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EVOLUTION OF THE MIND'S EYE: A POSSIBLE EXPLANATION FOR WHY EARLY HOMININS PRODUCED GEOMETRIC FIGURES BEFORE REPRESENTATIONAL ONES

Dean Falk

Abstract: Hominins' earliest renderings of visual images in both Old and New Worlds were geometric rather than representational figures. Because the reasons for this are mysterious, some have referred to the priority of geometric figures as the "geometric enigma." Here, evo-devo comparative studies of chimpanzees, humans, and the development of drawing and painting in the youngsters of both are discussed to explore the emergence and development of artistic skills during the earliest part of the hominin record. Topics include the nature of early hominins' visual habitats and the changes that likely occurred in the neurological underpinnings of their visual cortices as they shifted from arboreal to diurnal terrestrial habitats. Hominins inherited the derived behavior of weaving arboreal sleeping nests each day from plant matter from their apelike ancestors, and eventually used weaving skills to make baby slings, which were likely the first portable tools and textiles invented. Patterns inherent in simple woven textiles appear in some of the oldest paleoart, are among the earliest geometric images produced by young children and are perceived when the visual cortices of people are stimulated electrically, pharmaceutically, or during migraine auras. These data are synthesized, and a testable "woven world" hypothesis is proposed as one possible explanation for the geometric enigma.

Introduction

An ability to infer what other individuals are thinking and how they are likely to behave is especially well-honed in contemporary humans. This capacity, 'Theory of Mind' (ToM), begins to develop shortly after birth as infants observe the behaviors of others and unconsciously compare them with their own experiences (Meltzoff 2007). Unlike inferring the thoughts and feelings of contemporary people, and for obvious reasons, attribution of mental states to our ancestors lacks grounding in ToM developed from experiences within corresponding cultures. Such attributions must, therefore, be viewed cautiously.

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When scholars interpret Paleolithic art, including rock art, they attempt to apply ToM that derives from the present to the past. However, "to just report discoveries of rock art sites, subjectively describing the motifs depicted in them and proceeding straight to their interpretation by imposing our conditioned mind has been standard practice throughout the world. After so many decades of applying this traditional archaeological approach, it has helped us little to answer significant research questions" (Kumar 2021:25). As with discussions about manufactured lithic tools, Paleolithic art has frequently been attributed anonymously to presumed males (Fritz et al. 2016), although the contributions of women and children have become a recent focus of discussion (Goldhahn et al. 2020; Janik and Williams 2018; Langley and Lister 2018; Snow 2013). Fortunately, rock art studies are beginning to adopt scientific approaches based on understanding "the lithology, taphonomy, topography, sedimentology, palaeoclimate of the sites and the epistemology of our ideas about rock art" (Kumar 2021:23).

Although determining the ages of rock art remains for the most part extremely difficult (Kumar 2021), humans are estimated to have produced it in the form of hand stencils and naturalistic depictions of animals "by ~40 kyr ago at opposite ends of the Pleistocene Eurasian world" (Aubert el al. 2014:223; Aubert et al. 2018; Tacon et al. 2018), while systematic processing and use of pigments, art (e.g. in the form of beads), and decoration occurred considerably earlier in Africa (Henshilwood et al. 2011; McBrearty and Brooks 2000). Notably, a cross-hatched pattern was applied with red ochre onto a 73,000-year-old flake from Bombos Cave, South Africa, which "predates the earliest previously known abstract figurative drawings by at least 30,000 years" (Henshilwood et al. 2018). Clearly, the Eurocentric idea of a relatively sudden cognitive revolution having occurred in association with Upper Paleolithic art in Western European *Homo sapiens* has been put to rest (Mc Brearty and Brooks 2000).

Despite this welcome development, very few researchers have sought evidence regarding the origins of artistic impulses in the earliest hominins that evolved after their lineage diverged from that of chimpanzees ~6.5 million years ago (mya, Kumar et al. 2022)—impulses that long preceded the emergence of rock art (and other creative forms). Even fewer have explored the possible biological bases for visually perceiving and producing art (but see Hodgson 2019). Robert Bednarik has done both (Bednarik 1984, 1987, 1998, 2006, 2020, 2021). After reviewing relevant background information, this paper picks up and expands on these two facets of Bednarik's research.

Visual perceptions are assembled from features that are extracted separately in the primary visual cortex

Although it may seem counterintuitive, visual perception does not happen in the eyes. When light from an object enters the eyes and stimulates the retina, the latter projects information to the lateral geniculate nucleus of the thalamus that, in turn, stimulates the primary visual cortex (V1, Brodmann area [BA] 17) at the back of the brain. It is here where the initial stages of visual processing take place. In V1, individual neurons respond selectively to specific orientations of lines/edges that contribute to the perception of shape in localized parts of the visual field (e.g., some neurons respond to vertical lines in a particular part of the visual field; others fire selectively for lines at other orientations, e.g. at a particular angle or horizontal) or contours (Hubel and Wiesel 1959). Other neurons in VI respond to specific colors at certain locations (Garg et al. 2019) or motion in a particular direction. After preliminary processing, neurons in V1 project discrete bits of information forward to higher visual areas in the occipital and temporal lobes, which process the stimuli further. Although V1 is particularly adept at detecting edges because of its many neurons that are selective for orientations, "for the visual system to extract a specific piece of information about a feature, such as the orientation and length, shape, color, and movement … require[s] a comparison of the outputs of may cells" (Podoll and Robinson 2008: 246-247). The forward flowing accretionary processing that begins with VI results, eventually, in assembled unified visual perceptions.

Seminal experiments on animals demonstrate that the orientations of VI neurons are programmed during a critical period of postnatal development in response to environmental factors that help shape the physiological underpinnings of visual perceptions. In a classic example, recordings were made from single neurons in VI of kittens that were raised in two cohorts that lived in different environments in which high-contrast black-and-white stripes were oriented exclusively in either vertical or horizontal directions. Results showed that the distributions of the preferred orientations of VI neurons that were programmed during the kittens' critical period were completely abnormal and highly skewed toward the particular orientation of the stripes to which each cohort had been exposed (Blakemore and Cooper 1970).

Although one cannot, of course, perform such experiments on humans, it is interesting that people who were raised in so-called carpentered worlds that have lots of sharply defined edges at different orientations (e.g., in industrialized societies) are more susceptible to optical illusions that entail expectations about edges, lines and orientations (e.g., the famous Ponzo and Müller-Lyer illusions) than people who live in more rounded natural environments that lack these features (Phillips 2019; Segall et al. 1963). Similarly, people raised in different environments respond differently to depth cues in two-dimensional pictures. Whether or not the effects that the physical world has on visual perception in different cultures is associated with significantly different distributions of preferred orientations in VI neurons has not, to my not knowledge, been determined. It may, in fact, be that susceptibility to optical illusions depends on higher level visual processing than that which takes place in VI (BA 17) as suggested, for example, by a functional magnetic resonance imaging (fMRI) study that found that visual perceptions of everyday items by East Asian and American participants were associated with different activation patterns in visual areas BA 18 and 19 (Ksander et al. 2018).

That said, humans universally share certain evolved features of VI that differ from those of nonhuman primates. VI has migrated caudally and medially along the outside surface of the occipital lobes so that most of it is not visible on the external surface of the brain, as it is for other primates. Presumably in conjunction with this process, the proportion of VI that represents peripheral vision became significantly larger in the human lineage: "The difference between these two species appears to be that the function of the peripheral cortex has been strengthened in humans, most likely because the observation of the surroundings and objects is more complicated in humans compared to macaques," and may reflect differences between "arboreal primates vs. bipedal ground-dwellers" (Wu et al. 2012:1739). When it comes to the sensitivity of individual neurons in VI to lines with particular orientations, however, humans and macaques map similarly: "Despite 25 million years of evolutionary separation between humans and macaques, the monkeys showed essentially the same orientation-retinotopy relationship as the humans" (Sasaki et al. 2006:662). Although the organization/location of VI in humans including its relatively large representation of peripheral vision distinguishes them from monkeys, and despite the fact that culture and environment impact the ways in which people process visual stimuli, the neurons in VI that respond selectively to orientations of lines and edges appear to be fundamentally similar across primates.

As we will see, the basic perceptions that arise when VI neurons are stimulated contribute not only to the assemblage of unified visual perceptions as signals move forward in the brain (i.e., sensory processing), they also play a role in the development of artistic skills in youngsters. More to the point, and as Bednarik hypothesized (1984, 1987), neurons in VI were also likely crucial for the perception and production of proto-artistic expressions in early hominins, as suggested by the kinds of visual experiences that are produced—patterns known as phosphenes—when the visual cortex is stimulated mechanically (e.g., by pressing on the eyelids), electrically (Penfield and Rasmussen 1968: Knoll and Kugler 1959), pharmaceutically (Lewis-Williams et al. 1988; Siegal 1977) or spontaneously (e.g., as part of migraine auras, Charles and Baca 2013).

Perception and production of phosphenes in humans

The anatomical substrates for processing vision are extremely complex, which makes them subject to possible disruption. Indeed, for this reason some visual perceptions do not have actual referents out there in the "real world." Phosphenes (meaning "light show"), for example, are imaginary shapes, lights, colors and movements such as "shooting stars" or geometric patterns (Savigny 1838) that may be experienced when individuals rub their eyes, stand up too quickly, or receive pressure or electrical stimulation anywhere along the optic pathway, including in the primary visual cortex. Although phosphenes occur in a huge variety of geometrical forms, analysis of 520 that were experienced from electrical stimulations by 313 adults yielded an illustrated taxonomy of 15 typical phosphene form groups (a so-called "phosphene-Linnaeus) (Fig. 1), which the authors compared to 300,000 drawings and paintings made by pre-school children from diverse ethnic backgrounds ("scribblings-Linnaeus," Kellogg et al. 1965).

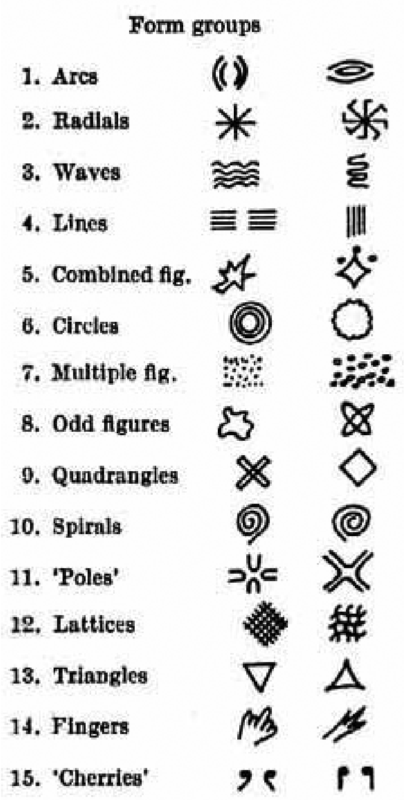

Figure 1: Fifteen typical phosphene form groups obtained by electrically stimulating the brains of 313 adults, which comprise the "phosphene-Linnaeus" of Kellogg et al. (1965: extracted from Table 1).

Nearly 90% of the phosphene forms stimulated electrically in adults appeared in the children's artwork, leading the authors to conclude that "such 'outlinings in geometrical style' play an important part in the development of a child's expression in drawing or painting." Thus, infants typically practice motor skills by scribbling, which will eventually be used to draw or paint images by the time they are two, similar to infants' prelinguistic babbles that precede their acquisition of speech (Falk 2009). As young children mature, so do their scribbles. They can, thus, typically scribble simple "geometric patterns" by the time they are three and are able to use them to produce elementary renderings of objects such as people, animals, houses, and the sun by around age four (Kellogg et al. 1965:1130). Phosphenes and children's early art both contain arcs, waves, lines, circles, dots, and triangles, etc. (Fig. 1). What's especially relevant for the present discussion is that infants' artistic skills develop through a predictable series of stages and entail production of images like the phosphenes that are experienced by adults when their primary visual cortices are stimulated. Clearly, there is something very fundamental about children's use of basic geometric patterns to depict objects in their visual worlds.

There is also something fundamental about the adult facility for subjectively perceiving images (with or without the eyes closed) of phantom geometric forms—i.e., forms that have no correspondents in the real world. Although, as noted, this experience can happen in response to mechanical, pharmaceutical, or externally applied electrical stimulation, perception of geometric (and other) forms can also occur spontaneously in association with (usually harmless) visual auras that precede migraine headaches in about 10-15% of the people that have them (Grüsser 1995), which is estimated to be about 6-8% of men and 15-25% of women in Western countries (Dreier 2011). Such auras "typically develop in a creeping fashion—a typical migraine aura might start as a scintillation-scotoma (spot of flickering light) in the visual field center and propagate to the field periphery of one visual hemifield of both eyes within about fifteen minutes, corresponding to a spreading depression of brain electrical activity that propagates in the primary visual cortex from the occipital pole forward" (Dreier 2011:443). Although visual auras may entail any of the geometric patterns discussed above as well as many other images (see Podoll and Robinson 2008 for hundreds of illustrations and Viana et al. 2019 for review), the archetype of visual aura, known as a "fortification" spectra (Hadjikhani and Vincent 2021), usually begins centrally as a small flickering zigzag and consists of a grayish C-shaped region that expands as it drifts laterally to one side or the other. (The propagation can also be from the outside to the center of the visual field, Queiroz et al. 2011.) The shifting crescentic region is a traveling blind spot, or scotoma, which has a visible leading edge that appears to be a bright zigzag line. The line and its trailing blind spot eventually drift off into the periphery and disappear.

The physiological events that underpin the fortification (and myriad other) visual auras appear to entail propagating waves in VI that sequentially excite, depolarize and depress columns of neurons with specific orientations (Hubel and Wiesel 1959). In the case of the classic fortification phosphene pattern, zigzags probably appear at the leading edge because excitatory transmitters simultaneously activate distinct groups of neurons that have different preferred orientations, i.e., that subserve extraction of specific information about the orientations of objects' various definitive lines and, thus, their shape (Grüsser 1995 for details). (Much more information about the neurological underpinnings of phosphenes is available in Podoll and Robinson 2008: 239-251.) What is important for the present discussion is that the geometric forms of phosphenes appear to be intrinsically constrained/shaped by the properties of VI neurons, especially the orientations they respond to.

Although, as mentioned, VI also contains neurons that respond to color (clusters of which are called blobs) and studies frequently note in passing that phosphenes may appear in bright shimmering colors, not much attention has been paid to specific details about the colors. Brighter colors have been reported for auras in about 20% of the individuals who had them preceding migraines and "this sensation was sometimes very marked ('colours get so bright that I feel they will attack me')" (Vincent and Hadjikhani 2007:1369). Elsewhere, colors were reported to occur in about 40% of the migraineurs (with or without accompanying black, white and/or silver shades) who experienced visual auras, as compared to 50% whose phosphenes always appeared in black-and-white or black-and-silver (Queiroz et al. 2011). Another study found that, with respect to zigzags of fortification phosphenes, "the colours are seen as very pure; red and green are reported more frequently than the other colours of the spectrum. Some of the flickering particles are of a deep, 'brilliant' black" (Grüsser 1995: 1130). On the other hand, a survey of the non-black-and-white colors in 397 pictures that migraineurs produced to illustrate visual hallucinations reported the colors used from most to least often were yellow, red, blue, green, orange, purple, and brown (Podoll and Robinson 2008: Table 7.11). (Around 20% of the pictures were only in black-and-white.)

Phosphenes in early and recent art

It has long been recognized that geometric images like phosphenes are abundant in the textiles and art of nonindustrialized cultures (Blackburn 1977; Oster 1970; Siegal 1977) and that the earliest images depicted in the Paleolithic record of the Old World were geometric rather than iconic (Lewis-Williams et al. 1988), as was also true for the earliest human-made depictions in the (much more recently settled) Americas (Malotki and Dissanayake 2018; Dissanayake et al. 2019) during a time recognized as equivalent to the Upper Paleolithic elsewhere (Williams and Madsen 2020):

> Since the Late Pleistocene, combinations of straight lines are commonly found, for instance in the engraved ochre plaquettes from Blombos cave, South Africa (about 75,000 years old), as are dots on Franco-Cantabrian cave walls (e.g., the spotted horses from Pech Merle, France, 16,000 years old). Such designs are also observed on artifacts from diverse periods (e.g., decorative lines and also dots on earthenware from the Linear Pottery culture from the European Neolithic, 5500-4500 BC) and in the artistic production of many nonwestern cultures (e.g., geometric patterns on basketry or cloth). The pervasiveness of geometric designs across widely divergent cultures and periods may be explained by the fact that they are appealing to the early human visual system (De Smedt and De Cruz 2010: 699).

It almost goes without saying that some forms of modern art also incorporate phosphene-like geometric images that may derive from or appeal to the physiological underpinnings of the human visual system. Thus, "abstract art often appeals strongly to early perceptual systems, by using vivid colors, straight lines, or sharp contrasts…. In the work of well-known artists like Klee, Mondriaan and Matisse…. 'to abstract' means 'going back to the essentials,' abstract art has indeed succeeded in stripping away cultural conventions by reverting to elementary responses of the human perceptual systems" (De Smedt and De Cruz 2010:702).

As we have seen, geometric images are not only the first hominin-made engravings/paintings in the archaeological record of people everywhere, they are also the first visual perceptions stimulated by the primary visual cortex and the first images that children produce once they are able to control scribbling. Although this remarkable confluence calls for investigation of the emergence and development of hominin's sensitivity to and production of geometrical images in the deep past, few researchers have taken such an evo-devo (evolutionary developmental biology) approach. Robert Bednarik (1984, 1987), however, not only observed that nearly all the phosphenes shown in Figure 1 (i.e., from Kellog et al. 1965's "phosphene- Linnaeus") appear among the non-figurative petroglyphs found across Australia, he also compared phosphene types from different sites and hypothesized that "the more frequently phosphene types occur in rock art, the more archaic it is. In the oldest traditions they may dominate to the point of exclusiveness. This suggests that the ability to externalize concepts of reality (i.e. art) was derived from phosphenes" (Bednarik 1984: 30). The hypothesis that phosphenes themselves may have developed over time is an important one that sets Bednarik's analyses apart from those of others, as does his appreciation of some of the earliest paleoart on record, including beads, pendants, portable plaques, figurines, use of pigments, australopithecine manuports (Bednarik 1998), and petroglyphs (Bednarik 2021).

Some time ago, Bednarik suggested that hominins may have begun externalizing certain geometric patterns beginning with parallel lines (1984:29), which appears to have been prophetic given that Wonderwerk Cave in South Africa has yielded around 20 incised slabs (mobiliary art) "that often feature well-spaced parallel curved lines … from stratified cave contexts extending back to ~ 0.5 Myr ago" (Beaumont and Vogel 2006: 222). Around the same time, but far away in Java, a *Homo erectus* individual engraved a shell from a mussel that "was considerably older than the oldest geometric engravings described so far" with a simple pattern that included parallel lines and zigzags (Joordens et al. 2015: 228). The fact that these earliest known engraved geometric patterns preceded the later production of iconic petroglyphs as, indeed, seems to have been the case worldwide raises the question of what accounts for this so-called "geometric enigma" (Malotki and Dissanayake 2018). As Bednarik recently put it, "Malotki and Dissanayake have most competently identified the 'geometric enigma.' Let us see if archaeometry can rise to the challenge of undoing this veritable Gordian knot" (Bednarik 2020:114). As discussed below, an evo-devo approach may be helpful for exploring the mysterious reasons for the priority of geometric over representational images in the oldest known prehistoric art.

Woven world hypothesis

If one compares artistic development of young children and captive juvenile chimpanzees, gorillas, and orangutans, the scribbles of great apes and humans appear similar (Vancatova 2008). Like children, apes seem to enjoy making drawings and paintings, although they are often less engaged with the process than children and, at times, ignore or attempt to eat the art supplies (Pelé et al. 2021; Saito et al. 2014). One comparative study observed that, despite the non-figurative nature of ape art, "there is a choice in the use of colour, the type of strokes, and the use of space … drawings from great apes do not result from totally random scribbles" (Pelé et al. 2021). Apes sometimes produce fans, loops and occasional shapes that appear somewhat geometrical (Pelé et al. 2021) and experiments suggest their art reveals a remarkable sense of composition and balance (Vancatova 2008), which is perhaps not surprising since great apes have a good grasp of 'folk physics and balance' when navigating their arboreal habitats (Falk 2024).

Nonetheless, apes never develop an ability to produce the six well-formed typical diagrams (Greek cross, square, circle, triangle, odd-shaped area and diagonal cross) that follow the emergence of 20 basic scribbles in children from diverse backgrounds (Kellogg 1955), let alone the elementary pictorial figures that children eventually make (see Kellogg et al. 1965 for illustrations of children's developing artistic output). Consistent with this, a study that compared artistic development in human toddlers and chimpanzees, found that the children, on average, could imitate humans' horizontal and vertical lines by around age 2&1/2 years, circles by about age 3, crosses by 3&1/2, and squares by age 4, but the chimpanzees were unable to imitate the images freely, although they developed the motoric skills to trace them (Saito et al. 2014). Unlike the children, chimpanzees were never able to fill in missing parts on images of faces, despite having good motor control. Significantly, the authors attributed these results to cognitive differences between the species that might be related to the development of global processing abilities in children compared to chimpanzees. In this context, it is interesting that children frequently comment on the scribbles they are producing, but apes make pictures without vocalizing (Vancatova 2008), and that by the time children begin producing well-formed geometric figures they are also in the process of acquiring grammatical language (Falk 2009).

The above comparative studies of artistic abilities are consistent with other data that support the idea that hominins may have evolved global neurological processing that became important for the evolution of visual perception and production. Recall, for example, that people utilize relatively more visual cortex to process objects in peripheral surroundings compared to other primates, likely due to humans' habitually terrestrial lifestyle (Wu et al. 2012). We should also remember that the lines and shapes that dominate individual's visual environments during critical stages of development influence how they, and the populations to which they belong, eventually process visual information, be they cats or people (Hubel and Wiesel 1959, Phillips 2019). Indeed, the carpentered world hypothesis that attributes susceptibility to certain optical illusions to formative experiences with parallel lines and sharp angles in manmade as opposed to natural environments (Segall et al. 1963) may be relevant when considering the geometric enigma.

The hominin and chimpanzee lineages are widely believed to have diverged from an apelike common ancestor (CA) around 6.5 mya (Kumar et al. 2022), after which hominins became increasingly adapted for, and committed to, terrestrial bipedalism. After they split, both groups shared a legacy from their arboreal ancestors, however, namely the visuospatial and motor skills for weaving and bending branches, twigs, and leaves together to make new sleeping nests in trees every evening. (Long after they had shifted to diurnal life on the ground, hominins continued sleeping in trees for safety's sake.) The great apes, in fact, invented tree nests among higher primates—i.e., making them is a derived and rather complex ability that eludes the 200 or so species of monkeys. Further, it is likely that arboreal sleeping nests were the first “tools” that apes invented after they separated long ago from monkeys (Fruth and Hohmann 1996). We humans have retained the great ape habit of sleeping in nests, although we’ve brought them to the ground.

Sleeping nests are constructed from plant matter including wood and, in a sense, the ancestors of chimpanzees and humans who invented them were, if not the first carpenters, at least the first proto-carpenters:

> Nests of all great apes are similarly constructed, despite interspecies differences in habitat and social organization…Nest-builders usually select horizontal side branches for the foundation, over which they bend and break adjacent branches. The rim of these platforms is formed by bending, breaking and occasionally interweaving additional smaller branches from the outer to the inner surfaces, resulting in a circular or oval, bowl-shaped structure. The center of this ‘bowl’ is often lined with detached leafy twigs …. construction types range from sturdy nests on side branches or in single treetops to nests integrating several adjacent trees, sometimes so flexible that the ‘bowl’ resembles a hammock (Fruth et al. 2018:501).

Because apes typically build a new nest each day, they are likely to build many thousands of them during their lives. The arboreal habitats of apes are filled not only with vertical vines and tree trunks, but also with horizontal branches and other variously angled tree limbs. When bending and weaving branches into bowl-shaped nests (some chimps build triangular nests), apes see (and feel) branches crossing each other at different angles as well as coursing approximately in parallel with each other. Thus, although the visual worlds of apes are not carpentered like the industrialized environments of many humans, they contain an abundance of lines, angles, and shapes.

After hominins shifted to ground living, physical changes in the feet associated with bipedalism prevented infants from developing an apelike ability to cling independently to their traveling mothers (Falk 2009). This potentially disastrous situation for hominin survival was averted, I believe, because mothers used their innate nest weaving skills to invent little portable botanical nests with which to attach and carry their helpless infants—the first baby slings, which were likely hominins’ first portable tools (Falk 2024). Ethnographic evidence suggests the first slings would have been extremely simple straps made of pliable plant matter, loosely woven baskets, or net bags. If so, natural textiles were invented very early in prehistory and so, too, was the routine manufacture of geometrical cross-hatching and other designs similar to some of the phosphenes that appear in paleoart.

Although the archaeological record of baby carrying devices is extremely recent, other evidence indicates that textiles were being made from botanic matter much earlier. Take, for instance, the cross-hatched patterns that are the oldest abstract representations in the archaeological record. These patterns were incised on pieces of ochre and engraved on stones from 100,000-60,000 years ago and somewhat more recently on ostrich eggshell containers in South Africa. As Helen Anderson of the British Museum in London observes, however, by the time these artifacts show up in the archaeological record, they do so fully formed. "What we may regard as abstract patterns may be, in fact, representational. Cross-hatch designs on stone, ochre, and ostrich eggshell … dating to the Middle Stone Age…may indicate the transference of patterns and designs emanating from cordage, thread, nets, traps, and woven containers" (Anderson 2013:27). Anderson, like Bednarik and others, is keenly aware of the 5.0 mya engraved *Homo erectus* shell mentioned above. Significantly, when interpreting early engravings, she focuses on the possible role that weaving may have had in terms of stimulating the emergence of such apparently neurocognitively-based patterns:

> "Basketry, in all its various forms, is characteristic of our species and is ubiquitous. There are few cultures who have not used basket-weaving skills for fundamental purposes related to shelter, protection, harvesting food, storage etc. I think in evolutionary terms, the capacity to weave developed our cognitive abilities related to numbers, patterns and structures. Basketry may, indeed, have had a longer and more meaningful place in human culture than previously considered and may have played a role in the evolution of wider patterns of cognition and understanding" (Anderson quoted in Falk 2024).

Bednarik's suggestion that some phosphenes such as parallel lines may have appeared before others is consistent with the hypothesis that the earliest geometric engravings seen in paleoart might be derived from even earlier patterns related to the emergence of ubiquitous activities such as the weaving of pliable plant materials into slings, nets, and baskets (which I call the woven world [WW] hypothesis). As discussed, the WW hypothesis is compatible with the fact that hominin visual systems likely evolved, at least in part, in response to the lines, angles, etc. that predominated in their prehistorically earliest arboreal and terrestrial environments. The implication that phosphene images in paleoart may have become more derived over time is also consistent with the likelihood that, after hominins shifted to ground living, their visual systems adapted to incorporate greater attention to the peripheral world through which they routinely walked to obtain resources. In other words, becoming fully terrestrial may have contributed to the development of global visual processing abilities like those discussed above that separate the art of young children from the renderings of chimpanzees.

The WW hypothesis is compatible with the prediction that of the 15 typical phosphene form groups in the "phosphene-Linnaeus" of Kellogg et al. (1965), the relative frequencies of those that most closely resemble patterns associated with weaving (e.g., the ones labeled arcs, waves, lines, and lattices above in Fig. 1) will be higher than the others as one goes further back in the archaeological record of graphic/pictorial expressions of extant and extinct hominins. On the other hand, the typical forms that do not seem to be geometrical shapes associated with weaving (e.g., combined figs., fingers, 'cherries,' and perhaps triangles in Fig. 1) probably would not have appeared until more recently, just as the appearance of iconic/representational images in rock art and other paleoart postdate the emergence of purely geometrical patterns.

In sum, consideration of the earliest ecological and behavioral factors that may have contributed to the eventual emergence and evolution of artistic expression in hominins incorporates an evo-devo and phylogenetically dynamic approach that might, hopefully, generate testable hypotheses that explore the geometric enigma.

Conclusion

Although the archaeological record of hominin material culture is virtually empty during the first several million years following the divergence of chimpanzees and hominins, one can use comparative evo-devo analyses to begin to explore the likely events that sparked the eventual emergence of advanced hominin cognition, including the ability to conceptualize and make art. I have been reluctant to speculate about the intended meanings of paleoart, however, not because the topic isn't fascinating (it is), but for reasons discussed in the introduction, i.e., I don't have an adequate theory of mind for intuiting the thoughts of paleoartists. Not to mention, rock art and indeed most paleoart, is so recent with respect to the hominin timespan, and probably so relatively developed, that it casts little light that might help elucidate what Bednarik (2020) refers to as the "veritable Gordian knot" of the geometric enigma.

Ethnographic accounts are, of course, potentially relevant, although I have not focused much on them here. But who can fail to see the significance of ethnographic data that strongly suggest that artifacts associated with children's play may, at times, have been/be misinterpreted by archaeologists as evidence of adult ritual behavior (Langley and Lister 2018)? Or fail to consider the insights into the social and cultural context of rock art suggested by one woman's account as a child witness and participant in many rock art paintings during the 1950s and 1960s in the Northern Territory of Australia (Goldhahn et al. 2020)? However, it is important to keep in mind that such reports involve completely modern *Homo sapiens*.

I have long believed that the thing that drove the evolution of advanced cognition in hominins was the emergence and refinement of language and, further, that the distributed neurological networks associated with its emergence were exapted more recently for the invention of other advanced cognitive abilities such as mathematics, musical arts, and reading. I also think the neurological underpinnings that eventually supported language evolution began in conjunction with selection for bipedalism very soon after the divergence between chimpanzees and hominins (Larsson and Falk 2024). However, it is exceedingly difficult to identify criteria that can help pinpoint times by which humanlike (i.e., grammatical) language might have "arrived." The evo-devo comparison of art production in chimpanzee and human youngsters, discussed above, suggests that by the time early hominins were able to produce well-formed geometric patterns, they were likely developing grammatical language. Although others may disagree, for me the 500,000-year-old mussel shell engraved by *Homo erectus* in Java and the equally old engraved slabs from Wonderwerk Cave, South Africa, suggest a most recent date by which hominins in Asia and Africa were at least in the process of refining grammatical language. This estimate will become even earlier, of course, with the next discovery of an older artifact that was deliberately engraved with lines, zigzags, or perhaps other geometric patterns that appear in simple textiles.

Prof. Dean Falk
Department of Anthropology
Florida State University
Tallahassee, Florida 32306, USA
Email: dfalk@fsu.edu

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