THE EVOLUTIONARY ROLE OF PARANASAL SINUS PNEUMATIZATION IN HUMANS AND NEANDERTHALS AS AN ADAPTATION TO EXTREME COLD

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ABSTRACT. In this paper, we examine a case of scientific controversy over the evolving role of the paranasal sinuses, comparing Neanderthals and humans by analyzing two rival hypotheses. The first hypothesis states that the paranasal sinuses do not represent an adaptation to extreme cold, while the second claims the contrary. The two articles partially use the same database and employ identical methodologies and evolutionary theoretical assumptions. This example is interesting because, in terms of Nudler's concepts of controversial and non-controversial spaces, the problem lies in the latter, i.e., the biases of the two articles and their mistakes. Our paper highlights the misunderstandings that can arise when an attempt is made to analyze a complex structure from an evolutionary perspective using two-dimensional analytical techniques, that is to say, explaining a trait in isolation and, consequently, losing an integrated approach to the organism and its multiple interactions with the environment.

KEY WORDS. Scientific controversy, paranasal sinuses, Neanderthals, humans, complex systems, modularity, controversial spaces, methodologies, evolutionary explanations, philosophy of biology.

INTRODUCTION

Scientific controversies constitute an interesting vantage point from which to observe the state of a given discipline. Indeed, several authors (Engelhardt and Caplan, 1987; McMullin, 1987) have acknowledged the importance of studying such controversies to account for the development of a certain field of study. Some authors (Dascal, 1995, 1998; Nudler, 2001, 2002, 2009) have even considered them as one of the main driving forces behind scientific change. Thus, the study of scientific controversies allows us to

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understand the history of a discipline and the different research traditions existing in the scientific community at a given time (Laudan, 1977). Moreover, although most studies on the history and philosophy of science have traditionally been based on examples from the field of physics, biology has come to the forefront of debates in recent years. Thanks to this shift, it has been realized that there are different determining factors in the latter science that have influenced the construction of theories (in a broad sense), and that transformations have occurred over time.

A possible example of scientific dynamics, as well as changes in the approach to biological phenomena is provided by the development of complexity theories, which are being successfully applied in several disciplines, such as neurobiology, genetics, ecology, and some others. Nevertheless, one-dimensional and two-dimensional explanations for phenomena that are clearly multidimensional still persist in areas connected to adaptive and evolutionary biology. This entails enormous costs in research studies, which are known *a priori* to crumble in the face of a comprehensive and necessarily complex proposal. In fact, evolutionary processes are a clear example of complexity that cannot be approached by means of traditional methodologies. Further, partial studies carried out to explain evolutionary processes frequently come to misleading or confusing conclusions. This does not mean that every study must be necessarily conducted within the paradigm of complexity. Indeed, specific disciplinary studies can be undertaken following traditional methodologies, depending on the extent or scope of the phenomenon to be explained.

In relation to the previous point, the various aspects of human evolution constitute a scenario of considerable interest for the community of biological anthropologists, in particular, and for the community of biologists in general. Nevertheless, the hypotheses put forward and the conclusions reached in many studies seem to be somehow disconnected. The problem seems to lie in the epistemic errors and in using inadequate methodologies when answering the concerns of those studies.

In this regard, the discussion about the role of paranasal sinuses becomes a paradigmatic case of scientific controversy. Historically, several explanatory hypotheses have been formulated to account for the existence of such sinuses. According to Blanton and Biggs (1969), the hypotheses that began with Galen (130-201 AD) included—among other explanations—air humidification, resonance of the voice, increase in the olfactory membrane, lightening of the skull for better balance, absorption of the impact generated by the masticatory force, and the thermal insulation role of the nerve centers. These authors found nineteen different explanations for the existence of the paranasal sinuses throughout 1 800 years of controversies. It is worth highlighting that, due to the time that has elapsed since Blanton and Biggs's study, the methodologies used and the interpretations made have changed considerably, especially from the twentieth century to the present day. Although the controversy still continued, an evolutionary interpretation of the role of paranasal sinus pneumatization was put forward in 2011 within the framework of the synthetic theory. To this end, Neanderthals' paranasal sinuses were compared to those of today's humans, and the proposed hypothesis was that paranasal sinuses played a role in adaptation to extreme cold.

The aim of this paper is to prove that an interdisciplinary approach is needed for the study and understanding of biological phenomena following the complex systems approach. For this purpose, we will carry out a case study of opposing points of view on the evolutionary scope of paranasal sinuses in both Neanderthals and humans. In this way, we intend to show the numerous problems that can be found in some of the current literature on evolution occur where epistemic problems, research traditions and methodological issues converge.

COMPLEX SYSTEMS AND COMPLEXITY

One of the problems faced by experienced biologists is a certain feeling of dissatisfaction after conducting a traditional study of an organism, population or ecosystem. In fact, in spite of the availability of statistical (say, multivariate analysis and the like) and/or statistical-mathematical tools (data mining), the problem of achieving "real" insight into the system under study leaves much to be desired. This does not mean ignoring the importance of every preliminary study that is carried out when no knowledge of a given system is available; it means the study lacks epistemological planning. In other words, it lacks a clear definition of the relevant questions—which take into account the possible contributions of other disciplines—taken as a basis to conduct the research.

Generally speaking, it is usually difficult to conceptualize a complex system. This may be associated with a superficial understanding of "complex systems theory" (CST) and the underlying assumptions. Without purporting to undertake an exhaustive analysis of CST—since this is not the aim of the present study—we have deemed it necessary to introduce certain basic concepts that focus specifically on the epistemic framework and on the boundary line between interdisciplinary and multidisciplinary studies.

According to García (2006), a complex system is a reduced representation of a complex reality, conceptualized as an organized whole, the elements of which cannot be separated and, therefore, cannot be studied in isolation. This definition of complex systems requires disciplinary integration processes that lead to fundamental reformulations that are not limited to "putting together" knowledge from different domains. This conceptualization necessarily entails the formation of interdisciplinary teams, which do not constitute a mere group of specialists from a range of disciplines, but rather a group with a shared vision on the construction of knowledge.

In this context, the consideration of common epistemic questions will be a point of agreement among researchers from different disciplines who, in spite of this, do not lose sight of the problems arising from their own disciplines. Each disciplinary field follows its own methodology and theoretical frameworks, but share with other disciplines the need for a more comprehensive approach to understand how a system works. The questions that researchers ask themselves about a certain domain of reality constitute the *epistemic framework.* Further, this epistemic framework is influenced by the particular worldview of the researcher, and thus it may be modified if such worldview changes.

As mentioned above, the need for an interdisciplinary approach to the object of study is a consequence of the complexity approach. In addition, this interdisciplinarity does not entail—as is generally understood—a group of specialists who analyze an object of study without following the same epistemic framework. In this sense, for example, it is meaningless to refer to an ecological system under study as a "complex system" or to a study on "complexity" when the contributions of anthropologists, biochemists, botanists, zoologists, and so forth, do not follow the same epistemic approach, since such kind of study does not differ from traditional disciplinary studies.

At this point, it is paramount to distinguish between the terms *interdisciplinarity* and *transdisciplinarity* or *multidisciplinarity*, which are frequently used interchangeably in certain fields of biology. According to García (2006), the main difference between interdisciplinary and multidisciplinary or transdisciplinary research studies lies both in the approach used to tackle the problem posed by the object of study, and in the epistemological and methodological consensus reached among the researchers carrying out the study. Whereas in *multidisciplinary* or *transdisciplinary* work teams each researcher contributes to the study from their particular discipline, *interdisciplinary* work necessarily integrates the different approaches before defining the problem that will be studied. This means, according to García (2006: 33),

> while in one case the results of different studies on a common problem are then integrated, in the case of interdisciplinary studies the various approaches are integrated in the definition of the problem. This implies conceiving any problem as a system containing elements that are interdefined and the study of which calls for the coordination of disciplinary approaches that must be integrated in a single approach. Therefore, interdisciplinarity entails the study

of problems conceived as complex systems, and the study of complex systems requires interdisciplinary research.

Given the above definitions, by *multidisciplinary* or *transdisciplinary* research we mean those studies conducted by specialists from different disciplines who, after analyzing a research problem from the perspective of their own discipline, relate it to the results obtained from other disciplines who have studied the same problem. On the other hand, by *interdisciplinary research studies* we mean those studies carried out by specialists of different disciplines who have reached an agreement on the methodology and research problem prior to conducting the study. Thus, prior agreement among specialists is what differentiates the two approaches.

In order to carry out an interdisciplinary research study, it is necessary to clearly conceptualize the parcel of reality that is being analyzed and the factors influencing such reality. These involve different factors, such as biotic and abiotic variables that influence the system, the researcher's ideological or philosophical determinants, the pressure of influential groups that sponsor that research, and so on. Some of these aspects will become evident in this case study on the cranial pneumatization in humans and its relation to the same thing in the Neanderthals.

CRANIAL PNEUMATIZATION IN NEANDERTHALS AND ITS RELATION TO CRANIAL PNEUMATIZATION IN HUMANS AS A WAY OF EXPLAINING ADAPTATION TO EXTREME COLD

The issue of pneumatization has been widely debated in relation to several animal groups (Bignon, 1889; Paulli, 1900; Weidenreich, 1924; Tillier, 1977) and no consensus has been reached over its function. Nevertheless, cranial pneumatization is one of the unresolved problems in hominid evolution in general and in *Homo* in particular. The appearance and disappearance of pneumatized spaces in several taxa among unrelated lineages are also unresolved issues. In this respect, as was mentioned in the introduction, Blanton and Biggs (1969) have suggested several theories or have proposed explanations, ranging from hypotheses about the function of these spaces for the lightening of the skull or morphofunctional hypotheses involving a response to biomechanical demands, to adaptive hypotheses of response to cold. Márquez (2008) conducted a compilation which revealed the wide variety of explanations proposed by several authors for the existence of paranasal sinuses in different groups of vertebrates over a period of 65 million of years, including old and new world primates and hominids. Those explanations included structural functions, lightening the skull, the function of pillars to disperse the effects of masticatory forces, the storage of medullar substance, and their consideration as evolutionary remnants of useless air spaces. This diversity of explanations clearly reflects an unresolved problem concerning the origin and function of these structures in vertebrates in general, and in Neanderthals and humans in particular. Furthermore, the methodologies of study used are as inadequate as the hypotheses proposed.

At this point, it is worth posing the following questions. If the origin and function of paranasal sinuses has not been yet clarified, how can it be argued that they arise as an adaptation to extreme cold? What are the epistemological and methodological assumptions that lead to this type of arguments? This issue is particularly relevant since the paranasal sinuses are considered to be a diagnostic feature in human phylogeny (Hill, 2008). Apart from not knowing clearly what the function of paranasal sinuses is, nor what their origin or their use as a diagnostic feature in phylogenetic studies is, the situation becomes even more bewildering when an attempt is made to explain their evolution through natural selection. In fact, Holton, et al. (2011) point out that the absence of one or more paranasal sinuses in humans does not represent a significant adaptation problem, yet their evolution can be explained in terms of natural selection all the same.

Neither physiological, morphological, or genetic approaches have deciphered the origin and function of these structures. Nevertheless, an unexpected revelation arose from the epigenetic studies carried out both in bull terriers dogs (Fondon and Gadner, 2004) and in wild foxes that were subsequently domesticated (Trut, 1989), since these studies showed the effects that man-made chemicals had on the evolution of these species. For instance, in bull terriers, endocrine disruptors have markedly modified the splanchnocranium angle downwards; in foxes, these disruptors have also modified their ears, skin color, and others. In both cases, the endocrine disruptors originated in agrochemicals and in the feed given to animals over decades. In sum, an artificial selection, resulting from the breeders' objectives and the "pathological" effects of the chemical disruptors which guided the evolution of these stocks, both acted upon these species, which have been studied over many years. Furthermore, Haberland, et al. (2009) showed the effect of histone deacetylase 8 on the epigenetic control of specific parts of the skull in vertebrates. This enzyme removes histone acetyl groups and therefore promotes chromatin compaction, making genetic transcription difficult. Moreover, deacetylase 8 is known to participate in the growth repression of the anterior parts of the skull. These data suggest the possible participation of epigenetic processes as an important variable to be taken into account in the process of cranial pneumatization, which was not duly examined in the studies analyzed. Finally, the hypothesis about the probable epigenetic role does not provide a definitive solution to the problem posed by pneumatization, let alone its relationship with adaptation to extreme cold.

At present, every adaptive study implies the acknowledgement of complex systems; in fact, studies do not usually refer to *adaptation* anymore, but rather to *adaptive complex systems*. Hence, the hypotheses provided by the abovementioned disciplines lack a unifying criterion and, therefore, are not able to provide a satisfactory explanation for the phenomenon under analysis. This is reflected in biochemical, physiological and other explanations, as stated above. Thus, paranasal sinus pneumatization is the product of a series of factors which, analyzed in isolation, lack explanatory power.

The proposed case study constitutes an ideal example for the analysis of the problems mentioned above. It is important to highlight that certain biological disciplines clearly fall within the framework of "complexity". Examples of this include ecology, certain epigenetic studies, neurobiology, and others. Thus, the need to include different disciplines in complex studies led to the creation of relevant new disciplines, such as immunoneuroendocrinology, ecomorphology, and so on, which are giving way to new contexts for the understanding of certain problems derived from stress, such as certain types of cancers.

ANALYSIS OF A SCIENTIFIC CONTROVERSY: EPISTEMIC AND METHODOLOGICAL ERRORS

Scientific controversies have occupied an important place in the debates and analysis in philosophy of science, and in recent years, their theoretical value has been reconsidered. In this regard, it is interesting to recover the concept of *controversial spaces* within disciplines (Nudler, 2009), in which the debate is focused on specific aspects of a given topic. Further, these areas are related to *non-controversial spaces* that are linked to metaphysical, methodological and theoretical assumptions that are shared by the actors involved in the dispute, and which serve as common ground for debating. It is interesting to note that when disputes become profound enough to provoke a domino effect on the basic theoretical postulates, those spaces tend to be shut down because they could undermine the whole theory (Lamas and Dressino, 2010).

The point above provides a framework in which to analyze the controversy about the significance of paranasal sinuses in Neanderthals as an adaptation to extreme cold. In fact, according to Rae, et al. (2011), these structures that are present in Neanderthals and humans do not represent a climate adaptation. This hypothesis was based on the idea that the evolution of paranasal sinuses responded to two assumptions. First, that the increase in cranial pneumatization was not an adaptive response to the demands imposed by intense cold. Second, that Neanderthals' paranasal sinuses were not larger than those of humans.

In order to respond to these arguments, Rae, et al. set themselves two objectives: i) to determine the relative size of sinuses in *Homo neanderthalensis,* and ii) to determine whether those sinuses represented an adaptation to extreme cold. For this purpose they used computed tomography (CT scan) in twenty six humans from different geographical regions and nine Neanderthals. The authors explained that many of the measurements could not be used since some skulls were damaged. This limited sample was used to calculate the relative size of sinuses compared to an estimate of the bifrontomalar width. They employed univariate analysis, correlations and linear regressions with log-log correction. The interpretations did not include any analysis of regression slopes. Despite working with poor and dissimilar samples, the authors reach two conclusions: i) there are no differences between frontal and maxillary sinuses between humans and Neanderthals, and ii) facial pneumatization in Neanderthals does not represent an adaptation to cold.

Once the work of Rae, et al. was published, the response of Holton, et al. (2011) appeared in the same journal. Regarding this point, it should be noted that the conclusions reached by Rae, et al. contradicted an earlier work published by Holton and Franciscus (2008), in which they had concluded that the characteristics of the nasal opening in Neanderthals represented an adaptation to cold. Thus, Holton, et al. (2011) carried out a study in which they set two objectives: i) to discuss the importance of climatically relevant aspects of the naso-facial skeleton when evaluating climate evolution in recent humans and Neanderthals, and ii) to assess the importance of appropriate sampling when testing hypotheses related to climate and facial adaptation.

In order to achieve this, Holton, et al. (2011) took into account data from CT scans of skulls of modern humans from Africa and Europe that had been used for another study (sic) ($n = 40$) and data from two Neanderthal skulls, taken from the work of Rae, et al. (2011). Based on this biased sample that clearly contradicts the second objective of their study, they calculated the volume of the maxillary sinus (cm^3) vs. the bifrontomalar width (mm) as an indicator of facial size, using the methodology employed by Rae et al. ANCOVA analysis and correlations and linear regressions were performed on these data. As in the case of Rae, et al. (2011) no comparisons were made between slopes nor between correlation coefficients. Based on the composition of the sample and on the statistical calculations, Holton, et al. (2011) came to the conclusion that pneumatization in Neanderthals represents an adaptation to cold.

This controversy clearly reveals that the discussion focuses on paranasal sinuses as an indicator of a process of adaptation to cold. However, as noted above, neither study indicates the degree of significance on the differences between the analyses, which constitutes a mayor methodological error. The main methodological problem in both studies is the bias of the sample, which may even render them invalid if statistical theory is taken into account.

Furthermore, as also noted above, from an epistemic perspective both studies adhere to the same *non-controversial* space, i.e., they both adhere to the synthetic theory of evolution and its postulates, according to which a trait may represent an adaptive response to the climate. In addition, they both use, in part, the same data. As has been shown, this example reveals the erroneous conclusions that can be reached when an analysis rests on biased data and when a small number of variables is used to account for a complex phenomenon in relation to climate adaptation.

CONCLUSIONS

The problem of cranial pneumatization in the human lineage reveals the enormous problems that arise at the level of biological explanations in general, and of evolutionary explanations in particular. In the latter field, the conclusions drawn may lack an adequate biological basis. The case study presented in this paper concerning the possible explanations for the presence of paranasal sinuses in Neanderthals and humans is paradigmatic. Indeed, as has been previously argued, these sinuses cannot be appropriately explained by partial approaches, since these lose sight of their inherent complexity. On the other hand, evolutionary biology has long since acknowledged that adaptive phenomena consist of inherently complex interactions, which are very difficult to solve using traditional methodologies.

Furthermore, as has already been shown, the two opposing schools of thought reflected in the analyzed works, which argue in favor or against the idea of sinuses resulting from an adaptation to cold, are based on partial disciplinary perspectives with no interaction with other branches of knowledge. However, paranasal sinuses are considered to have diagnostic value at the phylogenetic level. Despite this, approximately 150 papers published in specialized journals, books, chapters of books, and the like, suffer from this flaw (lack of appropriate methods of analysis, lack of interdisciplinary work, and so on).

From a current perspective of adaptation in humans, we can call into question these explanations where no mention is made on the cultural adaptations that have undoubtedly affected members of our species, and most certainly also Neanderthals, nor of epigenetic explanations, many of which may be conceptually associated with cultural accounts. In short, the origin and function of these structures still lack an integrated explanation that goes beyond the approaches of individual disciplines.

At this point, and in relation to what has been argued throughout this paper, the presence of paranasal sinuses is likely to be the result of a spandrel. In general, spandrel hypotheses are difficult to prove using traditional methodologies with their corresponding conceptual frameworks. Nevertheless, this problem can be solved by adopting the complex systems approach. This necessarily requires studies carried out from an interdisciplinary perspective, in other words, it should be grounded on basic epistemic questions which can be addressed taking into account the particular characteristics of each discipline.

This controversy will possibly be settled when *non-controversial* hypotheses are critically analyzed and when the biological sense of explaining such trait in an isolated manner, and only from the theoretical framework of adaptation to cold can be appropriately revised.

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