Meditation: Cognitive Mapping

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Glossary

EEG (Electroencephalography) - A non-invasive method used to record the electrical activity of the brain via electrodes placed along the scalp. EEG is significant in studying the effects on the brain from meditation.

Fractal Geometry - A field of mathematics that studies complex shapes and patterns that are self-similar across different scales. Used in various scientific fields to describe irregular and fragmented patterns.

Box-Counting Method - A method used in fractal geometry to calculate the fractal dimension of a dataset. It involves covering the object of study with boxes of various sizes and counting how many boxes are needed to cover the pattern at each size.

Lyapunov Exponent - A quantity that characterizes the rate of separation of infinitesimally close trajectories. Positive values indicate chaos and sensitivity to initial conditions in dynamical systems.

Fractal Dimension - A statistical quantity that indicates how completely a fractal appears to fill space, as the scale of measurement gets smaller. It describes the ratio of the change in detail to the change in scale.

Chaos Theory - A branch of mathematics focusing on nonlinear dynamical systems that exhibit an apparent randomness and sensitivity to initial conditions.

Computational Neuroscience - A field of science that employs mathematical models, theoretical analysis, and abstractions of the brain to understand the principles that govern the development, structure, physiology, and cognitive abilities of the nervous system.

Mind Wandering - The experience of thoughts not remaining on a single topic for an extended period, particularly when people are not engaged in a task.

Default Mode Network (DMN) - A network of brain regions that is typically active when one is not focused on the outside world and the brain is at wakeful rest, such as during daydreaming and mind-wandering.

Abstract

This research project presents an investigation into the effects of meditation on human thoughts, employing computational algorithms to analyse electroencephalogram (EEG) data.

The overarching aim is to understand how human thoughts evolve and transform during meditation sessions and to discern patterns and insights that emerge from this by using computational techniques.

The research is structured around three primary objectives:

1. Exploring human thought patterns during specific meditation techniques.
2. Assessment of Fractal Geometry and Chaos Theory in Modelling Thought Patterns in Meditation.
3. Connecting the findings with existing research and proposing practical applications and theoretical advancements.

The methodology centres on analysing EEG data collected during meditation sessions, focusing on a single meditation technique to maintain a controlled study environment. The fractal dimension of the EEG data is calculated using the box-counting method, a technique derived from fractal geometry is used to quantify the complexity of brainwave patterns during meditation.

Although the project initially aimed to include chaos theory analysis through Lyapunov exponents, computational challenges made it necessary to focus solely on fractal geometry through a mathematical technique called box-counting method.

A quantitative analysis is done on the results of the experiments performed in this project. The Findings show that the project encountered challenges, due to how it was executed as there were computational problems faced in the execution of the project. Definitive conclusions could not be drawn from EEG data analysis. These challenges have hindered the ability to achieve the desired results. Despite this, this study can showcase the potential and value of applying computational methods to the study of mediation, with results showing that definitive conclusions could not be drawn from EEG data analysis.

In conclusion, this dissertation showcases the difficulties in bridging computer science with neuroscience to study mediation.

This research project opens new avenues for future studies where computer science is applied to the field of meditation and new insights can be gained.

Chapter 1: Introduction

Meditation is a practice that spans a range of cultures and religions and has garnered scientific interest due to its health benefits. This practice has been used for thousands of years and has been embraced across Europe and North America as a tool in clinical health. (Micheal West ,1979). Meditation refers to many techniques that are loosely defined, that include meditative movement exercises, guided meditation, breathing exercises, mantras and even the involvement of different disciplines through exercises. Some of the disciplines are Yoga, Tai Chi and Qigong. (Sharma, H., 2015) That involves the focus of attention or a thought or activity to achieve a certain state. One interpretation of mediation is that it means to participate in deliberation or contemplation (Marchand W. R. (2014). Originally emerging in ancient India, meditation was primarily a spiritual and ascetic discipline. It is believed that as early as 1500 BCE, meditation was documented as integral to the religious practices in the Indian scriptures known as the Vedas. This early form of meditation focused on connecting oneself to one`s inner self. Over time mediation practices have evolved and spread across world through the development of mediation techniques and practices as well as their adoption. (Jo Nash,2019). Scientific interest in the practice called mediation began to pick attention with papers being published around the 1980s, that examined meditation's effects (Brown, D.P. and Engler, J.,1980) specifically evaluating the validity of mediation and querying the experience people have had with it, making a statement that the learning process of mediation is comparative to a cognitive skill that requires those who persist in attention and awareness training to undergo their desired results through a set of mediation experiences that occur in stages. Outside of this scope, the application of a type of relaxation meditation technique has been examined with the findings highlighting meditation's role in reducing stress. (Carrington P, et al 1980) Meditation and EEG around this period Is still in its early stages and there is a need for precisely formulated research to be done, that is scientifically valid and pushes the field further. (West, M.A., 1980). This evidence has propelled meditation research further and helped prompt it into the wellness practices of the Western world, where it is now embraced by health professionals and the mainstream public alike. The use of EEG to measure a person`s brainwaves is very common in present society, this is where sensors are attached to the scalp of a person/thing being investigated to pick up electrical signals produced by the brain, although it does have limitations it is used in healthcare to achieve goals such as investigating cognitive functions and even determining current brain activity as well as much more. (Beres, A.M., 2017).

This research paper endeavours to explore these effects further, by employing computational algorithms to analyse EEG data and uncover the underpinnings of it.

By integrating principles from chaos theory and fractal geometry, this study aims to provide a deeper understanding of the cognitive processes involved during meditation and identify patterns that could inform both theoretical advancements and practical applications.

Purpose and Justification

The purpose of this study is to explore the potential of chaos theory and fractal geometry in interpreting the complexity of EEG data obtained during meditation. As meditation moves in a realm of large-scale scientific exploration, valid scientific research is crucial to move the field of mediation research forward as well as enabling future research that results in real-world applications.

This research aims to bridge the gap between traditional meditation research and a scientific inquiry, to provide insights into the processes that occur during meditation specifically cognitive processes.

Motivation

The motivation for this stems from the interest in the tangible health benefits of meditation, which is a subject of both commercial and academic significance.

With there already existing compelling evidence supporting the positive impacts of meditation on well-being, there is a need to delve deeper into the processes that are involved.

This is particularly pressing considering the breakthroughs achieved through neural networks in artificial intelligence, sparking a question of importance: Can the application of neuroscience to the realm of meditation unlock similar revolutionary insights into human thoughts?

On a personal note, the prospect of harnessing neuroscience to decode human thoughts during meditation is thrilling. The potential for discoveries in this field could set the stage for enhanced well-being solutions and more effective meditation techniques, contributing to a world with better health and well-being solutions.

Scope and Limitations

The scope of this research is confined to the analysis of EEG data from individuals engaged in a specific meditation technique. This focus is done to ensure that there is a detailed and focused examination of the findings.

This study acknowledges the limitations surrounding the research that is done in its execution:

Misinterpretation of the Data – It is possible to incorrectly interpret the results and what they mean. Not only that, but the algorithms used to analyse the EEG data might not be properly configured to get the desired results leading to results that only partially achieve the desired result or they don`t at all. As EEG data is very complex, it is possible to not get any useful results.

Variability in individual experience - As meditation is a personal practice, the true effectiveness may be the results are not entirely true, meaning it's not possible to generalize the results due to external factors. An example of this is an individual`s level of experience with mediation, this can be an issue when interpreting data as information about a participant in a study can be confused with other variables making the interpretation of data challenging. (Davidson, R.J. and Kaszniak, A.W., 2015.)

Dissertation Structure

The dissertation is structured as follows to provide a coherent and comprehensive exploration of the research topic:

Literature Review: Examines existing research on meditation, EEG analysis, chaos theory, and fractal geometry.

Methodology: Describes the data collection process, the computational techniques used, and the rationale behind the chosen mathematical models.

Experiments and Analysis: Details the application of chaos theory and fractal geometry to EEG data, including experimental setup and data analysis methods.

Results: Presents the findings of the study, comparing them with existing literature and discussing their implications.

Conclusion and Future Work: Summarizes the study's contributions to the field and suggests directions for future research.

Problem overview

The problem that is addressed is understanding and scientifically proving how meditation affects the human brain. Traditionally, people talk about how meditation helps them, but these benefits haven’t been measured in a detailed or scientific way.

Proposed Solution

This project proposes understanding meditation through the computational analysis of EEG data, utilizing chaos theory and fractal geometry.

By conducting experiments using these mathematical techniques, the study aims to assess their effectiveness in capturing the essence of meditative brain activity.

Conclusion

In conclusion, this research project is aimed at shedding light on the cognitive processes of meditation through the application of maths chaos to EEG data analysis to help contribute insights to the understanding of mediation and its effects.

Chapter 2: Literature Review

Introduction:

The purpose of the literature review is to serve as a prologue to the contents that are in the later sections of this research paper, by reviewing and reflecting on the areas that this paper covers.

The scope of the literature is:

Mathematics - Utilizing fractal geometry and chaos theory to model human thought patterns observed during meditation via EEG data analysis and computational algorithms.

Neuroscience - Exploring the background of meditation, focusing on the phenomena of Default Mode Network (DMN) and mind wandering.

Computer Science - Applying computational techniques and EEG data analysis to decode brain wave signals during meditation.

The boundaries of the project are:

Start: The project starts with a comprehensive literature review to identify existing gaps in the understanding of meditation's impact on the human brain.

End: A conclusion of the literature review offering a review of the current state of work and areas to be explored in terms of research directions.

The methodology of the literature review is the selection of academic research papers and sources of information regarding the literature examination of the research area of human thoughts during mediation through keyword searches through research journals and through the search engines of Google search, Bing and Google Scholar.

Definitions and characteristics

Meditation- This refers to the set of techniques used during meditation to make it occur as well as referring to the practice itself and what it does. It is a practice that has a range of health benefits and there is a range of techniques but a few of the most popular ones are Transcendental Meditation, Loving-Kindness meditation and Mantra meditation.

Human Thought Patterns – Human thought patterns encompass the various types of brain waves exhibited by the human brain, which are indicative of different states cognitively and mentally. Although the ranges are the brain waves can vary, below is a general outline which is Delta (0.5-4 Hz), Theta (4-8Hz), Alpha (8-13Hz), and Beta (14-31 Hz) and Gamma (35- 80hz). Each brain wave frequency corresponds to distinct mental activities, such as deep sleep (Delta), inward-focused and deeply relaxed (Theta), restful (Alpha), and active mind (Beta) and high concertation (Gamma).

Electroencephalogram - An electroencephalogram (EEG) is a non-invasive neuroimaging technique used to record and measure electrical activity in the brain. It involves placing electrodes on the scalp to detect and amplify the tiny electrical signals generated by neurons. EEG recordings provide valuable insights into the behaviour and function of the human brain.

Fractal Geometry – Fractal geometry is a branch of mathematics concerned with the study of fractals, which are geometric shapes characterized by self-similarity at different scales. Fractals exhibit intricate and complex patterns that repeat at increasingly finer levels of detail, this detail makes it useful for modelling natural phenomena such as human brain waves as it may offer insights into the properties and behaviour of brain activity during meditation,

Chaos Theory – Chaos theory is a branch of mathematics and physics concerned with the study of nonlinear dynamical systems that exhibit sensitive dependence on initial conditions. These systems, often characterized by deterministic yet unpredictable behaviour, are governed by simple rules but can produce complex and random outcomes over time.

Box Counting Method - The box-counting method is a technique used in fractal geometry to quantify the fractal dimension of complex geometric objects or patterns. It involves dividing a space into a grid of equally sized boxes and counting the number of boxes needed to cover the object or pattern at various scales. By analysing how the number of boxes required changes with the size of the boxes, the fractal dimension of an object can be estimated.

Lyapunov Exponent- The Lyapunov exponent is a numerical measure used to quantify the rate of divergence or convergence of trajectories in dynamical systems. It characterizes the sensitivity of a system to small perturbations in its initial conditions, reflecting its degree of chaotic behaviour. A positive Lyapunov exponent indicates exponential divergence of nearby trajectories, suggesting chaotic dynamics, whereas a negative exponent signifies convergence towards a stable attractor.

Related works

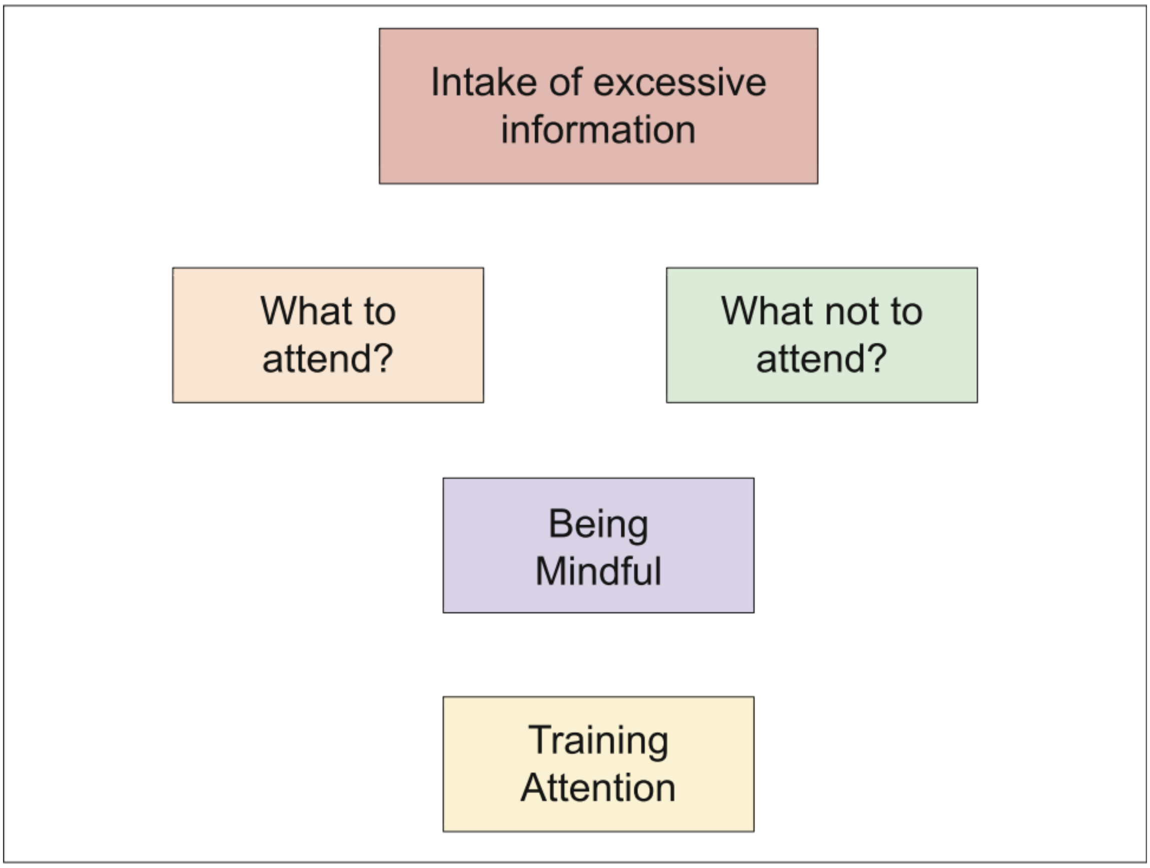
This subsection showcases how two existing studies are related to the research project that is in question in this paper and how their findings relate to the research.

(Arvidsson, A., 2018. et al). This paper gives an analysis of the neuroscience connection between meditation and the human brain, specifically investing expert-related changes induced by focused attention mediation and open monitoring mediation. The results indicate that expert meditators show greater activation in some meditation-related brain areas, as well as less activation in other areas when compared to novice meditators. The results also suggest that long-term meditation practice induces some structural changes in the brain and that meditation seems to enhance the practitioners' attentional control. These findings relate to the research project because factors of whether the individual in the EEG dataset used for experimentation and data analysis is experienced or not in the practice of mediation affect the dissemination of the results of this study. As the results can be interpreted incorrectly. This also shows that doing a focused examination on a single mediation technique makes sense as the application of computational techniques to the area of study human thoughts during mediation is a solid step towards getting viable to get results about how mediation affects the human brain. (Pagnoni, G. et al 2008)The investigation of neural correlates processing during zen meditation via the neuroimaging tool called fMRI showed that Zen practitioners displayed a reduced duration of the neural response linked to conceptual processing in regions of the default network, suggesting that meditative training may foster the ability to control the automatic cascade of semantic associations triggered by a stimulus and, by extension, to voluntarily regulate the flow of spontaneous mentation. This means improved cognitive functions like improved attention and being able to control mind-wandering. The default mode network plays a key role in the human brain and is worth investing. By outlining the neural correlates underlying meditation during this process the field can be advanced as this is an area of research with clinical relevance, that has not yet been done.

Upon reviewing these related works regarding the area of research on human thoughts during meditation, I have decided that this area of research is still early and that there is still a long way to go intill there is a conclusive answer and understanding of everything in this area, not only that but I have discovered that there are problems that understanding mind wandering during meditation would help with, especially with the health industry as a better understanding of it would result in better health solutions, one example of an immediate benefit is in the area of mental health because there would be a better understanding of the human brain due to neural correlates as well as other brain-related functions being understood during this mental practice which will result in improvements in other areas of healthcare given the fact there are studies that currently exist that show positive wellbeing effects from the practice and its effectiveness as a therapeutic tool.

Electroencephalography (EEG)

Electroencephalography (EEG) is a useful tool for delving into the neural activities associated with meditation. This significance is marked by the range of studies that have investigated meditation, specifically the processes that occur during it. Despite this, few studies fully investigate human thoughts during meditation and its effects on the human brain. A notable investigation in this field is the study of nonlinear EEG signatures to better understand mind wandering during breath-focused meditation among novice practitioners. In this study, three algorithms Higuchi's fractal dimension, Lempel-Ziv complexity, and Sample entropy in addition to a nonlinear EEG metric, reveal that EEG complexity significantly diminishes during mind wandering compared to focused meditation states. These results show the efficacy of nonlinear EEG metrics in capturing complex behaviour of the brain and the effects of meditation. (Lu C Rodriguez-Larios). There is a focused effort in using EEG when it comes to physiological research especially when it comes to analysing neural processes, however according to (Chamandeep and Singh) there is a lack of control when these studies are being conducted and better design is needed. Rigorous studies are needed that contain highly detailed approaches to scientifically explore the underlying brain functions. This is apparent as data analysis is always apparent in electroencephalography but human brain waves are complex to analyse due to their inherent noise, one of these instances is the analysis of mind wandering during meditation through machine learning, where an extensive examination was performed to analyse EEG data with the findings showing that a heightened level of band alpha activity and a heightened theta frequency. (Bruno et al 2023). In general, there is a range of things to pay attention to during meditation, despite the benefits such as the ability to sustain the mind there is a problem with not getting overwhelmed by thoughts it is deemed a common problem faced by meditation practitioners with mind wandering referred to as task unrelated thought which is very common in daily life. (Chaudhary, S et al 2022).



The figure above is a visual representation sustaining mind-full moments during mediation. (Chaudhary et al 2022).

Chaos Theory

Chaos Theory is an area of maths that deals with randomness, systems that are highly sensitive to slight changes in conditions that can give rise to big changes. This is determined by changes in initial conditions or unpredictable behaviour that follows a precise set of rules. (Bishop, R. (2015). The interpretation of complex and unpredictable events from data is an area of data analysis that involves a detailed examination of the results, a study that showcases this concerning the human brain and cognitive functions (M. Hernan Diaz et al 2015) examined the brain`s electrical activity using mathematical models specifically through time series analysis to describe the behaviour of brainwave data with the results indicating that the rate of order and chaos emerging from functional processing of the brain varies according to the difficulty of the cognitive task executed. This indicates that through nonlinear analysis of data, it's possible to gain deep insight into the physical process underlying EEG data. (Goshvarpour, A. and Goshvarpour, A., 2012) In this study machine learning was applied to analyse the human heart rate during meditation through the use of four classifier algorithms Fisher linear discriminant, Quadratic classifier, K-Nearest Neighbour and Parzen classifier, before this occurred there was the collection of EEG data and the extraction of features after the application of the machine learning algorithms the results were calculated.

Regarding the results, it was discovered that the mathematical technique called Lyapunov exponent which is from chaos theory serves as a clinically useful parameter in the analysis of data and that the algorithm called Quadratic classifier is best for classifying heart rate signals during mediation.

Fractal Geometry

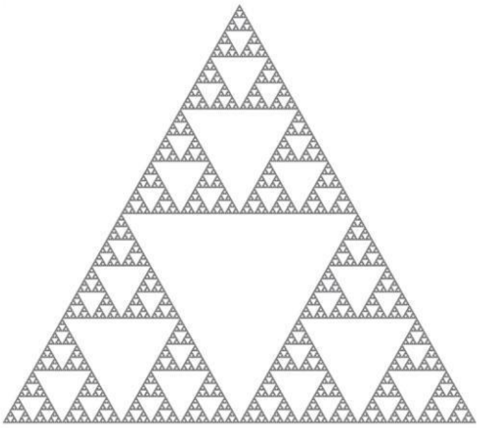
Fractal Geometry is mathematics, to be specific this is a form of repetition in a certain type of shape which is called a fractal which has these attributes:

-A fine structure, has detail on small scales.

-Possess a form of self-similar, meaning that small parts of the shape are like a larger part of it.

-A Never ending pattern, that repeats itself.

Below is an image of such a fractal shape, which is called Sierpinski triangle (MacIntosh, Andrew. (2014).)



The human brain is said to be fractal with how it's made up, this is because areas of fractal geometry can be found in the human brain, (Di leva et al 2016)

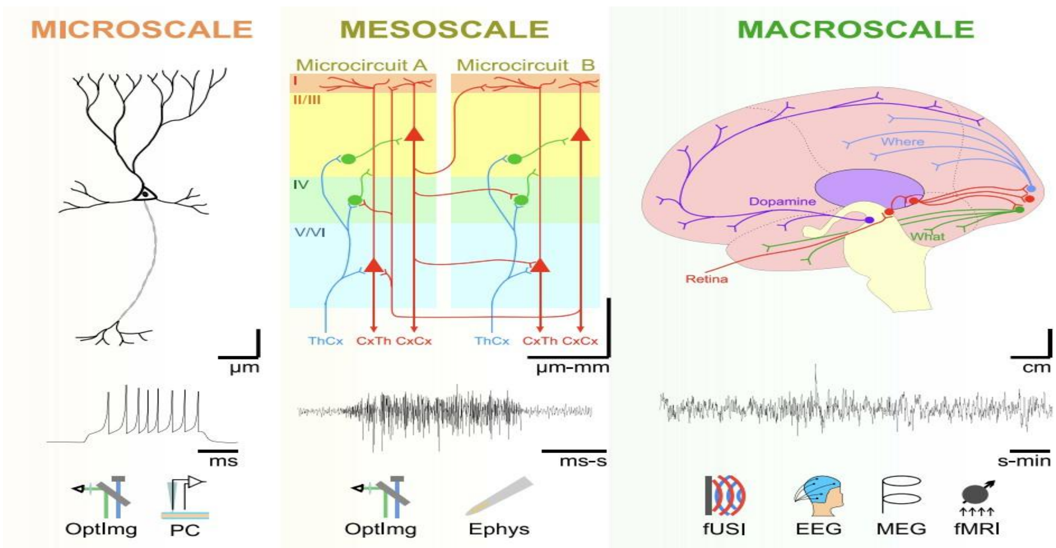


Image of the microscale, mesocale and macroscale parts of the brain (Grosu, G.F., et al 2023)

The microscale is microscopic structures, at cellular and subcellular level (µm) with dynamics expressed on very fast timescales (ms), captured with recording techniques such as optical imaging (OptImg), or patch clamp electrophysiology (PC). The mesoscale, the level of the neuronal circuits, spans a spatial range of micrometers to millimeters, with its activity being observed using optical imaging (OptImg) or extracellular electrophysiology (Ephys). In addition to this, the macroscale is at the level of brain areas and global brain networks, spanning cm in humans and with global activity traces that encompass seconds to minutes. The latter is usually observed using functional ultrasound imaging (fUSI), EEG, MEG, or fMRI.
(Grosu, G.F., et al 2023)

Literature review research questions

What role do computational algorithms play in enhancing the analysis of EEG data during meditation?

How can computational techniques transform the understanding and applications of EEG in meditation research?

Identification of relevant literature

The exploration of existing literature forms the basis of understanding the current landscape involved in this study, To ensure a comprehensive and unbiased selection of sources, a systemic strategy was implemented.

The review of the literature was facilitated by databases like Google Scholar as well as by me just findings papers through Google search and Google Bing.

Validation set from existing review

The below contains the literature used to benchmark the paper against, basically validate it.

Author	Year	Key Findings	Relevance to This Study
Sivaramakrishnan Rajaraman	2013	Reviewed various mediation techniques and their effects.	Provides a background on the nature of mediation and its effects on the mind.
Deka, B. and Deka, D	2023	Reviewed Heart Rate Dynamics during meditation and its effects.	Provides a thorough area of support in the analysis of data and info on meditation currently.
Davis, J.J.J., Lin, C.T., Gillett, G. and Kozma, R	2017	Using Computational techniques to analyse EEG has led to successfully analysing cognitive states in brain wave data.	Provides methodology foundation in support of using computational techniques to analyse EEG data analysis in meditation
Feruglio, S., Matiz, A., Pagnoni, G., Fabbro, F. and Crescentini, C	2021	Reviews Mindfulness Meditation and its Impact on Mind Wandering.	Provides an area of support in the analysis of data and explaining its behaviour.
Rajalakshmi, A. ., C Sridhar, S	2023	Understanding EEG signals significantly contributes to the benefits of meditation and yoga practices.	Outlines computational analysis of EEG and the relation of its effects on brain waves.

Exploring keywords

Category	Keywords
EEG Data Analysis	Alpha Waves in Meditation, Brainwave Patterns in Meditation, EEG Biomarkers and Meditation, Neurophysiology of Meditation, EEG Neurofeedback and Meditation, Long-term Effects of Meditation on EEG, Theta Waves and Meditation, Comparative EEG Studies in Meditation, Meditation and EEG Signal Analysis
Fractal Geometry and Chaos Theory	Fractal Geometry in Cognitive Science, Complex System and Mediation, Mathematical Models of Meditation, Fractal Brain Waves and Meditation, Fractal Analysis in Neuroscience, Fractal and Mindfulness Mediation, Chaos Theory and Human Cognition, Nonlinear Dynamics in Meditation, Chaos Theory, Fractals and Mental Health
Neuroscience	Neuroscience of mediation, brain changes in meditation, Neuroplasticity and mediation, EEG and Meditation, Mediation and neural connectivity, mindfulness and brain function, cognitive neuroscience of mediation, mediation and neurotransmitters, default mode network and mediation
Human Thoughts During Meditation	Conscious awareness during meditation, Zen meditation, Transcendental meditation, cultural practices of mediation, Himalayan Yoga meditation, Mind Wandering during meditation, Mindfulness-Based Cognitive Therapy (MBCT), Emotional Regulation through Meditation, Executive Functioning and Meditation, Neural Correlates of Meditation
Health and Wellness	Quantitative Analysis of Mediation Effects, Cognitive Process Modelling in Mediation, Computational Neuroscience, Meditation Chaos and human cognition, Fractal Geometry in Cognitive Science
Computer Science	EEG Analysis using Computer Science, Technology-assisted mediation practices, data analysis techniques in mediation studies, Computer Science in Mediation Research, Machine Learning in Cognitive Science, Computational Modelling in Meditation

Title and abstract scanning

Step	Description	Purpose
1	Gathering All Potential Research Papers	Creating a comprehensive list of literature in the field. This is to get a general overview of the field in question.
2	Reviewing Titles For Relevance	Filtering out irrelevant papers based on their title. Ensure that only relevant papers are used/mentioned in the literature review.
3	Reading And Assessing The Papers	To understand the papers that are selected in the previous step and to understand the selected literature as well as what they mean for the research study being done in this paper.
4	Classifying as relevant or irrelevant	To further refine the search criteria the papers and to ensure that only studies relevant to the research project are reviewed in the literature review.
5	Record the reasons for selection or exclusion	This is for record-keeping purposes and to maintain a transparent research process
6	Create a curated list of relevant literature	This is so I have a list to refer to when I am reviewing the literature and so I can explain the findings from the literature review.

Forwarding snowballing

Core Paper	Cited Paper	Relevance	Key Findings	Year	Cited Paper 2	Relevance	Key Findings	Year
Brandmeyer, T. and Delorme, A., 2018. (Reduced mind wandering in experienced meditators and associated EEG correlates.)	Brandmeyer, T et al (The neuroscience of meditation: classification, phenomenology, correlates, and mechanisms)	Correlates the findings with contemplative neuroscience and examines mind-wandering	Further examination is needed around terminology in mediation and certain mediation practices are characterized by distinct phenomenological experiences	2019	Pernet, C.R et al (EEG-BIDS, an extension to the brain imaging data structure for electroencephalography)	Scientifically valid standards around EEG datasets.	The creation of standards for EEG datasets	2019
Kora, P., Meenakshi, K., Swaraja, K., Rajani, A. and Raju, M.S., 2021. (EEG-based interpretation of human brain activity during yoga and meditation using machine learning: A systematic review.)	Dutta, A.K. et al (Deep learning-based multi-head self-attention model for human epilepsy identification from EEG signal for biomedical traits)	Address Machine in meditation and it examines the analysis of EEG data	There is a neural network that can analyse EEG data for epilepsy detection and it is efficient due to inherent factors like using multiple-channel EEG signals.	2024	van't Westeinde, A. and Patel, K.D.(Heartfulness meditation: A yogic and neuroscientific perspective)	A deep inspection of one type of mediation and its effects on the brain.	Heartfulness Mediation aims to develop consciousness and it is a simple mediation method.	2022
Lin, H. and Li, Y., 2017. (Using EEG Data Analytics to Measure Meditation)	Shang, B et al (EEG-based investigation of effects of mindfulness meditation training on state and trait by deep learning and traditional machine learning)	Studies the short-term effects of mindfulness meditation specifically mindfulness-based stress reduction.	Deep learning serves as a strong tool for meditation state recognition among meditation practitioners.	2023	Panachakel, J.T et al (Binary classification of meditative state from the resting state using EEG.)	Objective classification of the meditative state of the brain is attempted using EEG.	Distinguishing between the brain`s conscious states during Rejayoga meditation and rest. A system is made for this and a baseline.	2021

Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Focus	Studies focused on EEG analysis during meditation	Studies not involving EEG or Mediation.
Date	Studies published in the Last 30 years	Studies older than 30 years.
Methodology	Studies using quantitative analysis of EEG data.	Qualitative studies without empirical EEG data analysis.
Participants	Studies involving human participants practising mediation.	Studies involving non-human subjects or no meditation-related activities
Language	Studies published in English	Studies published in languages other than English.

Data extraction

Study Reference	Study Objectives	Methods Used	Key Findings	Relevance To This Study
Borghesi, F. et al.	Examine the state, trait, and neurophysiological correlates of NGALSO mediation practice.	EEG, Machine Learning, longitudinal bipolar montage, MATLAB	A Machine learning approach has led to successfully predicting and classifying data regarding the NGLASO practice.	Validates the neuroscience impact of mediation and aligns with the theme of EEG analysis.
Rodriguez-Larios, J., de Oca, E.A.B.M. and Alaerts, K.	Assess whether putative differences in the subjective experience of meditation between meditators and non-meditators are reflected in EEG spectral modulations.	EEG, Nexus-32 system and BioTrace software, 19-electrode cap, MATLAB	The subjective experience of meditation and mind wandering differs between meditators and novices and this is reflected in oscillatory and non-oscillatory properties of EEG	Validates the subjective experience individuals face in mediation and the theme of EEG data analysis.
Fucci, E et al	Asses the auditory mismatch negativity	ActiveTwo System, EEG, Biosemi ActiView data acquisition system	The study found no impact on focused attention and	Examines an area of cognitive neuroscience through computational tools and it

	Component during mediation		open monitoring meditation on auditory mismatch negativity. Publication bias might have led to studies, where the results can`t be replicated.	investigates EEG during mediation regarding this.
Lagopoulos, J et al	Assing the effects of EEG during meditation	EEG, 20 scalp electrode site, Neuroscan Quik-Cap	Nondirective meditation techniques alter theta and alpha EEG patterns significantly more than regular relaxation, in a manner that is perhaps similar to methods-based on mindfulness or concentration.	Support the area of research which is EEG data analysis of mediation and the effects of it.
Aviva Berkovich-Ohana et al	Examining EEG and Mindfulness meditation as well as what it means for the default mode network	EEG, 65-channel geodesic sensor net (EGI)	During meditation, there is an increase in alpha waves that might indicate a reduction in the brain`s default mode network activity.	Supports the analysis of EEG and the examination of underlaying functions of the brain that happen during meditation.
Faber, P.L et al	The aim is to compare brain activity in Qigong meditators during two different	EEG, Neuroscan electrode cap, portable 24-channel EEG acquisition system (TEAC AP1000)	During "Qigong," brain areas involved in self-reference and attention were more active, , while during	The ideas of processing and attention is relevant to human thoughts during mediation when it comes to studying what is occurring in the brain purely through EEG data analysis.

	meditation techniques.		"Thinking of Nothing," brain areas associated with control were more active, especially in the left hemisphere's anterior prefrontal areas. This suggests that "Qigong" meditation may focus more on self-reference and attention, while "Thinking of Nothing" meditation may involve more control-centered processing.	

Analysis

The literature review has examined areas of neuroscience, computer science and maths to understand the research area that is being investigated in this study called human thoughts during mediation. This analysis section serves as a synthesis of the findings with the literature review questions being addressed and the gaps in the current research being stated analysis as well as the research direction that this study will take to complete to get its desired results as well as linking this analysis with the three research questions and the overall aim that has been set for this study. Subjective experiences otherwise known as Qualia in psychology is a term used to review experiences that are unique to individuals meaning that can't be fully described or understood other than by the individual experiencing them, this is a common phenomenon in meditation as practitioners of this practice can have a range of experiences. (Cebolla, A., et al 2017) These experiences can vary as a few participants in a study that examined the unwanted effects of mediation, reported anxiety symptoms like panic attacks and even loss of consciousness/dizziness when performing the practice. Factors like these can affect the results of a study when it comes to interpreting data concerning understanding what it means and its implications. Neuroscience has a strong connection with machine learning especially with EEG data. (Bruder, J. (2022)The idea of putting the concept of mindfulness into artificial neural networks showcases the potential of an innovative theoretical framework that could lead to better results in the analysis of EEG mediation data. Neuroscience research has involved the analysis of EEG data using computational methods and mathematical models, to gain more insight when research projects are executed, whereas Fractal Geometry is used in the analysis of data in the healthcare industry where the mathematical method called box-counting method is used to analyse neuroimaging images and data. But Chaos Theory is used more for the analysis approach of analysing data specifically examining randomness, this is evident with lyapunov exponent being used to analyse data with the emphasis of analysing complex data.

Theme	Common Findings	Trends	Contradictions	Significance	Relation to Theoretical Framework	Impact on Understanding
Neuroscience and EEG	Extensive use of EGG with there being increased alpha and theta waves detected during mediation. The underlying functions of the brain are investigated like the functional processing of the brain to reflect brain activity.	There is a large rise towards using computational methods to analyse perform EEG data analysis.	The validity of the results of mediation research papers is a problem, as the ability to not be able to replicate results from existing research is problematic.	Highlights a common problem in research studies and brings it to attention that it is currently affecting the area of research that is called human thoughts during meditation.	Supports the hypotheses that mediation results in mind wandering and EGG can be used to discern it.	Provides a detailed understanding of meditation effects on the brain.
Fractal Geometry	Fractal Geometry provides quantitative tools like fractal dimension and permutation entropy to analyse complex data like brainwave patterns through EEG data analysis.	A trend is growing in applying fractal analysis to brainwave data to understand the underlying functions of the brain. An example of such is box-counting method.	The interpretation of quantitative data from fractal dimension can be questionable In pre-existing research studies.	Demonstrates fractal geometry applicability in the analysis of neuroimaging	Supports the hypothesis that fractal geometry could model human thoughts during mediation.	Shows fractal geometry as a viable tool to analyse neuroimaging data concerning the brain.

Chaos Theory	Chaos theory has revealed nonlinear dynamic complexity and chaotic dynamics in EEG data during meditation.	Increased use of metrics to analyse brain dynamics during mediation. An example of this is Lyapunov exponents.	Interpretation of results from studies, using chaos theory on EGG data concerning predictability.	Illustrates the complexity of brain activity , especially highlights the chaotic nature of cognitive process.	Support the theory that human cognition exhibits chaotic behaviour that can be modeled and understood through chaos theory.	Improves current understanding of the brain`s response to mediation and the need for models that describe cognitive processes in mediation.

Research Area	**Description**	**Identified Gaps**	**How Research Addresses Gaps**	**Relation to Research Questions**
Default Mode Network (DMN)	Examining the role of DMN during mind wandering and human thought during mediation.	Limited understanding of DMN effects during mediation	Utilizes EEG data analysis techniques to uncover DMN activity patterns during mediation.	Enhancing theoretical understating of DMN in cognitive processes during mediation
Mind Wandering	Investigating the patterns and effects of mind wandering during meditation.	A better understanding of mind wandering during mediation is needed.	Examines brainwave patterns during a single mediation technique to gain more insight.	Analyses data to gain a better understanding of human thought patterns during mediation

Quality Factor	Criteria	Method of Assessment	Target Outcome
Methodology	Appropriateness of research design	Review of implementation and design in the papers	The methodologies are suitable for research questions and objectives
Valid Data	Accuracy and reliability of data	Analysis of data sourcing and the data collection methods used	Confirming data authenticity and minimizing bias
Data Analysis	Robustness of data processing techniques	Evaluation of statistical and analytical methods used	The analysis methods are valid
Research Integrity	Adherence to ethical standards	Examination of ethics statement and approval	Upholding ethical standards in handling and reporting data

Conclusion of the Literature Review:

The literature review has outlined the current state of research on human thoughts during meditation and outlined gaps in the literature. Through a comprehensive review of the field ensuring that only relevant information is reviewed and information that isn't relevant is not included. This literature review has created a foundation of literature on human thoughts during meditation through EEG data analysis as well as info on the fields that are connected to this area and how they are all connected by the research that has been done over time. This sets the research direction of the methodology of the project in the direction of a focused EGG data analysis path. The literature questions have been answered through the analysis of data that has been done and it has set the main theme of the research methodology which is computer science oriented.

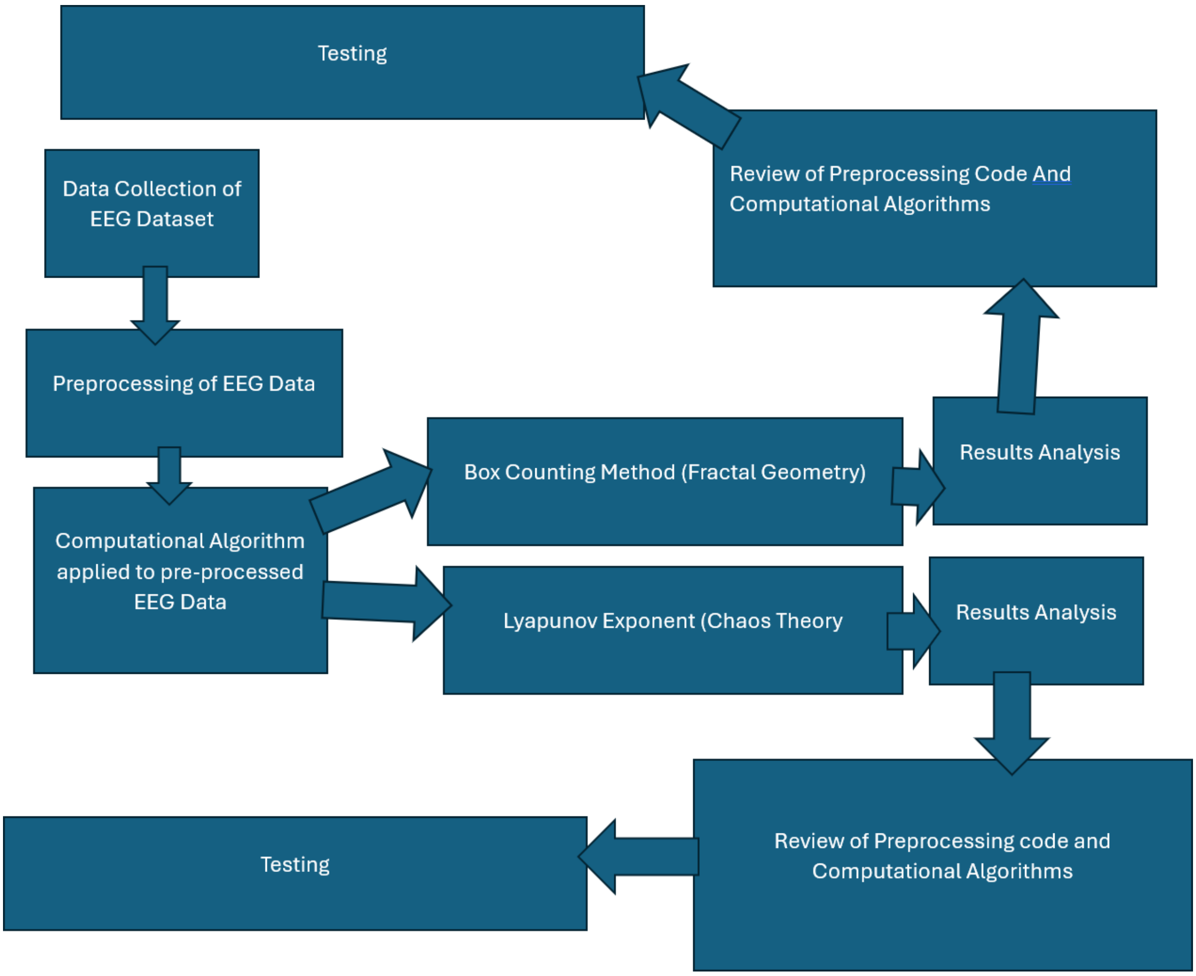
Chapter 3: Research Methodology

This chapter states the methodologies employed to investigate the cognitive effects of meditation using EEG data analysis. It outlines the quantitative strategies, tools and techniques used to analyse brainwave patterns and connect these findings.

The methodology adopts a quantitative research design for exploring specific scientific queries about the cognitive effects of meditation. This desk-based study involves data analysis to test the hypotheses concerning brainwave patterns observed in EEG data, to answer the overall aim of this study and the three research objectives. There will be an inclination towards using whichever method best answers each research question. While also working in the constraints of the resources that are available in this study, with pragmatism and action research being used concerning the attuite towards the execution of the project. The Ontological assumption is that the thoughts, feelings, and mental patterns occurring during meditation are individualistic and influenced by myriad internal and external factors, even though personal experiences during meditation are unique to everyone, there are still recognizable patterns and similarities that many people share. (Adom, Dickson et al 2016) The epistemological assumption is that knowledge is not merely discovered but constructed through human interactions and interpretations, this philosophical paradigm is crucial when dealing with data EGG that is complex. When engaging with the data involved in this study, critical realism will play a key role in terms of what can be discerned through rigorous, methodical analysis and synthesis of the results. (Zachariadis, M et al 2013) The Tools are Windows 11 laptop, Google Collab, PyCharm, Python. The approach taken is the analysis of the data that is collected in the execution of the project is an EEG dataset taken during mediation sessions with multiple human participants that are practitioners of Himalayan Yoga. This dataset is prepared already and it's secondary data. (Arnaud Delorme and Tracy Brandmeyer 2022) Two mathematical methods will be applied to the secondary data EEG dataset that will be used to gain more insight into meditation effects on the brain and how this relates to the cognitive process. The hypothesis is that by analysing the EEG for numerical results insight can be easily gained into the brain's underlying functions during mediation. The two mathematical methods used are Box counting method and Lyapunov exponent . With the viewpoint that by using the experimental method results can be gained that answer the question of meditation effects on the human brain in a measured numerical way and that through a computational method, human thoughts during meditation can be thoroughly analysed through theoretical analysis.

The Data for this study is derived from a single, pre-prepared EEG dataset obtained from OpenNeuro, a well-known database in neuroscience research. (Markiewicz, C.J 2021) .In addition to this, by using only one EEG dataset the study becomes focused and allows for a more detailed analysis resulting in more insights being gained from the experiment done in this project.

Design and Implementation



1. The EGG dataset is collected from OpenNeuro

2. The data in dataset is pre-processed so further analysis of data can occur.

3. Computational algorithms are applied to the pre-processed EEG data to see the effects of either box counting method or Lyapunov exponent on the EEG data.

4. The results are analysed, data analysis happens during this stage.

6. The computational algorithms from both Box Counting method and Lyapunov exponent are reviewed.

7. The code is evaluated for its efficiency and functionality.

Conclusion

This methodology has described all the tools that will be used in the execution of the project as well as the computational methods that will be used to extract insights from the EEG dataset that will be analysed in this study. Outside of this, additional factors like the nonlinear nature of EEG data and the statistical analysis of the results as well as measurement of variables in order to understand mediation and its effects on the human brain for example(Deolindo, C.S 2020) duration focused attention, level of mind wandering and its effects will be analysed based on the results from the experiments which is the application of Box Counting method and Lyapunov Exponent to a dataset with the results being quantitative. Quantitative is used instead of mixed methods, as despite the fact that mixed methods could lead to more insights being gained about human thoughts during meditation , there is a need for a short-term valid research paper that can be a foundation that can be later built upon by others.

Chapter 4: Evaluation

The Evaluation chapter covers the results of this study and its implications regarding the experimental work undertaken for the methodology of the project. Two types of evaluation types were used throughout the project to interpret the EEG data accurately through computational techniques. Formative Evaluation was done during the development stage of the project, periodic testing was performed on the EEG data analysis algorithms, including the pre-processing EEG script. To refine the approaches based on my viewpoint and the interpretation of the intermediate results. Summative Evaluation played the role of assessing the outcome of the experimental work to determine whether the computational methods provided new insights into the brain during meditation by comparing the final results with the objectives of the study and existing literature in the field of human thoughts during meditation. The evaluation procedure used consisted of the following four stages: Execution of Computational Algorithms and Analysis of Results - The box-counting method and Lyapunov exponent analysis are applied to pre-processed EEG data. Output from computational models is systematically analyzed to identify patterns and discrepancies. Comparison with Hypotheses - Results are compared against initial hypotheses formulated based on the literature review. Final Evaluation - Assessing the overall effectiveness and impact of the computational approaches after all analyses are complete. Documentation and Review - documenting all procedures, code changes, testing logs, and results for transparency and to facilitate reproducibility.

Chaos Theory - Lyapunov Exponent

Chaos theory examines systems that exhibit unpredictable yet deterministic behaviour, which often respond dramatically to small changes in initial conditions. The Lyapunov exponent is a quantitative measure from chaos theory that describes how rapidly nearby trajectories in a dynamical system diverge. In the context of EEG data analysis, understanding the Lyapunov exponent helps in assessing the sensitivity of brain activity to initial conditions, indicating the presence of chaotic behaviour within the brain during meditation. The results for Lyapunov exponent were calculated for each channel of the EGG data that was collected OpenNeuro with the type of mediation that was done is initial body scan and mantra mediation(Brandmeyer, T. and Delorme, A., 2018) :

The Lyapunov exponent values varied significantly across different EEG channels, indicating diverse dynamic behaviour across different regions of the brain.

Positive Exponents: Most channels exhibited positive Lyapunov exponents, suggesting chaotic dynamics in those brain regions during the meditation. Notably, the highest exponent was observed in Channel 6 with a value of 0.0312, indicating a high rate of divergence in that area.

Negative Exponents: Some channels, such as Channel 9 and Channel 21, showed negative exponents, which might indicate converging or stable dynamics in those regions during the meditation session.

Here are the Lyapunov exponents for some selected channels to illustrate the range and diversity:

Channel 0.002751386747791169

Channel 6: 0.031204801751661692 (highest positive exponent)

Channel 9: -0.004246756891022242 (negative exponent)

Channel 21: -0.002966864243236369 (negative exponent)

These variations show Lyapunov exponents across different channels could reflect the complex nature of brain dynamics during meditation. The presence of both positive and negative exponents across the channels might indicate that while some areas of the brain engage in chaotic activity, others may operate in a more stable or regular regime. (Rodriguez-Bermudez, G. and Garcia-Laencina, P.J., 2015.) The brain is widely accepted as a chaotic system and the chaotic behaviour from analysis of it with Lyapunov exponent showcases that cognitive and emotional processes involved in meditation, where certain areas of the brain may be more active or reactive while others remain stable or less engaged.

Fractal Geometry - Box-Counting Method

The Box-Counting Method is a common approach within fractal geometry used to calculate the fractal dimension of a dataset. It involves plotting the scale of observation against the number of boxes or cells that data points occupy, generally on a logarithmic scale. .(Wu, J et al 2020)This method provides a metric value known as the fractal dimension, which indicates the complexity of a waveform or a spatial pattern, such as the electrical activity of the brain captured through EEG

The Results –

The fractal dimensions are calculated from the EEG dataset using Box counting method from PyCharm–

Scale: 1, Fractal Dimension: 0

Scale: 2, Fractal Dimension: 6.321928094887362

....

Scale: 19, Fractal Dimension: 1.4882382231994553

Google Collab -

Scale: 1, Fractal Dimension: inf

Scale: 2, Fractal Dimension: -6.321928094887362

...

Scale: 20, Fractal Dimension: -1.4627564263195183

These results show negative values possibly due to an error in the calculations in the algorithms used to compute the results.(likely due to the base of the logarithm or handling of zero values). The presence of 'inf' suggests extreme values , as this suggests there is data that could not be measured.

The variations between the results from PyCharm and Google Collab indicate problems in the data , as negative fractal dimensions suggest an issue with the calculation or interpretation method.(Brewer, J. and Di Girolamo, L., 2006)

The expected trend in fractal dimension calculations usually should show a gradual decrease, reflecting the increasing homogeneity of the dataset at larger scales, which is consistent with the PyCharm results but not with the Google Collab results. This result could signal a significant point of discussion for assessing the reliability of computational methods in EEG data analysis. The use of the Box-Counting Method to compute fractal dimensions has provided insights into the structural complexity of EEG data during meditation. The results, particularly from PyCharm, help in understanding the dynamic nature of the EEG signals. However, the discrepancies observed with Google Collab results highlight the need for careful validation of computational tools and methods in scientific research. The data analysis from the results has shown that EEG data analysis using fractal geometry and chaos theory provides insight into the underlying dynamics of the brain during meditation. By applying these computational methods, this paper has shown an attempt to model and understand how human thoughts evolve and transform during meditation sessions, and how these changes might reflect on broader cognitive processes through quantitative data analysis.

Despite the computational challenges and potential errors in data interpretation, these findings provide crucial insights:

Brain Activity Modulation: The data underscores the potential of meditation to modulate brain activity, evident from the changes in calculated fractal dimensions across different scales. This modulation may correlate with the subjective experiences of depth or intensity of meditation.

Potential for Cognitive and Neurological Insights: The application of complex mathematical models like fractal geometry and chaos theory to EEG data can further our understanding of the neural underpinnings of meditation, offering a bridge between computational neuroscience and mental health therapies.

Summary of the Findings and Implications

The study's approach, using fractal geometry’s Box-Counting Method and chaos theory’s Lyapunov exponents, has highlighted both the potential and limitations of applying advanced mathematical concepts to the analysis of EEG data in meditation research. The results emphasize the need for:

Enhanced Data Processing Techniques: To address anomalies that lead to negative fractal dimensions and ensure the reliability of the findings.

Deeper Understanding of Meditation Effects: Through refined computational methods that can accurately capture the nuanced changes in brain dynamics during different meditation practices.

These insights contribute to a broader understanding of how meditation affects brain activity and can guide future research to explore the therapeutic potentials of meditation in cognitive and mental health disciplines.

Overall Aim:

The overarching aim of the study was to understand how human thoughts evolve and transform during meditation sessions and to discern patterns and insights that emerge using computational techniques.

Research Objectives:

Exploring human thought patterns during specific meditation techniques: The results from the EEG data analysis using the Box-Counting Method and Lyapunov exponent provided insights into the complexity and dynamic changes in brainwave patterns, indicating varying thought patterns during stages of meditation.

Assessment of Fractal Geometry and Chaos Theory in Modelling Thought Patterns in Meditation: The application of these mathematical models revealed details about the fractal nature and chaotic dynamics of brain activity during meditation.

Connecting the findings with existing research and proposing practical applications and theoretical advancements: The study identified connections between meditation-induced brainwave patterns and existing neuroscience theories, suggesting avenues for future research and practical applications in mental health and cognitive therapies.

Literature Review Questions and Gaps:

The results help bridge gaps identified in the literature, such as the lack of quantitative tools to measure the complexity of brain activity during meditation. The study's findings on fractal dimensions and chaotic dynamics provide quantitative measures that could be further explored in future research.

Limitations:

Data Interpretation: Negative fractal dimensions suggest potential issues in the mathematical calculation or data anomalies, limiting the interpretability of these results.

Generalizability: Since the study focused on EEG data from a single meditation technique, the findings may not be generalizable to other forms of meditation or broader populations.

Challenges:

Computational Limitations: Difficulties in accurately computing fractal dimensions and Lyapunov exponents due to the inherent complexities of EEG data.

Interpretation of Negative Values: The presence of negative values in fractal dimensions posed significant challenges in interpreting the results within the expected theoretical frameworks of fractal geometry.

Application of Findings in Real-World Scenarios:

Cognitive Therapy: Insights from the fractal and chaotic nature of EEG during meditation can be used to develop targeted therapies for mental health conditions, focusing on brainwave modulation.

Meditation Training: The findings can inform the development of biofeedback systems that help individuals optimize their meditation practices by aiming for brainwave patterns associated with positive fractal dimensions.

How Results Align or Contrast with Existing Research:

Alignment: The study supports existing research suggesting that meditation affects brainwave complexity and can modulate brain activity in measurable ways.

Contrast: Unlike some studies that report consistent increases in complexity, this study observed mixed results, including unexpected negative dimensions, indicating the need for further research to clarify these anomalies.

Interesting Point:

Dynamic Brainwave Patterns: The variability in fractal dimensions and Lyapunov exponents across EEG channels suggests that meditation induces diverse and dynamically changing brain states.

Discussion:

The study's findings highlight the complexity of interpreting EEG data through mathematical models like fractal geometry and chaos theory. While the results provide new insights into the brain's behaviour during meditation, they also underscore the challenges and limitations inherent in such complex analyses. The discrepancies in data, particularly the appearance of negative fractal dimensions, suggest that further refinement of computational techniques and models is necessary to fully harness their potential in neuroscience research.

This research marks a significant step forward in the application of computational neuroscience to meditation, opening new avenues for understanding the cognitive and neurological effects of meditation practices. It lays the groundwork for future studies to build on these methodologies, aiming for a more comprehensive understanding of meditation's impact on the human brain.

Chapter 5: Conclusion and Future Work

The project unearthed significant insights into the complexity of brainwave patterns during meditation through the application of fractal geometry and chaos theory.

The Insights include:

Chaotic Dynamics: Highlighted by the variability in Lyapunov exponents across EEG channels, suggesting the brain's sensitive response to initial conditions during meditation.

This research contributes to the fields of computational neuroscience and meditation by:

Advancing Quantitative Analysis: Introducing and validating the use of fractal geometry and chaos theory in the analysis of EEG data.

Neuroscience and Meditation: Providing a quantitative framework to understand cognitive processes during meditation, which could aid in developing targeted therapeutic and wellness practices.

Refinement of Computational Methods: To address the anomalies observed in fractal dimensions and improve the accuracy of chaos measurements.

Expanding Data Sets: To include a broader variety of meditation techniques and participant demographics to enhance the generalizability of findings.

Integration of Qualitative Analysis: To complement the quantitative data with subjective reports on meditation experiences, which could provide a more holistic understanding of the meditation effects.

The journey through this research has been both challenging and enlightening, underscoring the complexity of marrying computational techniques with neuroscience. Despite computational challenges, such as those encountered in chaos theory applications, the project underscores the potential of these mathematical frameworks to provide new insights into the physiological and psychological impacts of meditation.

Future studies should focus on overcoming the limitations of current methodologies and exploring the integration of multimodal data analysis techniques that could provide deeper insights into the meditative states. The exploration of machine learning and AI could further the ability to predict and enhance meditation outcomes based on EEG data.

In conclusion, this research has laid foundational work for using advanced computational methods to understand meditation. It has opened new avenues for future studies where computer science can be applied to the field of meditation to derive new insights. Despite the challenges, the potential for computational methods to revolutionize our understanding of meditation and its effects on the brain remains vast and untapped. The journey continues to bridge the gap between theoretical research and practical applications, aiming for a future where meditation's benefits are fully harnessed through science and technology.

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Extra information

Some parts of the project were created with the assistance of AI tools for drafting and idea refinement.