, 25200 Kuantan, Pahang Darul Makmur, Malaysia.*

[2]*Kulliyyah of Information and Communication Technology, International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia.*

[3]*Department of Optometry and Visual Sciences, Kulliyyah of Allied Health Sciences, International Islamic University Malaysia, Kampus Kuantan, Jalan Sultan Ahmad Shah, 25200 Kuantan, Pahang Darul Makmur, Malaysia.*

Correspondence should be addressed to:
Mohd Zulfaezal Che Azemin; zulfaezal@iium.edu.my

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***Abstract*— This study explores sex-specific variations in brain complexity among Quran memorizers (Huffaz) and non-Huffaz using fractal dimension (FD) analysis, a novel method for quantifying structural intricacies of the brain. By employing both box-counting and Fourier FD techniques, we analysed T1-weighted MRI scans from 47 healthy young adults, investigating whether intensive cognitive practices, such as Quran memorization, impact brain structure differently in males and females. The findings reveal significant sex-related differences in FD across multiple brain regions, with the declive, lingual gyrus, and medial frontal gyrus emerging as key areas of interest. These differences persisted even after controlling for Huffaz status, suggesting that both inherent sexual dimorphism and cognitive engagement contribute to brain complexity. The study underscores the potential of FD as a tool for understanding the nuanced interplay between sex, cognition, and brain structure, offering insights that may inform future research on brain morphology and sex-based neurological differences.**

***Keywords*— MRI; Sexual Dimorphism; Fractal Dimension; Huffaz**

I. INTRODUCTION

The human brain's complex structure and function have been a focal point of neuroscience research, particularly in understanding variations in brain morphology that contribute to cognitive and behavioural differences. Advances in computational methods have enabled detailed characterizations of brain morphology, unveiling nuanced variations in physiological and pathological contexts. Sexual dimorphism in brain morphology, which refers to structural differences between male and female brains, has garnered significant attention due to its potential implications for cognitive abilities, behaviour, and susceptibility to neurological disorders. Traditional volumetric measurements have been instrumental in providing insights into brain size and overall structure. However, they may not fully capture the intricate cortical folding patterns and structural complexity that contribute to functional differences between male and female brains.

The human cerebral cortex exhibits fractal properties [1]. To address the limitations of traditional measurements, fractal dimension (FD)—a mathematical concept from fractal geometry—has emerged as a promising method to quantify the complexity of brain structures across multiple scales [2-4]. FD captures the 'roughness' or irregularity of cortical folding patterns, offering a more nuanced and detailed measure of brain organization than conventional volumetric analyses. This allows researchers to explore structural complexities that may be linked to functional differences and cognitive abilities. FD has been applied in various neuroimaging studies to investigate developmental changes, the effects of aging, and the structural alterations associated with neurological and psychiatric disorders, such as schizophrenia and Alzheimer's disease [5]. Despite its potential, the application of FD to uncover subtle sex-related differences in brain morphology has not been extensively explored, representing a significant gap in the literature.

This study aims to bridge this gap by employing FD analysis to explore and quantify structural differences between male and female brains. Specifically, we will utilize the box-counting and Fourier FD (FFD) techniques, two widely used methods for characterizing fractal patterns in neuroimaging data [6-7]. We hypothesize that FD analysis will reveal significant differences in structural complexity between male and female brains, particularly in regions associated with cognitive functions such as memory and spatial reasoning. These differences may help explain observed functional and developmental disparities. By investigating sex-related differences in brain complexity through FD analysis, this study aims to enhance our understanding of how structural variations contribute to sex-based cognitive and behavioural differences. The findings could have important implications for tailoring neurological research and clinical practices to account for these differences.

In addition to examining sex-related differences, this study uniquely explores how intensive cognitive practices, such as Quran memorization, may influence brain complexity. By comparing Huffaz (individuals who have memorized the entire Quran) with non-Huffaz, we aim to investigate whether such cognitive engagement differentially affects male and female brain structure. This comparison aims to investigate the potential influence of intensive cognitive practices, such as Quran memorization, on brain structure, particularly in the context of sex differences. Given that sexual dimorphism is known to affect verbal and visuospatial memory, we hypothesize that the cognitive demands of Quran memorization may lead to distinct patterns of brain complexity between males and females [8]. This study not only deepens our understanding of sex-related differences in brain structure but also uniquely highlights the impact of cultural and cognitive practices, such as Quran memorization, on neuroanatomical development. This dual focus offers novel insights into the dynamic interplay between sex, culture, and cognition in shaping brain morphology.

II. METHDOLOGY

A. Subjects

The present study utilized a retrospective dataset comprising T1-weighted MRI scans from 47 healthy young adults aged 20 to 25 years. Participants were recruited based on specific inclusion criteria, including being right-handed and having no history of neurological or psychiatric illness. These criteria were confirmed through self-reported questionnaires and further validated by a neuroradiologist. The sample consisted of 19 males and 28 females, with a mean age of 22.55 years (SD = 1.472). Among them, 23 were Huffaz (12 females and 11 males), and 24 were non-Huffaz (16 females and 8 males). Detailed demographic information is presented in Table I.

TABLE I. DEMOGRAPHICS DATA OF THE PARTICIPANTS WITH TOTAL SAMPLE OF 47

Sex	**N**	**N (Huffaz, non-Huffaz)**	**Age (years), mean± SD**
Male	19	11,8	22.47±1.22
Female	28	12,16	22.64±1.57

To delve deeper into the potential impact of cognitive practices on brain structure, the cohort was strategically divided into two groups: Huffaz and non-Huffaz. The Huffaz group consisted of individuals who had recently graduated (within four years) from the Tahfiz Certificate Program at Darul Quran-IIUM, an intensive 18-month program focused on the memorization of the entire Quran. This group was selected to investigate the potential effects of rigorous and sustained cognitive training on brain structure. These individuals also actively participated in recall memorization classes, ensuring a high level of engagement with the memorized material. This strategic selection of Huffaz aimed to maintain homogeneity in brain plasticity and isolate the effects of intensive memorization. By comparing brain morphology between Huffaz and non-Huffaz, and further stratifying this analysis by sex, the study seeks to uncover potential neuroanatomical variations associated with specialized cognitive activities. This multifaceted approach not only enhances our understanding of sex-related differences in brain structure but also highlights the potential influence of cultural and cognitive practices on shaping the human brain.

B. Ethical Considerations

Ethical approval for this study was granted by the IIUM Research Ethics Committee (IREC) under reference number IREC: IIUM/504/14/11/2/ IREC 2024-040, dated 26 March 2024. All participants provided informed consent prior to their involvement in the study.

C. MRI Acquisition

High-resolution T1-weighted structural magnetic resonance imaging (MRI) data were acquired for each participant using a 3 Tesla Magnetom Siemens scanner (Erlangen, Germany) located at the Department of Radiology, IIUM Medical Centre in Kuantan, Pahang. The acquisition protocol employed a standardized 3D magnetization-prepared rapid gradient echo (MPRAGE) sequence. The following parameters were used during image acquisition: repetition time (TR) = 1880 ms, echo time (TE) = 3 ms, acquisition time (TA) = 4.23 minutes, field of view (FoV) = 250 mm in the read direction, and slice thickness = 1.0 mm with single averaging. This isotropic voxel size (1.0 mm x 1.0 mm x 1.0 mm) ensured high spatial resolution, facilitating the detailed analysis of brain morphology required for fractal dimension calculations.

D Fractal Dimension Estimation

Fractal dimension (FD) was computed for both cortical and subcortical brain regions using custom MATLAB scripts implementing the box-counting and Fourier transform algorithms. The box-counting method estimates FD by analysing the complexity of structures based on their space-filling properties, while the Fourier transform method assesses the frequency distribution of cortical patterns. These complementary approaches were chosen to provide a comprehensive assessment of brain complexity across different scales. The probabilistic atlas for Talairach Daemon [9] was employed to define and extract the specific brain structures of interest. The primary analysis involved an analysis of covariance (ANCOVA) to examine the impact of sex on gray matter (GM) volumes while controlling for the potential influence of Huffaz status (memorization expertise). This approach allowed for the identification of sex-related differences in brain morphology independent of the effects of intensive memorization. The statistical significance threshold was set at $p < 0.05$, and all analyses were conducted using SPSS (version 29.0).

III. RESULTS

A. Box Counting FD

The box-counting fractal dimension (FD) analysis identified significant sex-related differences in brain complexity across several regions, with certain patterns persisting even after controlling for Huffaz status. Controlling for Huffaz status in the box-counting FD analysis revealed that many of the observed sex-related differences remained significant, suggesting that these differences are inherent rather than influenced by Quran memorization practices. Notably, regions like the declive and lingual gyrus maintained significant sex differences even after controlling for Huffaz status. The following tables (Table II and Table III) summarize the key findings.

B. Fourier FD

The Fourier fractal dimension analysis corroborated the sex-related differences observed in the box-counting analysis, with overlapping findings in regions such as the lingual gyrus, declive, medial frontal gyrus. However, it also revealed unique differences, such as higher FD in males in the superior occipital gyrus and higher FD in females in the insula and posterior cingulate, which were not detected in the box-counting analysis. Table IV and Table V detail the results of the Fourier FD analysis, showing both uncontrolled and Huffaz-controlled outcomes. The controlled analysis highlighted that while some sex differences in FD were influenced by Quran memorization, key regions like the inferior occipital gyrus and medial frontal gyrus consistently exhibited sex-related differences regardless of cognitive training.

TABLE II. BOX-COUNTING FD-UNCONTROLLED FOR HUFFAZ. THE BRAIN REGIONS WERE ANALYSED FOR SEX DIFFERENCES IN FRACTAL DIMENSION (FD), AND THOSE SHOWING SIGNIFICANT DIFFERENCES WERE CATEGORIZED AS EITHER MAKE-DOMINAT (HIGHER FD IN MALES) OR FEMALE-DOMINANT (HIGHER FD IN FEMALES). THE MEAN FD, STANDARD DEVIATION (SD), AND P-VALUES FOR EACH GROUP ARE PROVIDED

Brain region	**Female**		**Male**		**P-value**
	Mean FD	**SD**	**Mean FD**	**SD**	
Male>female					
Claustrum	1.192	0.011	1.196	0.011	0.037
Culmen	1.710	0.005	1.714	0.006	0.027
Declive	1.715	0.002	1.717	0.002	0.001
Fusiform gyrus	1.674	0.001	1.675	0.001	0.015
Lentiform nucleus	1.486	0.012	1.495	0.010	0.017
Lingual gyrus	1.732	0.002	1.736	0.002	0.001
Pyramis	1.468	0.004	1.471	0.005	0.048
Tuber	1.540	0.006	1.543	0.004	0.044
Uncus	1.392	0.003	1.395	0.003	0.001
Uvula	1.508	0.002	1.510	0.003	0.018
Female>male					
Anterior cingulate	1.656	0.007	1.651	0.008	0.036
Culmen of vermis	0.830	0.000	0.830	0.000	0.001
Declive of vermis	0.974	0.000	0.974	0.000	0.001
Medial frontal gyrus	1.790	0.003	1.787	0.004	0.028
Parahippocampal gyrus	1.654	0.001	1.653	0.001	0.012
Postcentral gyrus	1.736	0.007	1.729	0.010	0.005
Pyramis of vermis	0.786	0.000	0.786	0.000	0.001
Superior temporal gyrus	1.809	0.001	1.808	0.002	0.023
Supramarginal gyrus	1.423	0.006	1.418	0.007	0.014
Thalamus	1.652	0.004	1.648	0.006	0.003
Tuber of vermis	0.662	0.000	0.662	0.000	0.001
Uvula of vermis	0.758	0.000	0.758	0.000	0.001

TABLE III. BOX-COUNTING FD-CONTROLLED FOR HUFFAZ STATUS

Brain Region	**P-value**
Culmen	0.026
Declive	0.005
Fusiform gyrus	0.039
Lentiform nucleus	0.023
Lingual gyrus	0.001
Medial frontal gyrus	0.045
Parahippocampal gyrus	0.014
Postcentral gyrus	0.006
Superior temporal gyrus	0.028
Supramarginal gyrus	0.025
Thalamus	0.002
Uncus	0.004
Uvula	0.019

TABLE IV. FOURIER FD-UNCONTROLLED. BRAIN REGIONS EXHIBITING SIGNIFICANT SEX DIFFERENCES IN FRACTAL DIMENSION (FD) WERE IDENTIFIED AND CLASSIFIED AS EITHER MALE-DOMINAT (HIGHER MEAN FD IN MALES) OR FEMALE DOMINANT (HIGHER FD IN FEMALES). FOR EACH CATEGORY, THE MEAN FD, STANDARD DEVIATION (SD), AND CORRESPONDING P-VALUES ARE PRESENTED

Brain region	Female		Male		P-value
	Mean FD	SD	Mean FD	SD	
Male>female					
Superior occipital gyrus	4.178	0.016	4.191	0.020	0.016
Tuber of vermis	4.792	0.002	4.793	0.003	0.007
Female>male					
Anterior cingulate	3.695	0.013	3.687	0.014	0.037
Cerebellar tonsil	3.616	0.024	3.599	0.024	0.023
Declive	3.791	0.013	3.776	0.012	0.001
Inferior semilunar lobule	3.678	0.034	3.657	0.029	0.035
Insula	3.896	0.009	3.890	0.011	0.031
Lingual gyrus	3.743	0.015	3.723	0.016	0.001
Posterior cingulate	3.646	0.011	3.632	0.014	0.001

TABLE V. FOURIER FD-CONTROLLED FOR HUFFAZ STATUS

Brain Region	P-value
Anterior cingulate	0.017
Cerebellar tonsil	0.039
Declive	0.001
Inferior occipital gyrus	0.040
Inferior semilunar lobule	0.043
Insula	0.032
Lingual gyrus	0.001
Medial frontal gyrus	0.028
Posterior cingulate	0.001
Superior occipital gyrus	0.018
Tuber of vermis	0.003

IV. DISCUSSIONS

The primary aim of this study was to investigate the potential of FD analysis as a tool for uncovering subtle sex-related differences in brain morphology. We hypothesized that FD, a measure of structural complexity, could reveal nuanced variations in brain organization between males and females. To test this hypothesis, we employed two distinct FD estimation methods, box-counting and Fourier analysis, and examined both cortical and subcortical brain regions in a cohort of healthy young adults. We further explored the potential influence of intensive memorization practices on brain complexity by comparing FD between Huffaz (individuals who have memorized the entire Quran) and non-Huffaz participants. This multifaceted approach aimed to shed light on the complex interplay between sex, cognition, and brain structure, offering novel insights into the neurobiological underpinnings of sex-related differences in cognition and behaviour.

The convergence of findings from both box-counting and Fourier fractal dimension analyses highlights the declive, lingual gyrus, and medial frontal gyrus as key regions exhibiting robust sex-related differences in brain complexity, even after accounting for the potential influence of intensive memorization practices. Regions such as the lingual gyrus, declive, and medial frontal gyrus were consistently identified across both box-counting and Fourier FD analyses, suggesting their significant role in contributing to sex-related differences in brain complexity.

The FD analyses, utilizing both box-counting and Fourier methods, unveiled a complex interplay between sex, cognitive practice, and brain complexity. Initially, numerous brain regions exhibited sex-related differences in FD, some of which persisted even after controlling for the potential influence of intensive memorization practices (Huffaz status). The persistence of sex-related differences after controlling for Huffaz status suggests that these variations may be inherent in brain organization, although other factors such as genetic or environmental influences cannot be ruled out.

In the box-counting FD analysis, regions consistently demonstrating higher FD in males included the fusiform gyrus, lentiform nucleus, and lingual gyrus. Conversely, regions with consistently higher FD in females encompassed the medial frontal gyrus, parahippocampal gyrus, postcentral gyrus, superior temporal gyrus, supramarginal gyrus, and thalamus.

The Fourier FD analysis further enriched our understanding of these differences. Controlling for Huffaz status revealed additional sex-related variations in the inferior occipital gyrus and medial frontal gyrus, underscoring the value of employing multiple methods to comprehensively capture brain complexity. The male-dominant regions identified through FFD analysis included the superior occipital gyrus and tuber of vermis (including the additional regions identified after controlling for Huffaz status). The female-dominant regions encompassed the anterior cingulate, cerebellar tonsil, declive, inferior semilunar lobule, insula, posterior cingulate, and lingual gyrus.

Notably, some initial sex differences in FD disappeared after controlling for Huffaz status, suggesting that intensive memorization practices may exert a modulating influence on brain complexity in a sex-dependent manner. This finding highlights the dynamic interplay between cognitive engagement and inherent sex-related differences in brain organization.

The findings of the present study, which reveal sex-related differences in brain complexity as measured by fractal dimension, both align and contrast with recent investigations in this emerging field. The observation of regional variations favouring both males and females echoes the broader trend in the literature, highlighting the intricate nature of brain sexual dimorphism.

The recent study by [10] in a large Chinese population, utilizing spherical harmonic reconstructions for FD estimation, provides a compelling point of comparison. In their young adult group (under 40 years old), females exhibited lower FD in the right inferior parietal lobule (IPL) and postcentral gyrus [10]. However, their whole-group analysis (age range 19-80) revealed female dominance in the bilateral rostral middle frontal gyrus, left pericalcarine cortex, and right lingual gyrus. The study by [11], also employing spherical harmonic reconstructions in a young adult population (age range 22-36), reported higher FD in males across the whole brain [11]. Finally, the study by [12] in an older population (70-90 years) revealed greater FD in males within the left thalamus, right pallidum, and bilateral amygdala highlights the potential influence of aging on sex-related differences in brain complexity [12].

The discrepancies observed between our findings and those of recent studies could indeed be attributed to several factors, including variations in sample characteristics and methodological approaches. The study by [10] involved predominantly Chinese populations, whereas our study focused on a Malaysian cohort, raising the possibility that population-specific genetic or environmental factors might contribute to the observed differences in brain complexity. The most striking methodological difference lies in the FD estimation techniques employed. While we utilized both box-counting and Fourier methods, the aforementioned studies relied on spherical harmonic reconstructions. The distinct mathematical underpinnings of these methods could lead to differential sensitivity to subtle variations in cortical folding patterns. The box-counting method, for instance, primarily assesses the space-filling properties of a structure, while spherical harmonic reconstructions analyse the cortical surface in terms of its spherical harmonic coefficients. These varying approaches might capture different aspects of brain complexity, contributing to the observed inconsistencies in sex-related differences across studies.

The lingual gyrus and declive exhibited contrasting patterns of sex-related differences depending on the FD estimation method employed. Box-counting analysis revealed higher FD in males, while Fourier analysis indicated greater complexity in females. A similar discrepancy was observed in the tuber of vermis, where box-counting favoured females and FFD favoured males. This discrepancy highlights the complexity of brain structure and suggests that different FD estimation methods may capture distinct aspects of cortical folding and organization. The box-counting method's emphasis on space-filling properties might highlight certain structural features of the lingual gyrus that differ between males and females, while the Fourier analysis's focus on spatial frequency distribution might reveal alternative patterns of variation. Despite this methodological discrepancy, the identification of the lingual gyrus as a region of interest in both analyses, along with its prominence in the findings of Chen et al. (2023), strongly suggests its importance in understanding sex-related differences in brain complexity. The lingual gyrus, implicated in various language and visual processing functions, may exhibit subtle structural variations between males and females that contribute to the observed disparities in FD. Further research is needed to elucidate the precise neuroanatomical and functional correlates of these differences, potentially shedding light on the neural underpinnings of sex-related variations in cognitive and behavioural domains.

V. LIMITATIONS

A limitation of the present study is the relatively small sample size and narrow age range, which may limit the statistical power of our analyses and restrict the generalizability of our findings to other age groups. Additionally, the scarcity of research specifically investigating sex differences in brain complexity using fractal dimension poses challenges in drawing definitive conclusions and contextualizing our results within a broader body of literature. Nevertheless, this study contributes valuable insights to the nascent but growing field of FD research, paving the way for future investigations with larger, more diverse samples that can further elucidate the complex interplay between sex, brain structure, and cognitive function.

VI. CONCLUSION

In conclusion, this study demonstrates significant sex-related variations in brain complexity, particularly in regions such as the lingual gyrus, declive, and medial frontal gyrus, as revealed through both box-counting and Fourier FD analyses. These findings contribute to the growing understanding of how sex influences brain structure. The observed regional variations in FD, with some regions showing higher complexity in males and others in females, highlight the intricate relationship between sex, cognitive engagement, and brain morphology. The modulation of these differences by Quran memorization suggests that cognitive practices can influence brain structure in a sex-specific manner. Discrepancies between our findings and those of recent studies may be attributed to differences in sample characteristics, FD estimation methods, and cultural contexts. These variations underscore the need for further research to clarify the functional implications of sex-related differences in brain complexity and to explore the influence of other cognitive activities on brain structure.

DECLARATION OF AI-ASSISTED TECHNOLOGY

During the preparation of this work the authors used Gemini Advanced to improve the manuscript's readability and language. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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