International Baccalaureate Diploma Programme

Biology

Extended Essay

Environmental Conditions on the Evolution of Hominin Brain

Research Question: Do habitat changes, indicated explicitly by shifts from quadrupedal to bipedal locomotion, affect brain development in Hominin Lineages (Asthropithecus aferensis, Asthropithecus africanus, Asthropithecus sediba, Homo erectus, Homo floresiensis, Homo neanderthalensis, and Homo sapiens) in terms of brain size?

Word Count: 3931

Table of Contents

1. Introduction

1.1. Background Information

The members of the hominin family are the only known species that can read and write these lines among the entire *regnum animale*. The uniqueness of our genus results from the selection of intelligence amidst many other traits, and understanding why such selection is not observable in other genera lineages is essential to determine its potential. In order to assay the evolution of human intelligence, this study aims to represent a rationale for the evolution of the volume of the hominin brains through million lineages and its relationship between the change in environmental conditions. In order to find out the potential relationship, if it exists, between ecological changes and intelligence, the fossil records of seven hominin species (*Asthropithecus aferensis, Asthropithecus africanus, Asthropithecus sediba, Homo erectus, Homo floresiensis, Homo neanderthalensis, and Homo sapiens*) are investigated to determine their pelvis structure and desired brain volume.

Determining the pelvis structure is essential in determining the locomotion type of the species, which is a distinctive tool to discern the species' intelligence. Locomotion types are classified under two general domains:

1) ***Quadrupedal Locomotion*** is the integrated biomechanical and neuromuscular process by which an organism employs four limbs to achieve coordinated, efficient, and adaptive movement.

2) ***Bipedal Locomotion*** which can be defined as the complex, adaptive process by which an organism achieves movement using two limbs, typically in an upright posture

The significance of these two distinctive locomotion traits are linked with and became an indicator of intelligence through several interlinked factors:

1.1.1. Liberation of the Upper Limbs

The evolution towards bipedalism freed the upper limbs from their basic role in locomotion. This new "liberation" allowed early hominins to develop sophisticated motor skills and increased manual dexterity, crucial for tool manufacture, object manipulation, and the eventual development of complex behaviours. As Darwin speculated[14] and Lieberman elaborated[30] in detail, the use of an upright posture represented a critical improvement that allowed for technological advancement and, in turn, the development of higher-order cognitive abilities[14,30].

1.1.2. Energetic Efficiency and Endurance

The shift to an upright posture not solely reduced the energetic expenditures associated with locomotion (as in comparison with energetically expensive quadrupedal traits) but also provided endurance benefits. By enabling a higher energy expenditure for brain tissue[19], bipedalism indirectly supported the evolution of intelligence by allowing early hominins to devote more resources to the metabolically demanding process[19] of developing more extensive, more complex brains.

1.1.3. Ecological and Behavioral Adaptations

An upright posture modifies hominins' interactions with their environment. For instance, bipedalism's advantages include long-distance travel and persistent hunting, which led to new foraging strategies and social behaviours. These ecological shifts necessitated advanced planning, communication, and problem-solving skills, all of which are components of higher intelligence. The transition to bipedalism, therefore, set off a cascade of adaptations that ultimately favoured cognitive development.

1.1.4. Evolutionary Contingency and Innovation:

As Lieberman testified in his essay "Four Legs Good, Two Legs Fortitious", the evolution of bipedality as a trait was a contingent event. This chance occurrence reconfigured the evolutionary trajectory of hominins[30]. This shift allowed the physical rearrangement of the body (freeing the arms) and created new selective pressures that favoured traits like tool use, complex social interaction, and, ultimately, enhanced cognitive capabilities. In this way, the locomotion type served as a foundational innovation that made subsequent evolutionary advances in intelligence possible.

1.1.5. The Social Brain Theory and Other Thesis on the Evolution of Hominin Intelligence

When the primary reason underlying the development of this and equivalent evolutionary adaptations is assessed, it is observed that the scientific conjuncture focuses on many different aspects, yet a consensus has not been reached. However, in the academic society, the acceptance of the Social Brain Hypothesis proposed by Robin Dunbar in his 1992 research depicts the quorum.

The social brain hypothesis is a hypothesis that explains a relationship between social group behaviour and neocortex size[2,3,17,31]. This hypothesis is based on a premise that as social structures in groups have grown to be more complex, people have developed increased cognitive functions to deal with sophisticated relationships[18]. The basic argument for this hypothesis is derived from evolutionary pressures that have pushed individuals to improve their ability to distinguish interactions, feelings, and social structures in sophisticated social networks in successive generations under selective pressures.

The imposition of selection pressure motivates such changes, forcing organisms to adjust to new environments. For example, hominins migrating into colder Eurasian climates would have faced novel challenges, such as seasonal food scarcity, requiring advanced planning and resource storage. Widespread migration out of the African continent resulted in dispersal to varied geographical areas, thus exposing organisms to various ecological conditions. Each habitat, characterised by different climatic conditions, food resources, and predator and prey relationships, was a challenging and intricate environmental backdrop that required adaptation.

While the hypothesis provides a necessary framework for understanding the evolution of human intelligence, it is not a complete explanation. Additionally, this hypothesis lacks a description of a basic cause for human intelligence's evolution. This research seeks to uncover the underlying cause by studying environmental changes that have been encountered by successive populations and their applicability in relation to selective pressures.

The modifications in question include climate changes[48], changes in diet[27], the need for increased cognitive capabilities in a foraging existence, and a greater complexity in tool use. However, within this set of changes, selection pressures brought about through migrations and changes in habitat have been influential.

The imposition of selection pressure is a motivating influence for such changes, forcing organisms to adjust to new environments. Widespread migration out of the African continent resulted in dispersal to varied geographical areas, thus exposing organisms to a range of ecological conditions. Each habitat, characterised by different climatic conditions, food resources, and predator and prey relationships, was a challenging and intricate environmental backdrop that required adaptation.

Environmental stressors directly impact cognitive ability selection. Inhabiting new environments requires sophisticated cognitive functions such as problem-solving, social cooperation, sophisticated communication, and creativity. This course of evolution led to increased brain size and to more sophisticated and flexible neural structures.

1.2. Hypothesis:

Null Hypothesis (H_0): Habitat changes indicated by locomotion adaptations (quadrupedal to bipedal locomotion) have no significant impact on the cranial volume hominin species.

Alternative Hypothesis: Habitat changes indicated by the transition from quadrupedal to bipedal locomotion significantly influence the evolutionary development of cranial volume in hominin species, resulting in increased brain volume and enhanced neural complexity associated with advanced cognitive functions.

1.3.Variables

Variables	Explanation	Apparatus or Value	How this Variable is Chosen	Why this Variable is Chosen
Independent Variable	Habitat Change via Locomotion Adaptaition	Bi-iliac breadth (mm) and estimated body mass (kg) are used to calculate the γ value.	Fossil specimens are selected based on the availability of reliable pelvic dimensions and body mass estimates from peer-reviewed sources.	Serves as an indicator of environmental adaptation, reflecting the transition from arboreal (quadrupedal) to terrestrial (bipedal) locomotion.
Dependent Variable	Brain Development	Cranial volume (cm^3) measured from fossil records; normalisation is achieved by calculating δ using the cranial volume divided by γ.	Selected based on the availability of accurate cranial capacity data from established databases and scholarly literature.	Evaluates the effect of locomotion adaptation (and, by proxy, habitat change) on the evolution of brain size and cognitive capacity.
Controlled Variable	Fossil Age	Secondary data from peer-reviewed academic journals and essays	Fossils with well-documented and reliable age determinations are chosen.	Controls for temporal variation, ensuring that morphological changes are compared within a coherent evolutionary framework.
Controlled Variable	Measurement Consistency	Standardised measurement protocols and calculation tools (e.g., Texas Instruments 84 CE-T Graphical Display Calculator).	Uniform methodologies are applied across all specimens, with cross-referencing among reliable sources.	Minimizes methodological biases and errors, which is critical for valid comparative analysis.
Controlled Variable	Geographical and Environmental Context	Qualitative data derived from paleoenvironmental reconstructions and published literature.	Specimens are selected from well-documented sites that provide a clear environmental	Accounts for external environmental factors that may influence both locomotion

			context.	adaptation and brain evolution, refining the overall analysis.

Table 1. The variables of the research

1.4. Methodology

1.4.1. Method Development

While developing the methodology, the locomotion type is first chosen to be classified based on qualitative descriptions of the pelvic morphology of the hominin species that are subject to this study. However, as it will be evident later, the qualitative discussion becomes insufficient and is chosen to be placed by quantitative measurement.

The original sample of hominins that are planned to be assayed under this research was widened to comprehend *Artipithecus ramidus*, *Ororin tugenensis*, *Homo ergaster*, and *Homo habilis*. However, when the scientific literature is reviewed, the absence of necessary fossil records is discovered and chosen to constrict the sample size to seven.

It was first planned to measure the Encephalization Quotient (EQ) of the species in order to have a comparison of the complexity of the intelligence; however, it is discovered that the utilisation of EQ to extinct species is a problematic methodology and may represent false assumptions. Also, this approach is withdrawn because of the absence of such information.

The locomotion type is classified under two general domains, and the environmental changes are constrained to two distinct categories in order to present a lean indication in analysing the data. Despite the conciseness, it is discovered that the adoption of this rationale is scientifically accurate and still preserves its robustness.

1.4.2. Selection of Hominin Species

- Select seven hominin species based on available and reliable fossil records. In this research it is selected:
    - *Australopithecus afarensis*
    - *Australopithecus africanus*
    - *Australopithecus sediba*
    - *Homo erectus*
    - *Homo floresiensis*
    - *Homo neanderthalensis*
    - *Homo sapiens*

1.4.3. Sample Size Selection Rationale

- The choice of the sample aligning these seven hominin species represents critical intersections in the transition from quadrupedal to bipedal locomotion. This ensures coverage of key morphological shifts relevant to the research question.

- Each of the selected species has sufficiently well-preserved and peer-reviewed morphological evidence (fossil records) pertaining to their pelvic dimensions, cranial capacity, and estimated body mass to allow accurate quantitative comparisons.

- Species with incomplete or highly speculative measurements were excluded to maintain data reliability.

- Including fossils from different geographical regions, like Africa, Eurasia, and Southeast Asia, helps in analysing the possible effect of diverse habitats on hominin morphology and cognitive development.

- The selected species display distinct pelvic morphologies that range from more arboreal, quadrupedal forms to obligate bipeds. This variation underpins the independent variable (habitat change indicated by locomotion type) and supports robust statistical comparisons.

1.4.4. Data Collection

Morphological Data:

- **Pelvic Dimensions:** Extract bi-iliac breadth measurements (mm) from reputable paleoanthropological sources.

- **Body Mass Estimates:** Collect corresponding body mass (kg) estimates, ensuring consistency in methodology across sources.

- **Brain Volume:** Gather cranial capacity (cm^3) from peer-reviewed journals or established databases.

Environmental and Habitat Context:

- Supplement morphological data with qualitative habitat information (e.g., open savanna vs. forested environment).

Data Reliability and Validation:

- Employ **cross-referencing** among sources to minimise errors.

1.4.5. Variable Standardisation

- Use bi-iliac breadth per mass to confirm the degree of pelvic narrowing relative to body mass (as an indication of bipedal adaptation) by utilising the formula:

$$\gamma = \frac{bi-iliac\ breadth\ (mm)}{mass\ of\ the\ species\ (kg)}$$

- Use normalised cranial volume to provide a metric for brain size standardised by pelvic morphology. Utilise the formula:

$$\delta = \frac{Cranial\ Volume\ (cm^3)}{\gamma\left(mm\cdot kg^{-1}\right)}$$

1.4.6. Correlation Analysis

- Perform Pearson's Correlation to asses the linear relationship between γ and δ
- Use Simple Linear Regression to model δ as a function of γ. Compute 95% confidence intervals for the slope and intercept to evaluate the reliability of the trend.
- If the p-value is less than 0.05, the null hypothesis (as there is no significant impact of habitat changes on brain evolution) will be rejected.
- The null hypothesis will not be rejected if the p-value is equal to or greater than 0.05.

2. Data Analysis

In order to conduct a comprehensive analysis of the relationship between environmental shifts and human intelligence, a three-step approach will be followed. As for the first step, the pelvic structure (especially their bi-iliac breadth) of the hominins in question is assayed, and their predisposition to bipedal locomotion as an indicator of change in habitat (*see 1.1. & Table 2*) is discussed. As for the second step, the hominin species' cranial volume (as a 1:1 indicator of brain volume) is listed (*see Table 4*). For the third step, the comparison between bipedal locomotion and brain volume is assessed, and environmental changes are discussed.

Name of the Hominin (*Genus species*)	**Fossil ages** (kya)	**Bi-iliac Breadth**[42,43] (mm)	**Estimated Body Mass** (kg)
Au. afarensis[35,44]	3180	268.3	24.1
Au. africanus[7,15]	2500	256.3	29.0
Au. sediba[27]	2000	250.0	35.5
H. erectus[12,23]	1150	288.0	66.0
H. neanderthalensis[1]	430	158.0	65.0
H. floresiensis[4,28,]	74 - 14	123.0	32.5
H. sapiens[19]	300	261.0	77.1

Table 2. The fossil ages, bi-iliac breadth and estimated body mass of hominin species. The fossil ages are given in kilo years ago; the bi-iliac breadth is given in millimetres, and the estimated body mass is shown in kilograms.
Au: Australopithecus, H: Homo.

As if the body mass of the species in question were the same, depressions in the bi-iliac breadth would indicate the aptitude of predisposition to bipedal locomotion of the species as the upright walking on two feet is intervened with narrowing in pelvic morphology. However, as the samples gathered are not on the same mass, it is found appropriate to measure the bi-iliac breadth per mass to have a standardised comparison of the pelvic morphology of the hominin species. In order to find out the bi-iliac breadth per mass, the following formula is used:

$$\gamma = \frac{bi\text{-}iliac\ breadth\ (mm)}{mass\ of\ the\ species\ (kg)}$$

where;

- γ: is the bi-iliac breadth per mass $\left(mm \cdot kg^{-1}\right)$

The γ is calculated for each hominin species which are investigated under this research and are displayed in *Table 3*. As a sample calculation, the γ value of *Au. afarensiensis* is shown below, and other γ values are calculated with the help of *Texas Instruments 84 CE-T* Graphical Display Calculator (GDC). The results are given corrected to three significant figures.

$$\gamma_{Au.\,aferensiensis} = \frac{268.3\ (mm)}{24.1\ (kg)} = 11.1$$

Name of the Hominin **(*Genus species*)**	γ $\left(mm \cdot kg^{-1}\right)$
Au. afarensis	11.1
Au. africanus	8.84
Au. sediba	7.04
H. erectus	4.43
H. neanderthalensis	2.43
H. floresiensis	3.78
H. sapiens	3.38

Table 3. Bi-iliac breadth per estimated body mass of hominin species is represented by γ *and measured in millimetres per kilogram.*
Au: Australopithecus, H: Homo.

As our objective is to obtain a comparison of the evolution of the brain volumes of the hominin species through lineages and environmental changes, it is found appropriate to assay the significance and correlation of the γ value and the fossil age. In order to assess that, the γ values and fossil ages are plotted on *Diagram 1* and a best-fit line is drawn. Then, Pearson's correlation coefficient (r) is calculated.

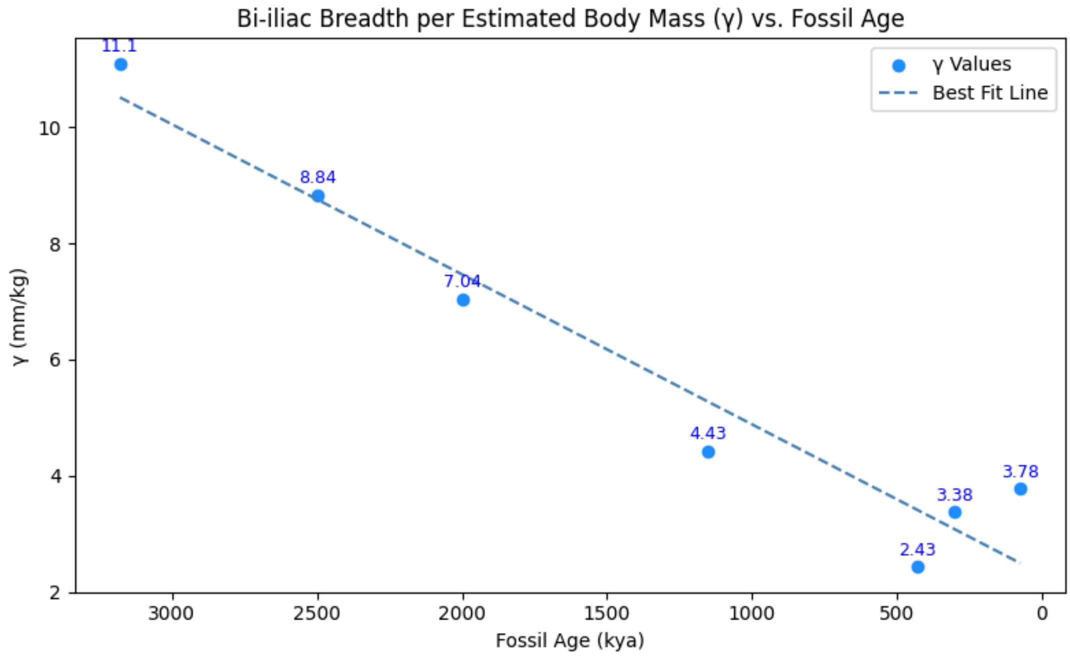

Diagram 1. Graph of Bi-iliac breadth per estimated body mass of hominin species is represented by γ fossil ages given in kilo years.

It is observed from *Diagram 1* that, as the age of the fossil approaches to today, the γ value tends to decrease since the formula of the best-fit line is approximately:

$$\gamma = 0.0020 \times Fossil\ Age + 2.1313$$

where 0.0020 indicates a positive slope. However, to propose a mathematically accurate correlation, the calculation of Pearson's correlation coefficient is performed by following the formula:

$$r = \frac{\sum_{i=1}^{n}\left[\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2 \sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2}}$$

where:

- r: is the Pearson's correlation coefficient
- x_i: is the fossil ages
- y_i: is the γ values calculated
- $\bar{x}$: is the arithmetic mean of fossil age values
- $\bar{y}$: is the arithmetic mean of the γ values

If the calculations are performed with the help of GDC, it is found that;

$$r \approx 0.968$$

Pearson's correlation coefficient indicates a strong, positive correlation as the r value converges to 1, proving that as fossil age (in kya) increases, bi-iliac breadth per body mass also predisposes to be larger.

It is shown mathematically, as the lineage of the *genus Homo,* as generations pass, the tendency to prefer open environments rather than forests is increased. This assumption could be nourished by the significance of γ value as a greater value indicates more arboreal-based quadrupedal locomotion and, as the value decreases, indicates the presence of adaptation to bipedal locomotion. These findings also correlate with the scientific conjecture and the locations where the fossil artefacts are found (*see references*)[40].

As it is found significant that bipedal locomotion increases throughout the hominin lineages, it will be aimed to determine a correlation, if it exists, between hominin intelligence and the environmental transition to open habitats. In order to accomplish this aim to test the hypotheses, it is chosen to study the cranial volumes of the hominins which are subject to this study.

If a comparison of intelligence proceeds between two or more species, the scientific methodology is predisposed to use a quantity which is Encephalization Quotient (EQ) as the utilisation of the volume of the cranium may be delusive, as a greatly massed species will naturally occupy a greater cranial capacity. However, as the calculation of EQ is the measure of the relative size of the brain of a particular species compared with the expected value for members of the group to which it belongs (*Oxford Reference*), the utilisation of hominin fossils seems impossible. Rather than a comparison with EQ, it is decided to calculate the cranial volume per γ value as displayed in *Table 4,* in order to have a standardised measure of cranial volumes relative to body mass and pelvic morphology.

The following formula is used in order to calculate the cranial volume per γ value;

$$\delta = \frac{Cranial\ Volume\ (cm^3)}{\gamma\ \left(mm \cdot kg^{-1}\right)}$$

where;

- δ: is the normalised cranial volume.

To perform a sample calculation, the calculation process of Au. afarensis is shown below, and the rest of the calculations are made using GDC.

$$\delta_{Au.\ afarensis} = \frac{446\ (cm^3)}{11.1\ \left(mm \cdot kg^{-1}\right)} \approx 40.2$$

Name of the Hominin (*Genus species*)	**Cranial Volume**[38] (cc)	$\boldsymbol{\gamma}$ $\left(mm \cdot kg^{-1}\right)$	$\boldsymbol{\delta}$ $\left(mm^2 \cdot kg\right)$
Au. afarensis	446	11.1	40.2
Au. africanus	461	8.84	52.1
Au. sediba	420	7.04	59.7
H. erectus	959	4.43	216
H. neanderthalensis	1415	2.48	571
H. floresiensis	426	3.78	113
H. sapiens	1330	3.38	393

Table 4. Cranial volume (in cubic centimetres) γ and δ values of hominin species.
Au: Australopithecus, H: Homo.

In order to have a precise analysis, the δ vs γ graph is shown in Diagram 2. It is used to laterally assess the existence of any correlations between bipedalism and cranial volume.

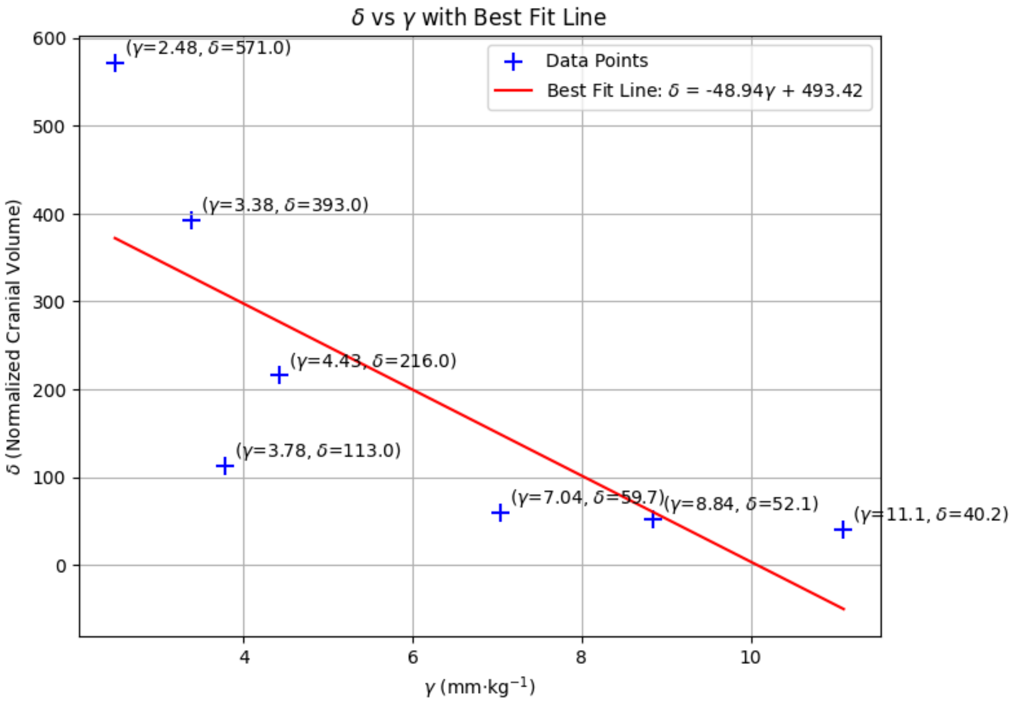

Diagram 2. Graph of normalised cranial volume against γ value

As it could be seen from the negative slope of the best-fit line, it is obvious that, there is an inverse correlation between the γ and δ values, signifies hominins with narrower pelvises (relative to mass) tend to have higher normalized brain volumes. In order to further assess the existence of such correlation, it is necessary to calculate Pearson's Correlation Coefficient.

When the Pearson's correlation coefficient is calculated via GDC, it is seen that;

$$r = -0.769$$

which indicates a strong negative correlation between normalised cranial volume and pelvis breadth. To further assess the significance of the findings, a simple linear regression is performed and the p-value is calculated as follows:

$$p = 0.043$$

This finding lets us conclude that, from an evolutionary standpoint, as hominins adapted to bipedal locomotion (reflected in pelvic morphology), their posture paved the way to the evolution of larger relative brain sizes, potentially reflecting an elevation in cognitive abilities.

3. Conclusion

The original aim of the study was to determine the origins of hominin intelligence under the influence of environmental shifts. The data was obtained and processed visually and empirically to answer the question: “Do habitat changes, indicated explicitly by shifts from quadrupedal to bipedal locomotion, affect brain development in Hominin Lineages in terms of brain size?” The study investigated under this research question has shown that habitat changes from woodlands to savannas significantly impact the evolution of larger brains in the hominin species over the lineages. As it is testified by the findings of this study, there is an inverse relationship between the pelvic width and the cranial volumes of the hominins, suggesting that, as the pelvic morphology of the hominins evolved to become narrower, which indicates a transition to bipedal locomotion, the normalised cranial volume is predisposed to be increasing.

Based on the data collected with the simulation, it is shown that the rejection of the null hypothesis is in order since it is proven that there is a robust negative correlation between the bi-iliac breadth and normalised cranial volume, which represents that there is a strong correlation between the increase in bipedal locomotion and the cranial capacity, indicating that, as change in environmental conditions enforced the selection of bipedal locomotion, consequently created a selection pressure on the hominin brains to utilise a more prominent space.

According to scientific consensus first shaped on Darwin's premises established in his 1889 publication, The Descent of Man and Selection in Relation to Sex[14]: "To gain this great advantage, the feet have been rendered flat; and the great toe has been peculiarly modified, though this has entailed the almost complete loss of its power of prehension. (…) If it be an advantage to man to stand firmly on his feet and to have his hands and arms free (…) then I can see no reason why it should not have been advantageous to the progenitors of man to have become more and more erect or bipedal." and as testified by various academic publications (*see references*), the evolution of upright posture due to its advantage in adaptation to open grasslands has a direct correlation with the evolution of the hominin intelligence as bipedalism let:

- Encephalisation of the cerebellum: standing upright on two feet requires the protection of balance,

- Encephalisation of occipital and parietal lobes: these brain lobes are directly related to visual processing and motor activity, respectively.

As the adoption of bipedality is increased among the genus Homo, the necessity of regulating the motor activity in a balanced manner is selected over lineages, and the expansion of brain volume with a combination of freed upper limbs lets the hominins adapt tool making. In an open grassland environment, with the tools made, ancestors of the Homo developed hunting strategies based on a communal hierarchy, which delineates the origins of our civilization today.

Understanding the chained relation between events that paved the way for being the sole species that can read and write these lines needs a holistic approach, and with this study it was aimed to bring that approach by achieving a mathematical correlation between bipedality and hominin intelligence. Our study clearly monitored that, as hominins adapted to open environments, the evolution of intelligence got accelerated.

4. Evaluation

4.1. Strengths

4.1.1. Systematic Species Selection

The deliberate choice of the seven hominin species ensures the comprehension of requisite evolutionary transitions from quadrupedal to bipedal locomotion. The intention of selecting this sample is committed in order to represent key morphological milestones and underpins of that the study aims to capture.

4.1.2. Robust Data Collection and Cross-Referencing

It is aimed to achieve reliability when sourcing pelvic dimensions, body mass, and cranial volumes from reputable, peer-reviewed paleoanthropological literature and databases. Cross-referencing among sources further minimises errors and reinforces the credibility of the findings.

4.1.3. Application of Established Statistical Techniques

Utilising Pearson's correlation coefficient and simple linear regression provides a precise and methodical framework to assess the relationship between pelvic morphology and brain development. The integration of significance testing (with a p-value threshold of 0.05) further underscores the methodological integrity and facilitates objective interpretation of the results.

4.1.4. Transparency and Reproducibility

It aims to promote transparency and reproducibility by providing detailed explanations of the formulas and sample calculations.

4.2. Weaknesses

Weakness	Impact	Possible Improvements
Limited Sample Size	Reduces statistical power and may not capture the full diversity of evolutionary transitions, increasing vulnerability to outlier effects.	Expansion of the dataset by including additional hominin species or more fossil records may enhance statistical robustness and generalizability.
Proxy Assumptions and	It may not fully capture	By incorporating additional or

Oversimplification	the complex interplay of factors influencing locomotion adaptation and brain development, potentially leading to biased interpretations.	alternative proxies and considering the multifactorial models that can address non-linear and complex interactions.
Measurement Uncertainties in Fossil Data	Inherent uncertainties in fossil measurements (e.g., body mass, cranial capacity) can propagate errors in derived calculations, affecting reliability.	By using advanced measurement techniques, applying sensitivity analyses, and considering statistical methods that account for uncertainty propagation in the data.
Reliance on Linear Statistical Models	May oversimplify relationships by neglecting non-linear dynamics and other confounding factors that influence evolutionary adaptations.	Exploring non-linear regression models or multivariate analysis to capture more complex relationships and account for additional confounding variables.
Temporal Resolution and Fossil Dating Inconsistencies	The inherent uncertainties in fossil dating can lead to imprecise correlations between morphological changes and evolutionary timelines, potentially confounding causal interpretations.	Integrating advanced dating techniques, incorporating error margins, and utilising Bayesian or other robust chronological frameworks to refine temporal analyses.
Oversimplified Environmental Categorization	road categorisation (e.g., open vs. forested) may overlook subtle yet influential habitat variations, thereby diluting the nuance required for precise evolutionary correlations.	Detailed paleoenvironmental reconstructions and multi-proxy data (such as isotopic analysis) are used to establish a more granular and representative habitat classification.
Limited Consideration of Alternative Evolutionary Drivers	Focusing solely on the relationship between locomotion and brain development may ignore other critical factors (e.g., social structures, dietary shifts, technological innovations) affecting cranial evolution.	Expanding the study to include additional variables or conducting multivariate analyses to account for and control other influential evolutionary drivers.

Table 5. Table of evaluation of weaknesses of the study and suggestion of possible improvements

4.3. Significance of the Research

This research holds a significant place in illuminating the evolutionary pathway of the genus homo and constitutes an archaea theory. This study has its significance in enlightening further studies pertaining to the evolution of intelligence and the possible evolution of other intelligent species. This perspective is also essential to distinguish the conditions in which intelligence is predisposed to evolve, especially for studies searching for extraterrestrial life forms.

4.4. Extensions

To further enhance this investigation, a reduction with larger samples including different fossil specimens for each species, is recommended. It is also recommended to further investigate the other possible impacts that may co-drove the selection of larger brains for instance, linguistic evolutions and dietary changes through lineages. It would be the most efficient methodology that investigates the Encephalization Quotient of the hominin species, and providing such rationale is beneficial for a comprehensive analysis of the cognitive abilities of the ancestral lineages of the genus Homo.

5. References

1. Adegboyega, Mayowa T., et al. “Virtual Reconstruction of the Kebara 2 Neanderthal Pelvis.” Journal of Human Evolution, vol. 151, 2021, p. 102922. Elsevier, doi:10.1016/j.jhevol.2020.102922.
2. Adolphs, Ralph. “The Social Brain: Neural Basis of Social Knowledge.” Annual Review of Psychology, vol. 60, 2009, pp. 693–716. Annual Reviews, doi:10.1146/annurev.psych.60.110707.163514.
3. Adolphs, Ralph. “The Social Brain: Neural Basis of Social Knowledge.” Annual Review of Psychology, vol. 60, 2009, pp. 693–716. NIH Public Access, doi:10.1146/annurev.psych.60.110707.163514.
4. Baab, Karen L. “Homo floresiensis: Making Sense of the Small-Bodied Hominin Fossils from Flores.” Nature Education Knowledge, vol. 3, no. 9, 2012, p. 4.
5. Baab, Karen L., and Kieran P. McNulty. “Size, Shape, and Asymmetry in Fossil Hominins: The Status of the LB1 Cranium Based on 3D Morphometric Analyses.” Journal of Human Evolution, vol. 57, no. 5, 2009, pp. 608–622. Elsevier, doi:10.1016/j.jhevol.2008.08.011.
6. Bastir, Markus, et al. “Effects of Brain and Facial Size on Basicranial Form in Human and Primate Evolution.” Journal of Human Evolution, vol. 58, no. 5, 2010, pp. 424–431. Elsevier, doi:10.1016/j.jhevol.2010.03.001.
7. Berge, Christine, and Dionysis Goularas. “A New Reconstruction of Sts 14 Pelvis (Australopithecus africanus) from Computed Tomography and Three-Dimensional Modeling Techniques.” Journal of Human Evolution, vol. 58, no. 3, 2010, pp. 262–272. Elsevier, doi:10.1016/j.jhevol.2009.11.006.
8. Bonmatí, Alejandro, et al. “Middle Pleistocene Lower Back and Pelvis from an Aged Human Individual from the Sima de los Huesos Site, Spain.” Proceedings of the National Academy of Sciences (PNAS), vol. 107, no. 43, 2010, pp. 18386–18391. National Academy of Sciences, doi:10.1073/pnas.1012131107.
9. Borrell, Víctor, and Federico Calegari. “Mechanisms of Brain Evolution: Regulation of Neural Progenitor Cell Diversity and Cell Cycle Length.” Neuroscience Research, vol. 86, 2014, pp. 14–24. Elsevier, doi:10.1016/j.neures.2014.04.004.
10. Bruner, E. “The Fossil Evidence of Human Brain Evolution.” Evolution of Nervous Systems, 2nd ed., vol. 4, Elsevier, 2017, pp. 63–88. doi:10.1016/B978-0-12-804042-3.00105-6.

11. Chin, Rowena, Steve W. C. Chang, and Avram J. Holmes. "Beyond Cortex: The Evolution of the Human Brain." Psychological Review, 2022, pp. 1–22. American Psychological Association, doi:10.1037/rev0000361.
12. Churchill, Steven E., and Caroline VanSickle. "Pelvic Morphology in Homo erectus and Early Homo." The Anatomical Record, vol. 300, no. 5, 2017, pp. 964–977. Wiley, doi:10.1002/ar.23576.
13. Darwin, Charles. On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life. 1859.
14. Darwin, Charles. The Descent of Man, and Selection in Relation to Sex. 2nd ed., revised and augmented, D. Appleton and Company, 1889.
15. Dart, Raymond A. "Australopithecus africanus: The Man-Ape of South Africa." Nature, vol. 115, no. 2884, 1925, pp. 195–199. Nature Publishing Group.
16. deMenocal, Peter B. "Climate and Human Evolution." Science, vol. 331, no. 6017, 2011, pp. 540–542. American Association for the Advancement of Science, doi:10.1126/science.1190683.
17. Dunbar, Robin. "Evolution of the Human Brain." Reference Module in Neuroscience and Biobehavioral Psychology, Elsevier, 2017, doi:10.1016/B978-0-12-809324-5.06853-X.
18. Dunbar, R. I. M. "Neocortex Size as a Constraint on Group Size in Primates." *Journal of Human Evolution*, no. 6, Elsevier BV, June 1992, pp. 469–93. *Crossref*, doi:10.1016/0047-2484(92)90081-j.
19. Eyre, Jennifer, et al. "The Effect of Bi-Iliac Breadth on Core Body Temperature." Journal of Human Evolution, vol. 195, 2024, p. 103580. Elsevier, doi:10.1016/j.jhevol.2024.103580.
20. González-Forero, Mauricio. "Evolutionary–Developmental (Evo-Devo) Dynamics of Hominin Brain Size." Nature Human Behaviour, vol. 8, July 2024, pp. 1321–1333. Nature Publishing Group, doi:10.1038/s41562-024-01887-8.
21. Grant, Peter R., et al. "Evolution Caused by Extreme Events." Philosophical Transactions of the Royal Society B, vol. 372, 2017, p. 20160146. Royal Society, doi:10.1098/rstb.2016.0146.
22. Gruss, Laura Tobias, and Daniel Schmitt. "The Evolution of the Human Pelvis: Changing Adaptations to Bipedalism, Obstetrics, and Thermoregulation." Philosophical Transactions of the Royal Society B, vol. 370, no. 1663, 2015, p. 20140063. Royal Society, doi:10.1098/rstb.2014.0063.
23. Hammond, Ashley S., et al. "New Hominin Remains and Revised Context from the Earliest Homo erectus Locality in East Turkana, Kenya." Nature Communications, vol. 12, 2021, p. 1939. Nature Publishing Group, doi:10.1038/s41467-021-22208-x.
24. Harcourt-Smith, W. E. H., and L. C. Aiello. "Fossils, Feet and the Evolution of Human Bipedal

Locomotion." Journal of Anatomy, vol. 204, no. 5, 2004, pp. 403–416. Anatomical Society of Great Britain and Ireland, doi:10.1111/j.1469-7580.2004.00296.x.
25. Hawks, John. "Human Evolution." Princeton University Press, 2021.
26. Hernaiz-García, María, et al. "Diet of Neanderthals and Early Homo sapiens from Macrowear Analysis of Mandibular Molars." Journal of Archaeological Science, vol. 164, 2024, p. 105950. Elsevier, doi:10.1016/j.jas.2024.105950.
27. Holliday, Trenton W., et al. "Body Size and Proportions of Australopithecus sediba." PaleoAnthropology, 2018, pp. 406–422. PaleoAnthropology Society, doi:10.4207/PA.2018.ART118.
28. Jungers, W. L., et al. "Descriptions of the Lower Limb Skeleton of Homo floresiensis." Journal of Human Evolution, vol. 57, no. 5, 2009, pp. 538–554. Elsevier, doi:10.1016/j.jhevol.2008.08.014.
29. Kimbel, William H., et al. "Ardipithecus ramidus and the Evolution of the Human Cranial Base." Proceedings of the National Academy of Sciences (PNAS), vol. 111, no. 3, 2014, pp. 948–953. National Academy of Sciences, doi:10.1073/pnas.1322639111.
30. Lieberman, Daniel E. "Four Legs Good, Two Legs Fortuitous: Brains, Brawn, and the Evolution of Human Bipedalism." In the Light of Evolution, 2010, pp. 1–20.
31. Lockwood, Patricia L., Matthew A. J. Apps, and Steve W. C. Chang. "Is There a 'Social' Brain? Implementations and Algorithms." Trends in Cognitive Sciences, vol. 24, no. 10, 2020, pp. 802–813. Elsevier, doi:10.1016/j.tics.2020.06.011.
32. Lovejoy, C. Owen. "Reexamining Human Origins in Light of Ardipithecus ramidus." Science, vol. 326, no. 5949, 2009, pp. 74–86. American Association for the Advancement of Science, doi:10.1126/science.1175834.
33. Lovejoy, C. Owen, et al. "The Pelvis and Femur of Ardipithecus ramidus: The Emergence of Upright Walking." Science, vol. 326, no. 5949, 2009, pp. 71–76. American Association for the Advancement of Science, doi:10.1126/science.1175831.
34. McHenry, Henry M., and Lee R. Berger. "Body Proportions in Australopithecus afarensis and A. africanus and the Origin of the Genus Homo." Journal of Human Evolution, vol. 35, no. 1, 1998, pp. 1–22. Academic Press, doi:10.1006/jhev.1997.0197.
35. Miller, George A. "The Cognitive Revolution: A Historical Perspective." Trends in Cognitive Sciences, vol. 7, no. 3, 2003, pp. 141–144. Elsevier, doi:10.1016/S1364-6613(03)00029-9.
36. Montgomery, Stephen H. "Primate Brains, the 'Island Rule,' and the Evolution of Homo floresiensis." Journal of Human Evolution, vol. 65, no. 6, 2013, pp. 750–760. Elsevier, doi:10.1016/j.jhevol.2013.08.006.
37. Naya, Daniel E., Hugo Naya, and Enrique P. Lessa. "Brain Size and

Thermoregulation During the Evolution of the Genus Homo.” Comparative Biochemistry and Physiology, Part A, vol. 191, 2016, pp. 66–73. Elsevier, doi:10.1016/j.cbpa.2015.09.017.

38. Neubauer, Simon, Jean-Jacques Hublin, and Philipp Gunz. “The Evolution of Modern Human Brain Shape.” Science Advances, vol. 4, no. 1, 2018, eaao5961. American Association for the Advancement of Science, doi:10.1126/sciadv.aao5961.
39. Oberheim, Nancy Ann, Xiaohai Wang, Steven Goldman, and Maiken Nedergaard. “Astrocytic Complexity Distinguishes the Human Brain.” Trends in Neurosciences, vol. 29, no. 10, 2006, pp. 527–535. Elsevier, doi:10.1016/j.tins.2006.08.004.
40. Pearson, Alannah, P. David Polly, and Emiliano Bruner. “Temporal Lobe Evolution in Javanese Homo erectus and African Homo ergaster: Inferences from the Cranial Base.” Quaternary International, vol. 603, 2021, pp. 5–21. Elsevier, doi:10.1016/j.quaint.2020.07.048.
41. Rosen, Kyle H., Caroline E. Jones, and Jeremy M. DeSilva. “Bipedal Locomotion in Zoo Apes: Revisiting the Hylobatian Model for Bipedal Origins.” Evolutionary Human Sciences, vol. 4, 2022, e12. Cambridge University Press, doi:10.1017/ehs.2022.9.
42. Ruff, Christopher. “Body Size and Body Shape in Early Hominins – Implications of the Gona Pelvis.” Journal of Human Evolution, vol. 58, no. 2, 2010, pp. 166–178. Elsevier, doi:10.1016/j.jhevol.2009.10.003.
43. Ruff, Christopher, et al. “Body Mass Prediction from Stature and Bi-Iliac Breadth in Two High Latitude Populations, with Application to Earlier Higher Latitude Humans.” Journal of Human Evolution, vol. 48, no. 4, 2005, pp. 381–392. Elsevier, doi:10.1016/j.jhevol.2004.11.009.
44. Shultz, Susanne, Emma Nelson, and Robin I. M. Dunbar. “Hominin Cognitive Evolution: Identifying Patterns and Processes in the Fossil and Archaeological Record.” Philosophical Transactions of the Royal Society B, vol. 367, no. 1599, 2012, pp. 2130–2140. Royal Society, doi:10.1098/rstb.2012.0115.
45. Tague, Robert G., and C. Owen Lovejoy. “AL 288-1—Lucy or Lucifer: Gender Confusion in the Pliocene.” Journal of Human Evolution, vol. 35, no. 1, 1998, pp. 75–94. Academic Press, doi:10.1016/S0047-2484(98)00023-7.
46. Tattersall, Ian. “Endocranial Volumes and Human Evolution [Version 1; Peer Review: 2 Approved].” F1000Research, vol. 12, 2023, p. 565, https://doi.org/10.12688/f1000research.131636.1.
47. Timmermann, Axel, et al. “Climate Effects on Archaic Human Habitats and Species Successions.” Nature, vol. 604, 2022, pp. 495–501. Nature Publishing Group, doi:10.1038/s41586-022-04600-9.
48. Waring, Timothy M., Zachary T. Wood, and Eörs Szathmáry.

49. “Characteristic Processes of Human Evolution Caused the Anthropocene and May Obstruct Its Global Solutions.” Philosophical Transactions of the Royal Society B, vol. 379, 2023, p. 20220259. Royal Society, doi:10.1098/rstb.2022.0259.
50. Grant, Peter R., et al. “Evolution Caused by Extreme Events.” Philosophical Transactions of the Royal Society B, vol. 372, 2017, p. 20160146. Royal Society, doi:10.1098/rstb.2016.0146.
51. Lovejoy, C. Owen, et al. “The Pelvis and Femur of Ardipithecus ramidus: The Emergence of Upright Walking.” Science, vol. 326, no. 5949, 2009, pp. 71–76. American Association for the Advancement of Science, doi:10.1126/science.1175831