The roots of STEM: what are the evolutionary and neural bases of human mathematics and technology?

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Abstract

Neural exaptations represent descent via transitions to novel neural functions. A primary transition in human cognitive and neural evolution was from a predominantly socially-oriented primate brain to a brain that also instantiates and subserves science, and technology, and engineering, all of which depend on mathematics. Upon what neural substrates, and upon what evolved cognitive mechanisms, did human capacities for STEM, and especially its mathematical underpinnings, emerge? Previous theory focuses on roles for tools, language, and arithmetic in the cognitive origins of STEM, but none of these factors appears sufficient to support the transition. In this article, I describe and evaluate a novel hypothesis for the neural origins and substrates of STEM-based cognition: that they are based in human kinship systems and human maximizing of inclusive fitness. The main evidence for this hypothesis is threefold. First, as demonstrated by anthropologists, human kinship systems exhibit complex mathematical and geometrical structures that function under sets of explicit rules, and such systems and rules pervade and organize all human cultures. Second, human kinship underlies the core algebraic mechanism of evolution, maximization of inclusive fitness, quantified as personal reproduction plus the sum of all effects on reproduction of others, each multiplied by their coefficient of relatedness to self. This is the only 'natural' equation expected to be represented in the human brain. Third, functional imaging studies show that kinship-related cognition activates frontal-parietal regions that are also activated in STEM-related tasks. In turn, the decision-making that integrates kinship levels with costs and benefits from alternative behaviors has recently been shown to recruit the lateral septum, a hub region that combines internal (from the prefrontal cortex, amygdala and other regions) and external information relevant to social behavior, using a dedicated subsystem of neurons specific to kinship. Taken together, these lines of evidence suggest that kinship systems, and kin-associated behaviors, may represent exaptations for the origin of human STEM.

'Anthropologists have documented kinship systems in Australia and Melanesia that resemble Western formal mathematical theories, with their use of axioms, propositions, and a strict set of rules to make valid propositions.'

Ascher 1998

Introduction

Major transitions in evolution commonly involve changes in the functions of traits (Smith and Szathary 1997). Such changes have given rise to the concept of 'exaptation' (Gould and Vrba 1982), whereby a trait is co-opted for a new function, in a new adaptive context. Classic examples of exaptational change include fins evolving to become legs, and thermoregulatory feathers evolving to support flight. Changes in function typically engender strong, novel selective pressures, and the resulting emergence of evolutionary novelties that can spur adaptive radiations or organism-wide phenotypic and ecological reorganizations within a species (Miller et al. 2022).

Ape and human evolution in particular are rife with changes in the functions of traits, from opposable thumbs used for grasping and complex manipulation of tools, to upright posture, and to the origin of speech and language. The most rapidly-changed human trait, and one of the most remarkable ones in its abiity to express new functions, is however the brain, which tripled in size over several million years. A series of comparative-phylogenetic studies has demonstrated that large social group size, with complex, bonded social interactions, represents the best correlate of larger brains in primates, with humans at the apex of the trend (e.g., Dunbar and Shultz 2021). These findings are corroborated by neurological studies showing that the brain regions most expanded in humans include the so-called 'social brain' areas, that underlie the acquisition, processing, and deployment of social information (Frith and Frith 2010). Humans thus show clear continuity with other primates as regards the brain's primary evolved function in the navigation of social complexity, despite their much larger brain size. What evolutionary transition involving the brain, then, best differentiates humans from other primates?

The answer, of course, is technology, without which humans would likely be just a neurally-upscaled version of a chimpanzee. 'Technology' can be represented more generally as STEM (science, technology, engineering, and mathematics). Two of these four, technology (considered as tool use) and engineering (considered in terms of tool and structure creation) have clear, albeit much simpler, antecedents and parallels among primates and other animals, as forms of tools, though these remain a far cry from STEM itself. The third component of STEM, science, can, in turn, be seen as derived, at least in part, from cognition regarding patterns and regularities in the physical and biological worlds that were useful in foraging, hunting, survival and reproduction during human evolution (e.g., Atran 1998)

In contrast to technology, engineering and science, mathematics, considered as the science of abstracted numbers, axioms, quantities, distances and shapes, has no clear counterparts or analogs outside of *Homo sapiens*, barring the simplest of object-oriented arithmetic. Although mathematics underpins and unifies all of modern science, technology and engineering (Sterpetti 2019), its value as regards components of human survival and reproduction is unclear at best. Mathematics can indeed be considered as 'an enormous Trojan Horse sitting firmly in the center of the citadel of naturism' such that 'it is very difficult even to envision how it could be possible to naturalistically account for what mathematics is and how we acquire mathematical knowledge' (Sterpetti 2019).

In what adaptive context, then, might the the neural and cognitive capacities for human STEM have evolved, especially with regard to mathematics? Such capacities are, inferentially, clear exaptations of something, because *some* function has fundamentally changed. But what?

In this article, I propose and evaluate a novel hypothesis for the origin of the neurological and cognitive structures that underlie human STEM. First, I provide a brief overview of the roles postulated by previous authors for various factors in the origin of human abilities related to STEM, and suggest that these accounts remain incomplete. Second, I describe a new hypothesis: that human STEM capabilities, especially with regard to mathematics, evolved via co-option (exaptation) of complex, rule-based and distance and geometry-based human kinship systems, and human cognitive algorithms and equations used in calculations regarding kinship and inclusive fitness in the contexts of these systems. Third, I evaluate the hypothesis by: (1) describing how kinship is linked with mathematics in small scale cultures; (2) comparing the neural substrates of STEM-based cognition with those used in explicit cognition about kinship; and (3) describing recent evidence of a specific, dedicated neural system for maximizing inclusive fitness, instantiated in the lateral septum. Finally, I describe the implictions of the hypothesis, and evidence salient to its further evaluation.

Potential roots of STEM

Given that STEM abilities, in the contexts of modern culture, are recent and novel in human ancestry, they presumably originated in some other selective contexts. Suggested primary options for such contexts include: (1) tool use and creation, originating mainly for hunting and foraging, and becoming more and more complex (e.g., Navarette Reader 2016); (2) language, whereby abstract symbols, combinatorial rules, and recursion, originating for social communication, were co-opted for mathematics (Chomsky 2006); (3) 'folk physics' and 'folk biology', untaught abilities used to infer possible causes of physical-world and biological-world events (Dennett 1987; Atran 1998; Baron-Cohen et al. 1999), that could serve as scaffolds for systematic inferences; and (4) basic arithmetic as found in many animals, used in human ancestors for simple decision related to foraging, food-sharing, trade, and the like, that became more and more complex and abstracted (Dehaene 2021).

Each of these four options, taken singly, exhibits important limitations as regards forming a bridge to STEM-related cognition, especially in the context of the mathematics that unifies these disciplines. Thus, tool use and creation only become technology and engineering if they are integrated with mathematics; otherwise they remain idiosyncratic, domain-specific, and ungeneralized, no matter how challenging or complex to build. Simple tool creation (e.g. stone knapping) also activates brain regions that instantiate perception of objects in space, visual imagery, planning, and sensorimotor programs that program hand movements - not the frontal-parietal connections that characterize STEM-related neural systems (Putt et al. 2017; Parteger 2019). Similar considerations apply to complex foraging systems and sequences, which will be food-specific and involve hands and fingers used as 'tools'; they may be important to survival but they do not directly connect with STEM.

Language, like tool use or creation, is subserved by brain regions largely distinct from those used in STEM tasks (e.g., Amalric and Dehaene 2019), and it evolved in the context of sociality. It has rules, symbols and abstraction, but the rules and units (words) are malleable and more or less arbitrary, differing between human groups, and language systems are characterized by extreme flexibility rather than deductive logical structures. As such, speech and language can facilitate STEM abilities especially through social learning, and they can favor the development and evolution of complex and symbolic mental representations that can be used for other cognitive purposes (Krebs 2011), but they appear to represent insufficient substrates for the origin of STEM. Folk physics similarly appears to serve as an inadequate base for STEM, in that does not lead naturally to the development of general rules or axioms, and indeed, most prescientific explanations of physical world events have been founded on myths and magical thinking; folk biology may likewise connect with scientific abilities, but it lacks the systematic character and formal rules (e.g., Darwinian natural selection) required for STEM capabilities. Finally, the transition from simple arithmetical operations to axioms, geometry, and abstract mathematics requires qualitative shifts in ways of thinking, and the preconditions and motivations for such shifts remain unclear.

These considerations suggest that, although tools, language, and simple mathematics may have been necessary for, or facilitate, the evolution of human STEM skills, they were by no means sufficient. What other adaptations may have served as precursors for mathematics and STEM, and how could they do so?

Human kinship in the exaptation of STEM

'To me it is striking to find that a logical structure studied abstractly and extensively by Western mathematicians plays a central and significant role in the day-to-day life of some peoples. And, what is possibly more surprising is that the realm of the logical structure is human relations rather than the physical or technological. '

Ascher 1998

The hypothesis evaluated here is that human kinship relationships and systems, due to their intrinsic mathematical and geometrical structures, and their complex, associated biological and cultural rules, generated neural systems that came to serve as exaptations for mathematical cognition specifically and STEM cognition in general. I first describe the properties of kinship, and so-called kinship systems, that generate the foundation for this claim.

Kinship, in its simplest form, represents the degree to which a pair of individuals are genetically related, one to the other. In turn, genetic relatedness can be considered as either the expected proportion of alleles shared between a pair of individuals, or as the probability that a specific allele in one individuals is also present, identically by inheritance (descent), in another. Typically, these proportions and probabilities refer to autosomes, which comprise the bulk of the genes in the genome.

Kinship can be represented in pedigrees, that show who is related to whom in terms of marriages and production of offspring. Each 'link' in a pedigree represents a meiotic event, with a probability of inheritance of an allele of one-half (again, for autosomes). Geneologies represent distances (close vs distant kin, with discrete units of meiotic-link distance), 'sides' (paternal vs maternal linaeages), vertical and lateral distances (representing generations, that go both 'up' and 'down', and collateral kin relations), and kin vs nonkin (in terms of affines, related 'by marriage'). Geneologies thus represent spatial (distance and pattern) imagery and discrete categories, as well as discrete mathematically-combinatorial units (pedigree links). As such, they are highly structured, comprising representations of distance, space, numbers, and qualitatively-different forms. No other aspects of the natural world exhibit such precise regularities and none, as described below, connect so closely with effects on fitness.

Kinship systems

"*Cashinahua kinship terms are combined so as to produce kinship terms. Numbers are combined so as to produce numbers, thus expressing the fact that kinship relations have a mathematical structure*"

Almeida 2023

Given kinship, a kinship 'system' can be considered as a culturally-constructed set of relationships that: (1) connects and describes, with kinship terms, individuals in a group who are more or less genetically related, and (2) regulates their 'proper' behavior towards one another in the context of such terms. A geneology, which represents the core of a kinship system, is a biological rather than cultural construct, with specific coefficients of relatedness between any pair of individuals. In most modern Western societies, these coefficients and kin terms are simple and familiar, such as mother to offspring (1/2), uncle to nieces (1/4), grandson to grandfather (1/4), and cousin to cousin (1/8), with other pairs, such as in-laws or husbands and wives, being unrelated (0), all for autosomes. Different human cultures, however, use different kinship systems and terms, that deliniate and name different categories of relatives quite differently than do people in the West. As such, kinship systems should be regarded as cultural constructs that correspond more, or less, to geneological structures in any given culture. For example, some cultures designate a mother' brother with a specific kin-related term; these individuals preferentially provide alloparental care to the mother' offspring, apparently in the context of low paternity certainty that favors investing more in maternal kin compared to putative paternal kin or putative own offspring (Greene 1978; Hartung 1981). Similarly, many cultures differentiate between parallel cousins (cousins from a parent's same-sex sibling) and cross cousins (cousins from a parent's opposite-sex siblings), with regard to preferred or proscribed marriages; these designations may be adaptive in the contexts of inheritance patterns, and incest taboos, under high uncertainty of paternity (e.g., Melotti 1984; Hartung 1985). Other cultures expand the concept of 'father' to include both the biological father and uncles, for reasons that may include the promotion of within-family cooperation in situations where it is especially beneficial. As such, kinship terms are commonly used in extended, manipulated and fictive ways that correspond partially to actual geneology and partially to the various means whereby individuals, lineages, and cultural groups can subserve their own evolutionary interests (Qirko 2011; Chagnon 2017).

Most generally, kinship systems appear to represent culture-specific adaptations that regulate patterns of marriage, inheritance, residence, cooperation partners, cooperation or conflict-based groupings, and other social behavioral fitness related interactions (Itao and Kaneno 2020; Racz Passmore 2020). The systems are notably variable across cultures and can be highly complex, with sets of rules that determine kin-related designations and prescribed or proscribed social and reproductive interactions (such as marriage, cooperation and inheritance) that follow from their rules and structure. As such, and most importantly, kinship terms and relationships, due to their inherent biological-geneological and cultural structures, can be represented in terms of mathematics and geometry (Sie Fat et al. 1981; Ascher 1986, 1991; Almeida 2022). It is such representations and their neural implications, in the broader context of pedigrees and kin-directed behaviors, that form the key component of the hypothesis proposed here.

Starting with the André Weil's mathematical analysis of an Australian aboriginal marriage system for the great anthropologist Claude Lévi-Strass, formal structures in kinship systems and rules have come to be studied by anthropologists and mathematicians under the rubric of 'ethnomathematics' (Ascher 1986, 1991; Rauff 2016). Table 1 describes examples of such anthropological links of mathematics with kinship systems, from a small set of cultures. These examples provide evidence for associations of kinship with mathematics, in the types of societies that typify most of human evolutionary history. An illustrative example, from the marriage system in the Warlpriri culture of Arhmen Land, Australia, is provided in Figure 1, showing how aspects of kinship systems can be symbolized in formal mathematical-geometrical ways.

Connections of kinship with mathematical and geometric structures exist not just in the minds and writings of ethnomathematicians, but also among the people in the societies: for example, the anthropologist A. Bernard Deacon, studying marriage systems in the New Hebrides (now Vanuatu), noted that "... *the system was explained to me perfectly lucidly ... it is perfectly clear that the natives do conceive of the system as a connected mechanism which they can represent by diagrams ... and the way that they could reason about relationships from their diagrams was on par with a good scientific exposition in a lecture room*". Members of a society indeed learn about their kin, and the kinship systems in their groups, from early ages, given the central importance of these systems' rules to their culture and their own ability to maximize their fitness within it. For example, among the Yolgnu Australian Aboriginals from northeast Arnhem Land "*right from the beginning of their lives ... babies are instructed on the relation that this or that person has to them. The set of relations involves notions of hierarchy and equivalence ... and ... the ideology achieves a general ordering of both the social and the natural world*" (Verran 2007).

With regard to associations of kinship with mathematics, the hypothesis evaluated here makes a clear prediction for anthopological data: that kinship systems should covary with mathematical systems with regard to their complexity, such that societies showing relatively simplified kinship systems should also exhibit relatively simple mathematics as expressed in their languages and cultures. A formal, statistical cross-cultural test of the prediction is beyond the scope of this article. However, information from several cultures, at the relative extremes of kinship-system and ethnomathematical diversity and complexity, provides suggestive evidence. For example:

(1) the Pirahã, an Amazonian tribe living along the Maici River in Brazil, speak a language that contains mathematical words only for 'small quantity' and 'larger quantity', that are distinguished only by tone and singular and plural are not separated grammatically (Everett 2005, 2008),. As such, the culture represents an extreme in terms of high mathematical simplicity. The Pirahã also exhibit 'the simpest known kinship system of any human culture' (Everett 2005), with, for example, a single term, *baixi*, used to represent father, mother, grandparent, and elder, a term for 'sibling', *xahaigi*, that can apply to any member of their community, and only five kinship terms in use overall (Everett 2008),. Other Amazonian tribes exhibit notably more-complex kinship systems, such as the form of Iroquois type found among the Yanomami (e.g. Chagnon 2007).

(2) the traditional Chinese kinship system, which represents an elaborated version of the Sudanese type (the most complicated of the six main human kinship systems), has a separate, distinct term for virtually every type of an individual's kin, based on variation in lineage position, generation, relative age, and gender (Chen 2019). China is also notable for the early, independent development of sophisticated mathematics (Martzloff 2007). The Sudanese kinship system is also representative of Arab cultures, with their own history of early development of advanced mathematics (Rāshid 2012). By contrast, cultures using the Hawaiian kinship system, the simplest of the six, appear to exhibit relatively simple mathematical systems, centered on forms of number system and counting, with additional specificities based on the types of objects counted, and 'multiplier' terms for larger quantities (e.g., Bender and Beller 2006).

These patterns are consistent with associations of kinship system complexity with mathematical complexity, but formal, controlled tests are certainly needed. More broadly, analyses of such diversity of human kinship systems across cultures, and the mathematical systems that characterize and formalize them, needs to be conducted in the context of socioecological factors that affect forms of cooperation, competition and inheritance, and variation in marriage, inheritance and mating systems (e.g., affecting risks of incest avoidance, uncertainty of paternity, and polygamy vs monogamy), all of which depend on local ecology, local history, and other aspects of the culture. For example, the Pirahã people live in small groups typified by communal, egalitarian cooperation; by contrast, traditional Arab and Chinese cultures are larger in population sizes, considerably more complex with regard to marriage, inheritance and other rules based around their patrilineality, ecologically distinct (with valuable inherited resources including land and livestock), and organized into kin-based groups that cooperate within lineages, and compete between them (e.g., Strassmann and Kurapati 2016). Kinship systems can thus be analyzed as forms of cultural adaptation that evolved to serve and support the interests of the group and its constituents, and that form the complex, structured framework within which each human, seeking to maximize their fitness, is embedded.

Geneologies and inclusive fitness

"Each system contains a ... set of rules which must be consistent and must lead to the desired outcomes, which incorporate the values and world view of the culture. Most important is that the members of the culture share the model and constantly draw inferences from it about their relationships to whomever they encounter and the appropriate behavior towards them."

Ascher 1991

Biological geneologies, and their cultural representations in kinship systems, represent arenas within which the cognition and social behavior of humans have evolved. The evolution of social traits involving relatives takes place within this context, represented by several key equations that appear to represent the only 'natural' equations expected to be embedded within the human psyche.

The first equation follows from the three necessary and sufficient conditions for evolution of traits by natural selection: variation, selection, and heritability, considered as individuals varying in survival and reproduction (fitness) in relation to their heritable expressed phenotype. For traits that involve interactions between individuals, two or more of whom are kin, the term for fitness needs to be modified in a simple but crucial manner. Thus, a decision about whether or not to engage in some specific self-costly social act evolves subject to the equation:

$r\,b - c > 0$

where r represents relatedness of the self to the other, b represents reproductive benefit of the act to the other individual, and c represents cost of the act to the self (Hamilton 1964). In this equation, higher relatedness (e.g., 1/2 compared to 1/4 or 1/8) results in the equation being satisfied with higher costs to the self, and lower benefits to the other (i.e., such that phenotypic altruism is more readily expressed). Ultimately, this equation is predicated on the fact that evolutionary change proceeds via changes in the frequencies of alleles, some of which can increase in frequency by coding for phenotypic effects that benefit relatives, who also tend to (probabilistically) bear copies of the same alleles identical by descent. Similarly to the case of altruism described just above, mutualistic acts (beneficial to both individuals) will be more favourable when they involve benefits to kin, and self-serving acts will be less beneficial if the are costly to close kin (compared to more distant kin or non-relatives). Individuals are thus always expected to take account, mathemetically albeit unconsciously and with 'rules of thumb', of benefits and costs to the self, benefits and costs to others, and genetic relatednesses to others, whenever they make a behavioral decision.

The second main equation that governs social decision-making involving kin derives from the concept of 'inclusive fitness', fitness effects of an act that *include* both: (1)

effects on one's own reproduction and (2) the summation of all effects on the reproduction of each other individual affected, each devalued by one's coefficient of relatedness r to that individual. By this equation, an individual decides between alternative actions (here, A and B) by determining which one yields the highest inclusive fitness to onesself.

$$\text{IF (act A)} = \text{Fitness effect (act A on self)} + \Sigma\left[\text{Fitness effects (act A, on others)} * r_{\text{other}}\right]$$

$$\text{IF (act B)} = \text{Fitness effect (act B on self)} + \Sigma\left[\text{Fitness effects (act B, on others)} * r_{\text{other}}\right]$$

$$\text{IF (A)} >? \text{IF (B)}$$

Alternative actions are, of course, not restricted to A and B, but are limited only by the imagination and capabilities of the actor. In this regard, it is the 'default' network of the brain, which subserves social imagination (Buckner et al. 2008; Carroll 2020), that generates alternative behaviors, for input into the neural machinery of the task-positive system that controls executive functions, STEM-related cognition, and decisions regarding what specific action is expected to yield higher inclusive fitness.

The inclusive fitness equation presented just above simply extends and expands the first equation to encompass effects on multiple other individuals, and subsumes the benefits and costs into fitness effects. As before, individuals are not expected to consciously calculate inclusive fitness, but their brains are expected to unconsciously do so, as one of the most foundational and well-supported expectations of evolutionary biology (Bourke 2011). Moreover, the neural and cognitive traits that make individuals better at maximizing inclusive fitness through use of these equations are expected to be strongly selected for, and these appear to be the only equations that animals, and especially humans that live in such complex social environments, are expected to 'naturally' use within their cognitive-behavioral systems. The key result from these considerations is that inclusive-fitness-related equations, and kinship system structures, are predicted by the theory described here to be instantiated in the brain, in regions that are also implicated in STEM-related thinking. Are they?

The neural bases of kinship and inclusive fitness, and their relations to STEM

The hypothesis evaluated here regarding kinship representing and generating exaptation for STEM cognition makes two main predictions regarding neural systems. First, the neural bases of geneologies and kinship system cognition should overlap broadly with the neural bases of mathematical and STEM cognition, that are well known to predominantly activate regions within and across the task-positive fronto-parietal network (Amalric and Dehaene 2016; Arsalidou et al 2017; Pishedda et al. 2017). Second, animals (especially social ones) should exhibit a neural system or network that is dedicated to maximizing inclusive fitness, that exhibits connectivity with brain areas that subserve kinship systems and STEM-related abilities,

Two studies meet the conditions for tests of the first prediction, in that they using brain imaging to localize regions that are involved in cognition regarding patterns and degrees of kinship. Wu et al (2015) provide the most direct and incisive test; they used functional imaging (fMRI) to elucidate the brain regions activated during cognition regarding kinship terms, using a kinship identification task that required participants to identify the kinship relationship (and term) for pairs of individuals in an geneology. Importantly, the participants included both 'native Chinese' and 'Caucasian English' speakers, with the Chinese-speaker lexicon including over twice as many kin terms (and more kinship rules) than the English one, reflecting their more-detailed and precise kinship system. The main results of the study were that (1) kinship-term cognition activated an extensive set of frontal and parietal areas in both groups; (2) the network was more responsive to closer kinship levels (i.e., closer relatives); and (3) the Chinese group, compared to the English one, exhibited longer reaction times to response, stronger fronto-parietal activations, and greater activations in regions subserving number magnitude, attentional control, and the processing of distance information. The authors interpreted these group differences as reflecting the more-complex kinship system used by the Chinese participants; they also suggested that in both groups, activations in the inferior parietal lobe represented levels and distances of kinship. This study clearly supports the hypothesis that kinship-related cognition is supported by STEM regions in the task-positive network of the brain (and vice versa), as well as providing evidence that cultural differences in kinship systems are instantiated in brain activation patterns, thereby providing evidence that culturally-based kinship systems and their instantiations in task-positive brain regions may evolve together.

In the only other study meeting necessary conditions to serve as a test of the hypothesis addressed here, Zou and Yan (2017) used event-related potentials to determine if and how degrees of kinship (e.g., father, uncle and non-relative) affected patterns and magnitudes of brain activation in the context of 'morally laden scenarios'. They demonstrated activations in fronto-central regions (at 180-230 ms) and central-parietal regions (at 350-500 ms) that were higher in association with closer kinship. Despite the limitations of ERP studies as regards functional interpretations, these results are generally concordant to those of Wu et al. (2015), in showing fronto-parietal activations, and activations that are stronger under higher levels of kinship.

Taken together, the studies by Wu et al. (2015) and Zou and Yan (2017) provide preliminary evidence that kinship systems and kin-related cognition activates fronto-parietal brain regions that now also subserve STEM-associated cognition (as shown in (e.g., Cantion 2012; Emerson Cantion 2012). Further tests are, however, required; for example, within populations, are better kinship-related abilities positively associated with better STEM skills? If so, are some STEM skills, such as those related to space, distance and network-embedded classification, most closely linked to proficiency with kinship? And across cultures, do the complexity and form of kinship systems, such as the especially-intricate form of the 'Sudanese' kinship system traditionally used in China, or the highly simplified 'Hawaiian' system (e.g., Rácz et al. 2020), covary with with aspects of brain activation related to STEM, and relative abilities in different aspects of STEM? More complex kinship systems might be expected to adapt the brain to quantitative processing involving numbers, distances, axioms, and geometry that serves as the bases for mathematics and related aspects of science. Whether such adaptations involve facultative, developmental effects in a system that is universal across humans, or genetically-mediated, gene by environment interaction effects, or both, also remains an open question.

The second main prediction, that social animals should exhibit a neural system that is dedicated to maximizing inclusive fitness, that connects with brain areas that subserve kinship systems and STEM-related abilities, can be evaluated first by considering the properties that any such system should exhibit. Most importantly, the system should be centrally-located in the brain and serve as a hub that receives inputs from brain regions that convey information on external conditions (indicating the anticipated benefits and costs to others of any given action), information on internal state (which reflects the self's current condition, which connects closely with costs and benefits), and information on kinship relationships relevant to any given alternative action. The system should then integrate this information, either making a yes-no decision regarding any specific social-behavioral action, or evaluating one action compared to another or more, leading to behavioral outputs. Finally, the system should be focused on processing and deploying information on social interactions with clear consequences for fitness, that commonly involve interactions with relatives or mates, and that have implications for the fitness of these individuals.

From recent neurobiological studies, most or all of these conditions appear to be met for the lateral septum, a large central brain region that derives inputs from the hippocampus, prefrontal cortex (among other neocortical regions), temporal lobe areas, as well as regions including the amygdala that instantiate emotional states, with outputs directed to regions including the hypothalamic nuclei, ventral tegumental area, and nucleus accumbens, that modulate the deployment of motivated behavioral outputs (Figure 2), in part via the stimulation of circuitry for pleasurable reward. Notably, the lateral septum is specialized for regulation of social behavior (including aspects of family-member bonding, mate bonding, social play, and social memory), via a variety of effects on circuitry that control reward, sociability, memory, feeding, anxiety and fear, all of which are expected to play central roles in inclusive fitness decision-making. This brain region is also rich in oxytocin and vasopressin neurons, that are well-documented to subserve social recognition and attachment, typically involving kin or mates (Crespi 2016).

The key feature of the lateral septum implicating it as a putative 'inclusive-fitness decision-making' region of the brain is its role in the neural representation of kinship. This region thus contains a topographically-structured representation of kin and non-kin responsive neurons, referred to as 'nepotopy' (Clemens et al. 2020; Clemens and Brecht 2021), that encode information regarding genetic relatedness. Experiments conducted thus far do not permit inferences regarding whether degrees of relatedness, or specific kinship relationships, are instantiated in this region, but such discrimination might well be expected in humans, if not in rodents for whom kin relationships are simpler and more predictable in space and time. The primary relevant study thus far conducted in humans (Moll et al. 2012) reported that affiliative close-kin stimuli (mother, father and offspring) differentially stimulated lateral septum circuitry, but neither degrees of kin, nor stimuli specifically designed to emulate inclusive-fitness-sensitive scenarios, were analyzed in this particular work.

By the lines of evidence described here, the lateral septum can be hypothesized to function as the brain region that, at least in mammals and especially in humans, subserves information processing and decision-making that uses the kinship equations described above, with data on relatedness provided from frontal-parietal regions that represent geneologies and kinship systems, and data on costs and benefits from alternative actions derived from neocortical and subcortical brain regions that converge on the lateral septum. Key questions remain: for example, are STEM functions, especially as regards representation of inclusive fitness equations (or 'rules of thumb' that approximate them), related to functions of the lateral septum, or are they mainly enacted in frontal-parietal regions and communicated to this region? Such studies hold promise for the conceptual and empirical unification of social-behavioral ecology with neurobiology, by characterizing the key proximate mechanisms that control social behavior involving kin.

DISCUSSION

"Number systems, spatial ordering, and kinship structures are of particular interest because they are fundamental."

Ascher 1991

In this paper, I have proposed a new hypothesis for the origin of STEM-related cognition in humans, that it was based initially in high social complexity, which led to intricate, geometrical, axiom-based, space and distance-structured kinship systems, that are subserved by neural substrates that came to function for thinking about the non-social mathematical and STEM world as well as the social one. The general idea of such neural exaptation has been described by other authors under different names, such as 'neural reuse' and 'neural recycling' (Dehaene et al. 2005; Dehaene 2005; Jones 2000). Krebs (2011) suggested the closest hypothesis to the one proposed here, that neurally based metarepresentation and theory of mind, that evolved under social selective pressures, could also serve for representation of mathematical objects and their relations. This hypothesis is compatible with the one described here, in that symbolic, recursive, abstract representational thought could facilitate both social and STEM neural abilities, and synergize with the rules, equations and axioms that kinship systems and inclusive fitness instantiated in the brain.

Hypotheses regarding exaptation, especially neural exaptation, are challenging to test, because the relevant transitions leave few traces in the fossil or archeological records. Here, three main lines of argument and evidence have been described to evaluate the hypothesis: (1) first principles of evolutionary theory, which stipulate that the evolution of brain and behavior proceed via maximization of inclusive fitness and the neural computation that doing so entails; (2) information on the functional domains of ethnomathematics across diverse extant human cultures, which demonstrates links between kinship systems and mathematical systems; and (3) information on the neural bases of kinship-related cognition in comparison to STEM-related cognition, as inferred from imaging experiments. The neural imaging studies described here support the hypothesis that scenarios with kinship-related cognition activate frontoparietal regions that also represent core regions for STEM; for example, frontoparietal connectivity in children predicts their mathematical, but not verbal, IQ (Emerson et al. 2012). Additional imaging studies are clearly needed, especially involving cognition about kinship systems and categories, and geneologies, among individuals of different ages from different cultures. Finally, the discovery of kinship-associated neurons in the lateral septum, that mediate social decision making, raises novel and exciting questions about human behavior, such as how precisely genetic relatedness is encoded, and how the PFC, and possibly parietal lobe regions, convey information about kinship to the lateral septum.

The hypothesis proposed here, that the neural substrates of human kinship systems and inclusive-fitness maximizing algorithms represent exaptations for STEM-related cognition, can ultimately be considered in both general and specific forms. Thus, in the most general case, kinship systems, geneologies, and inclusive fitness are instantiated within the neural systems of all humans, such that people in all cultures exhibit similar neural structures and functions that can support STEM-related cognition. The exaptive process from social cognition to STEM cognition would then have proceeded as human tools, technologies and symbolic thought processes complexified especially over the last 30,000 years, supported by the mathematical, geometrical, axiom-based thinking that kinship enabled. By this hypothesis, basic STEM-structured thought potentialities would be universal in humans, like capacities for speech, but their degree of expression would, in a specific form of the hypothesis, depend upon the complexity of the kinship system in the culture within which they developed.

This latter hypothesis is clearly testable, as suggested by the examples from the Pirahã and other cultures discussed here, but any such cross-cultural associations between kinship systems and mathematics could be interpreted in a number of different ways, including: (1) kinship systems providing cognitive scaffolding for mathematics and STEM (the hypothesis proposed here); (2) societal size and complexity representing a third factor that promotes both more-complex kinship systems and more-sophisticated mathematics; (3) coevolution of kinship systems with mathematical abilities; or even (4) mathematical skills, evolved and developed in some other context, facilitating complex kinship systems. Thus, although ethnomathematical studies have linked kinship systems with mathematical systems in various contexts, it remains unclear if kinship systems are causally associated with mathematics abilities, even if they necessarily came first in human evolution.

Finally, these considerations suggest that the teaching of mathematics might usefully apply the structures and axioms of genetic relatedness and kinship systems as scaffolds for more-advanced and abstracted STEM-related pedagogy. After all, being embedded in networks of kin, with formal rules to guide behavior towards them, we are already using mathematical thought, just without realizing how our social world may naturally foster the roots of STEM.

Table 1. Examples of correspondences between kinship structures and mathematical and geometrical structures and representations.

Culture	Kinship structure	Mathematical structure	References
Murngin culture, Australia	Marriage rules	Group theory and algebraic methods used by Andre Weil to classify prescribed marriage types based on kinship groups	Rauff 2016
Borana culture, Ethiopia and Southern Kenya	Gada system of kinship structure	Formal linear and cyclic configuration that classifies males and orders society and can be represented algebraically	Chahine 2020
Cashinahua culture, (Amazonia); Warlpiri culture (Australia) Malekula culture (Vanuatu)	Kin-group categories with regard to marriage, rights, and obligations	Kinship categories correspond to mathematical structures called dihedral groups	Almedia 2020, 2023; Ascher 1991
Aranda culture, Australia	Marriage rules based on kinship, with eight marriage classes	Rules represented as matricycles and patricyles in shape of torus, with past and future merged with present	Ascher and Ascher 1986

Yolngu culture, Australia	*Gurrutu* struture of kinship relations	Three-generation recursion structure orders kinship relations and marriage patterns	Verran 2016

Figure 1. A geometrical, group-theory-based depiction of marriage patterns proscribed by the kinship system of individuals in the Warlpiri culture of Arnham Land, Northern Territory, Australia. The kinship system has eight 'sections' and preferred marriages are between individuals of specific pairs of sections; children from the marriage are assigned to another section that depends upon the section of the mother. Mathematicians refer to the structure of the system as a dihedral group of order eight. See Ascher (1991) for details. Figure was adapted and redrawn from Figure 3.4 in Ascher (1991).

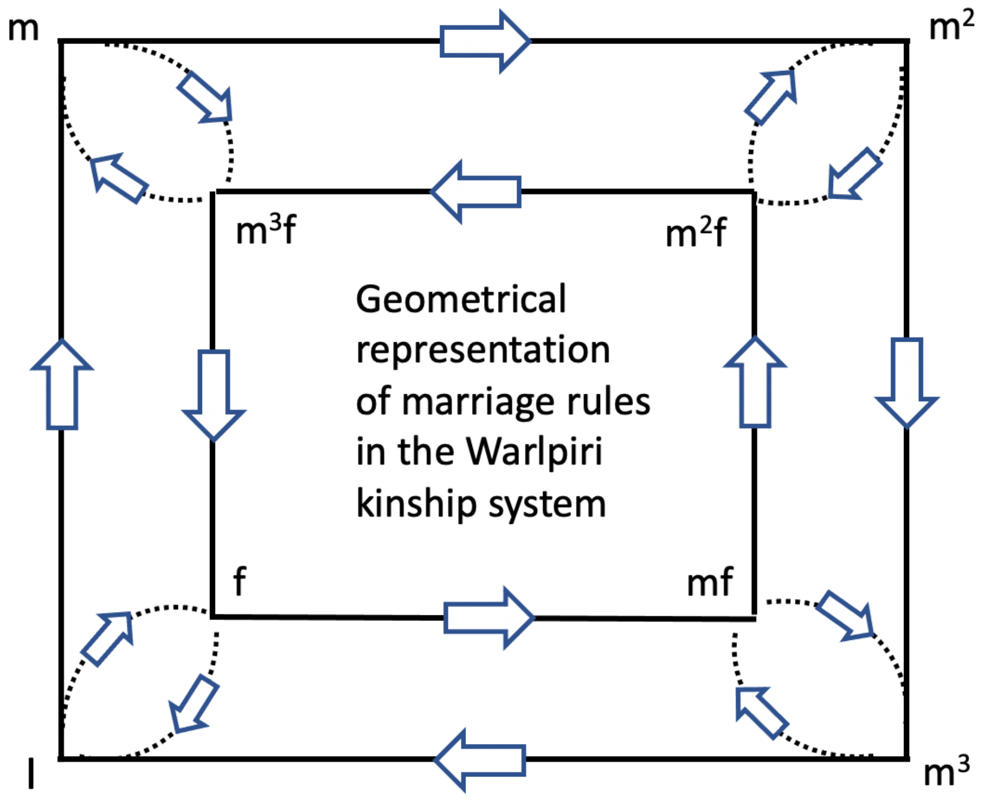
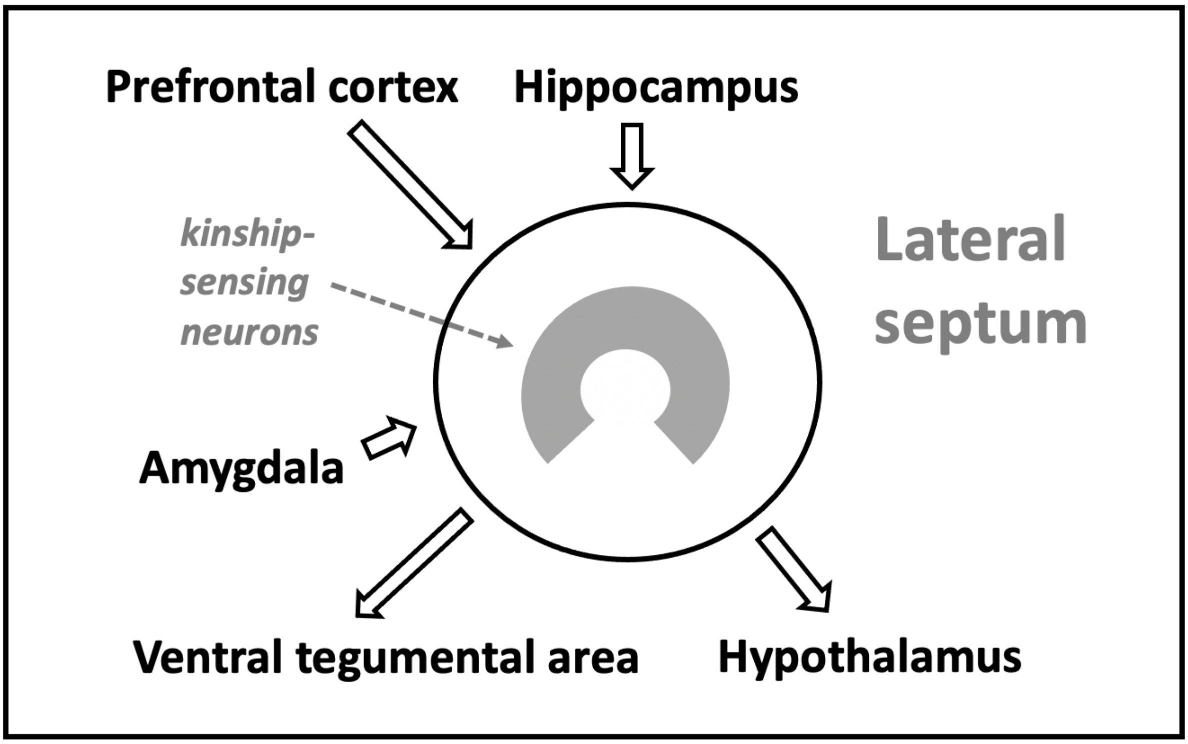


Figure 2. An idealized representation of the lateral septum and the primary brain regions with which is exhibits connectivity. This region has recently been demonstrated to subserve cognition and behavior involving kin, in part through the activities of a set of neurons that shows sensitivity to degrees of kinship, and in part through its integration of information regarding the expected benefits and costs of social behaviors.



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