

# The Critical Role of Dopamine in the Evolution of Human Intelligence and Thermal Tolerance

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**ABSTRACT:** Modern humans are unique among anthropoids in many key features, including our advanced intelligence, large brain-body size, thermal tolerance, and endurance capability. The objective of this theoretical review is to update the theory of Previc (1999) postulating the importance of dopamine in human evolution by synthesizing newer findings concerning dopamine's role in human intellectual and endurance capabilities. Recent evidence further supports the putative role of dopamine in advanced human intelligence (especially cognitive flexibility) and thermal tolerance and endurance. One key breakthrough is a collection of recent studies demonstrating a uniquely human dopaminergic innervation of the striatum and prefrontal cortex—both essential to human cognition. Another potentially important finding is the human-specific mutation of an enhancer to the EN1 gene that controls eccrine gland formation and plays a major role in the development of dopaminergic brain systems. A plausible evolutionary scenario is put forth in which the enhanced thermal capabilities linked to dopaminergic evolution may have gradually led to the enhanced intellects of modern humans.

**KEYWORDS:** dopamine, intelligence, endurance, evolution, human



Original article

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## Introduction

Humans are unique among primates and even most mammals in several key respects, most importantly our advanced intelligence and thermal endurance capacity during exercise. When these various traits emerged during hominin evolution remains speculative, but the theory presented in this paper—updated from that of Previc (1999)—is that, because of their synergistic relationships, most traits must have emerged concurrently between~ 2.8 million years ago (mya) (just prior to the emergence of *Homo habilis*) and ~1.2 mya (after the emergence of *Homo erectus*).

One key synergy is in the area of human thermal tolerance, which largely depends on the combined advantages of reduced body hair cover and predominantly eccrine sweating; one without the other would be much less advantageous (Lieberman 2015). Other linkages such as bipedalism and increased stature would further enhance thermal tolerance by decreasing exposure to solar irradiance (Wheeler 1985), and thermal exchange via the eccrine glands would be aided by the increased surface-to-mass ratio (Allen's rule) (Tilkens et al. 2007). In turn, the ability to travel long distances in the heat of the midday sun would allow early humans to scavenge and possibly chase-hunt for meat while predators would be resting to avoid hyperthermia (Carrier 1984; Bortz 1985; Lieberman 2015). The switch to a tyrosine-rich carnivorous diet would increase the brain-body ratio due to the combination of a larger brain (Previc 1999) and reduced intestinal mass characteristic of carnivores (Henneberg and Sarafis 1998) and lead to a concomitant increase in dopamine-mediated advanced intelligence.

This paper will postulate that all of these unique features of humans were

caused, causal to, or correlated with increases in the neurotransmitter dopamine and its precursor tyrosine during human evolution. The key roles of dopamine in the evolution of advanced intelligence and thermal tolerance were previously postulated (Previc 1999), but more recent findings to be reviewed here provide a more complete and compelling synthesis of the dopaminergic role in these interleaved components of human evolution. For one, massive and unique increases in dopamine innervation and activity in the human striatum and frontal lobes of humans—key areas involved in higher-level cognition—have been recently found. The importance of dopamine in speech, abstract representations, creativity and a host of other key intellectual functions has also been further demonstrated (see next section). In terms of thermal tolerance, new findings have documented the role of dopamine in creating hair loss and the genetic overlap between the formation of both brain dopaminergic systems and eccrine sweat glands during human evolution (see “The Role of Dopamine in Human Thermal Endurance—New Findings”). And, the importance of meat consumption—previously documented by cut marks on and stone-flaked tools near animal bones in early *Homo* sites—has been supported by genetic analyses of human tapeworms (Hoberg et al. 2001) and pH levels (Beasley et al. 2015) in the human stomach and gut.

## Brain Dopamine and Human Intelligence – New Findings

### Dopamine and Human Intelligence

Previc (1999) theorized the importance of neurochemical changes involving the neurotransmitter dopamine in the evolu-

tion of human intelligence, highlighting six key traits essential to human intelligence and human language—motor planning, working memory, cognitive flexibility, abstract reasoning, temporal analysis/sequencing, and generativity. Previc (1999) argued against the role of brain size and genetic factors in determining human intelligence, instead emphasizing the importance of epigenetic transmission during human evolution. He noted the role of prenatal factors in the creation of brain lateralization in humans (see also Previc 1991), which in most individuals is associated with profound differences in intellectual and other abilities between the left and right hemispheres despite their identical anatomical size and the absence of any known genetic influence. The importance of nongenetic factors in intelligence is supported by recent genome-wide analyses that have consistently shown that only about 5% of the variance in intelligence as measured through standard tests is directly attributable to genes (Benyamin et al. 2014; Davies et al. 2016; Sniekers et al. 2017; Kaminski et al. 2018), with many of the key ones involved in dopaminergic synaptic transmission (DeYoung et al. 2011; Zabelina et al. 2016; Kaminski et al. 2018). Indeed, epigenetic and genetic influences on just six genes involving the synthesis, transmission, breakdown, and re-uptake of dopamine at the synapse can predict much of the variance in childhood intelligence accounted by genome-wide models (Kaminski et al. 2018).

The critical role of dopamine in key “executive” abilities such as working memory, creativity and language has also been confirmed in numerous recent studies and reviews: working memory (D’Esposito and Postle 2015; Matzel and Sauce 2023); creativity/divergent think-

ing (Takeuchi et al. 2014; Lhommee et al. 2014; Zabelina et al. 2016); cognitive flexibility and set-shifting (Ko et al. 2008; Garcia-Garcia et al. 2010); speech (Simoyan et al. 2013; Fuertinger et al. 2018; Rusz et al. 2024); future goals and planning (Hart et al. 2024); and time perception and future orientation (Mitchell et al. 2018). An underlying component of dopamine’s role in most of these abilities is cognitive flexibility—the ability to update processing and actions on the basis of new information and contexts. For example, working memory requires constant updating and attentional disengagement when new information is processed (Matzel and Sauce 2023), divergent thinking requires switching to new mental models and approaches (Palmiero et al. 2022), and choice and switching of goals is correlated with cognitive flexibility scores (Leclercq et al. 2023). Cognitive flexibility stems from dopamine’s dual role in the prefrontal cortex, promoting the inhibition required to stop ongoing behavior and the excitation required to engage in new behavior and processing (Mitchell et al. 2018; Di Domenico and Mapelli 2023). This inhibition is carried out by interneurons in the prefrontal cortex, which are preferentially innervated by dopamine in humans (see next section).

## Unique Dopaminergic Features of the Human Brain

As of 1999, there was little direct evidence that dopaminergic innervation of the human brain had selectively increased relative to other hominids. A lone study by Ikemoto et al. (1997) showed many more neurons staining for dopa-decarboxylase, the enzyme that converts the precursor

L-dopa to dopamine, in the striatum of humans relative to monkeys. But the evolutionary significance of this finding was unclear since neither chimpanzee nor gorilla brains were used as comparisons.

Beginning in 2009, a series of studies carried out by Raghanti and colleagues (2009) found large increases in dopaminergic innervation in areas of the human brain critical to intelligence. All of these studies used stains for tyrosine hydroxylase (TH), the enzyme responsible for converting tyrosine to L-dopa, the immediate precursor to dopamine that crosses the blood-brain barrier.

Raghanti et al. (2009) showed substantial TH staining in human but not chimpanzee and gorilla prefrontal interneurons, suggesting selective catecholaminergic activity in humans. However, because TH is a precursor to noradrenaline via dopamine, no firm conclusion could be drawn as to the selectivity of dopaminergic innervation of human prefrontal cortex. Raghanti et al. (2016) later showed, using TH staining and a measure of axonal length to neuronal density, over twice as much dopaminergic innervation in the medial caudate portion of the dopamine-rich human dorsal striatum compared to that of gorillas and chimpanzees. The noradrenergic contribution to the TH increase in this case could be ruled out because noradrenaline concentrations in the human caudate are ~50 times less than those of dopamine (Tong et al. 2006), despite both catecholamines constituting only a tiny overall percentage of the total neurons in the caudate nucleus and dorsal striatum, the latter containing both the caudate and putamen. The reason for the huge difference in catecholamine concentrations is because of the extraordinary arborization of dopamine axons emanating from the

midbrain substantia nigra, with a single nigrostriatal axon on average contacting up to 75,000 striatal neurons, or 2.7% of the total volume of the neostriatum of the rat (Matsuda et al. 2009). Tyrosine hydroxylase staining in other subcortical dopamine-rich regions was generally greater in humans but less dramatically so than in the medial caudate nucleus. The differences between humans and other hominids in dopamine innervation in the medial caudate were especially impressive in Raghanti et al. (2016) due to the remarkably low variability in human TH levels in that region (Raghanti et al. 2016, Fig. 3).

Sousa et al. (2017) reported elevated TH expression as well as that of dopamine decarboxylase in a wide range of brain areas in humans relative to chimpanzees. The largest differences overall were in the dorsal striatum, but there were also major differences in prefrontal interneurons, with almost no ape prefrontal interneurons staining for TH. In yet another study using TH staining, Hirter et al. (2021) showed significantly greater dopaminergic innervation in the ventral striatum (ventral pallidum and nucleus accumbens) of humans relative to chimpanzees and gorillas. Finally, Ma et al. (2022) showed, based on the relative staining for TH vs. somatostatin (SST), that a remarkable substitution of dopamine for SST occurred during human evolution in prefrontal interneurons, with only 2.4% of human TH-stained interneurons co-localized with SST, in contrast to almost 50% in the macaque monkey. The percentage of TH staining could not even be calculated in the interneurons of chimpanzees and gorillas because it was essentially nonexistent (Ma et al. 2022), in line with the findings of Raghanti et al. (2009) and Sousa et al.

(2017). The significance of this intriguing substitution of SST for dopamine in the very interneurons presumed to be involved in the key ability of cognitive flexibility (see earlier section) remains unclear, however.

Doll et al. (2024) in their Figure 1b summarize the expansion of dopaminergic systems in the human brain that has been documented using TH staining as well as staining for dopa decarboxylase and DAT, which reabsorbs synaptic dopamine back into presynaptic neurons. Additional evidence of a dopaminergic-intelligence link in humans are the significant correlations between volume of the dopamine-rich dorsal striatum and intelligence (Grazioplene et al. 2015; Kaminski et al. 2018). (By contrast, overall brain volume predicts only a small amount of the variance in human intelligence—Pietschnig et al. 2015.) These findings confirm the previously documented importance of the integrity of striatal-frontal circuits (Kling and Tucker 1967) and of the striatum in particular (Goldman and Rosvold 1972) for primate cognitive development. Moreover, selective destruction of dopamine neurons (Brozoski et al. 1979) or blockade of D1 and D2 post-synaptic dopamine receptors (Ranganath and Jacob 2016) essentially replicates the cognitive deficits following lesioning of the prefrontal cortex.

In contrast to the expansion of dopaminergic innervation in the prefrontal cortex and striatum, expression of other major neurotransmitters such as norepinephrine, GABA, glutamate and acetylcholine appears either unchanged or even reduced in humans (Sousa et al. 2017; Raghanti et al. 2018). For example, TH staining in prefrontal interneurons did not co-locate with staining for

dopamine beta-hydroxylase (Sousa et al. 2017), which converts dopamine into norepinephrine, indicating that brain levels of norepinephrine are conserved in hominin evolution. While serotonergic innervation may have increased in certain areas of the human brain (Raghanti et al. 2009; Saniotis et al. 2021), there is little evidence that serotonin contributes to the advanced human cognitive skills listed by Previc (1999), as it even opposes dopamine action in the striatum and prefrontal cortex during learning and memory (Luciana et al. 1998; Daw et al. 2002; Olvera-Cortes et al. 2008). Also, unlike dopamine, serotonin in most humans does not more densely innervate the left hemisphere housing speech and analytical intelligence, nor can the hyperthermic action of serotonin (Tormoehlen and Rusyniak 2018) be reconciled with the greater thermal tolerance and endurance capabilities developed in early hominin evolution (see next section). However, brain serotonin does foster social cooperation and other prosocial behaviors (Crockett 2009), which may have facilitated the use of language and contributed to cultural and technological exchange during later human evolution (Raghanti et al. 2018; Saniotis et al. 2021).

Finally, the large increases in dopamine innervation of the human prefrontal cortex and striatum overall parallel the greater dopaminergic activity in the left hemisphere of most humans (Larsch et al. 1998; Previc 1999; Cho and Strafella 2009)—the citadel of advanced human thought with its dominance in speech, grammar, motor sequencing, abstract reasoning, analytical intelligence, and other unique characteristics of human cognition (Previc 1999; Simonyan et al. 2013; Fuertinger et al. 2018; Rusz et al. 2024). At least two of these

cognitive abilities—speech and cognitive flexibility—have been shown to involve dopamine circuits specifically in the left hemisphere (Ko et al. 2008; Simonyan et al. 2013; Fuertinger et al. 2018).

## The Role of Dopamine in Human Thermal Endurance—New Findings

It has long been theorized that the emergence of *Homo* coincided with an enhanced ability to endure strenuous activity over large distances and tolerate heat, useful in persistence hunting or scavenging (Carrier 1984; Bortz 1985; Wheeler 1985; Bramble and Lieberman 2004; Lieberman 2015). It is still debated whether early humans engaged in chase hunting (more likely to be associated with endurance running), active scavenging, or passive scavenging (Pobiner 2020), but all of these would have required great energy expenditures in the midday heat, when other predators would be inactive. Regardless of the specific means of procuring the meat, the ability of early *Homo* to tolerate heat would have been critical to overcoming these energetic demands.

Besides its direct role in intellectual functioning, a crucial role of dopamine in humans is to prevent hyperthermia during endurance activity. Dopamine levels are elevated during high-intensity and endurance activity (Bortz et al. 1981; Marques et al. 1984; Tyler et al. 2023), and dopamine cells in tissue slices from the anterior hypothalamus, important in temperature regulation, are mostly sensitive to temperature increases (Scott and Boulant 1984). The importance of dopamine in preventing hyperthermia during endurance exercise has been documented in many past studies (e.g., Cox and

Lee 1980; Marques et al. 1984; Lee et al. 1985; Bauer et al. 1989), and its benefits in sustaining endurance performance have been confirmed by more recent ones (Balthazar et al. 2010; Zheng and Hasegawa 2016). Recent clinical findings have also substantiated the important effects of reduced dopaminergic activity in hyperthermic syndromes such as the Parkinsonism Hyperpyrexia Syndrome (Newman et al. 2009; Linares et al. 2016; Coon and Low 2018) and the Neuroleptic Malignant Syndrome associated with anti-psychotic treatments in schizophrenia (Tormoehlen and Rusyniak 2018; Hirschbeck et al. 2022), both in contrast to the hypothermic effect of disinhibited dopamine activity in Huntington Disease (Weydt et al. 2018).

How dopamine transiently achieves its hypothermic action during endurance activity is unclear, since dopamine evidently does not directly control sweating (Shibasaki and Crandall 2010); rather, hyperhidrosis (excessive sweating) is part of the Dopamine Withdrawal Syndrome (Chaudhuri et al. 2015). Dopamine-induced vasodilation (Brodde 1982; Brown et al. 2007) is one potential mode of action, since shunting of the blood to extremities allows for more effective heat transfer (Charkoudian 2003). However, dopaminergic effects are complex in that they may be temperature dependent—hypothermic at high temperatures, hyperthermic at low ones (Brown et al. 2007)—and it has even been argued that there are beneficial effects of brain dopamine on endurance activity aside from its effects on temperatures (e.g., Balthazar et al. 2010; Zheng and Hasegawa 2016, Fig. 2). Previc (1999) speculated that dopamine's role in motor behavior may activate a caudate-hypothalamic axis (Lee et al. 1985) during exercise that enhanc-

es oxygen metabolism and delivery in advance of an actual rise in temperature.

Previc (1999) proposed that the enhanced endurance capability of humans gave rise to a surge in brain dopamine during early human evolution, mainly due to the increase in meat consumption, which would have provided a substantially greater amount of tyrosine in the diet. The evidence for increased meat consumption beginning around 2 mya is compelling (Ferraro et al. 2013; Zink and Lieberman 2016; Pobiner 2020), although sampling biases may distort some of the archaeological findings (Barr et al. 2022). The evidence for meat-eating includes: 1) stone artifacts and bone cut marks in close proximity to early human remains, suggesting meat extraction from carcasses (Pobiner 2020); 2) the reduced size of the modern human large intestine (Henneberg and Sarafis 1998) and an increase in stomach acidity (Beasley et al. 2015), both associated with carnivorous diets; 3) changes in dentition (smaller teeth, especially canines; more bite strength in molars) that could have reflected the consumption of softer, processed meat (Dean and Cole 2013; Zink and Lieberman 2016); and 4) the evolution of human-specific tapeworms linked to African fauna around 1.7 mya (Hoberg et al. 2001). The increased tyrosine in the diet of early *Homo* would have major consequences in that it could have stimulated growth hormone (Tam et al. 2020), thereby increasing stature and brain volume (Yuan et al. 2020), which are significantly correlated (Taki et al. 2012). The effect of meat consumption on height has been demonstrated in past as well as recent large-scale studies (Suzuki 1981; Desmond et al. 2021; Mosites et al. 2017). The enhancement of growth hormone by tyrosine may be mediated by dopamine, although not all evidence is supportive.

But it is clear that dopamine itself, in the brain and elsewhere, is dependent on tyrosine availability (Montgomery et al. 2003), as is cognitive capability, especially cognitive inhibition (Bloemendaal et al. 2018; Hase et al. 2015; Kuhn et al. 2019).

Despite dopamine's important role in thermal tolerance, a key issue was left unanswered in Previc (1999): How could brain dopamine have been a major force in the evolution of human endurance if it was *dependent* on that endurance capability and the consequent increase in meat consumption? A possible solution to this conundrum is the recent finding that the ENGRAILED gene (EN1), a transcription factor that facilitates the formation of eccrine sweat glands (Aldea et al. 2021; Aldea and Kamberov 2022), underwent an evolutionary change in humans due to repeated human-specific mutations of a key enhancer, ECE18. These mutations likely contributed to increasing eccrine density in humans ~10-fold relative to chimpanzees (Aldea and Kamberov 2022), which facilitates the phenomenal ability of humans to eliminate up to one liter of water per hour (Smith et al. 2021) and 12 liters per day by means of evaporative cooling in the skin. It is generally acknowledged that 90% of heat loss occurs through the skin, mostly by radiation and convection; however, evaporative cooling through the eccrine glands becomes more critical at high temperatures (Wang et al. 2016). What is intriguing about the EN1 evolutionary progression is that this gene is also important in the development of midbrain dopaminergic systems (Simon et al. 2004; LePen et al. 2008; Nordstroma et al. 2018; Nouri and Awatramani 2017), the primary source of dopamine in the forebrain. EN1 is part of a constellation of genes and pathways with

many diverse effects in the human body but which all interact to influence both sweating and exercise tolerance as well as the formation and sustenance of brain dopamine systems. These include NURR1 (Amoasii et al. 2019), the WNT family (Alves dos Santos and Smidt 2011), and especially FOXA1 (Ferri et al. 2007; Cui et al. 2012), the latter of which helps regulate both EN1 and NURR1 (Ferri et al. 2007). However, only EN1 via mutations of its enhancer ECE18 is confirmed to have undergone a major functional alteration in humans (Aldea et al. 2021).

Given the fact that each of these genes has multiple regulatory functions in human development, it is possible that the links between these key dopaminergic genes and sweating are coincidental. Or, the EN1 mutation may have affected dopamine and eccrine sweating independently, since eccrine function is largely controlled by cholinergic rather than dopaminergic transmission (Shibasaki and Crandall 2010). Regardless, mutations of an enhancer to a major gene regulating both sweat gland formation and dopaminergic brain development offers a tantalizing clue as to how dopamine and thermal tolerance linked up during human evolution.

In contrast, the reduced body hair cover may have been more directly influenced by dopamine in that dopamine agonists are known to decrease hair cover by stimulating catagen (Langan et al. 2013), which prevents the transformation of fine vellus hair into fully mature terminal hair. The role of dopamine in hair loss is demonstrated by the hair loss in >50% of all Parkinson's patients receiving dopaminergic therapy (Lee et al. 2024). Decreased hair cover would combine with increased dopaminergic vasodilation (Brodde 1982; Brown et al.

2007) to dissipate heat through the skin via the eccrine glands. A final thermal advantage possibly conferred by the tyrosine-dopamine link is the elongation of the human body, which would decrease solar irradiance and increase surface-to-mass ratio, thereby enhancing dermal heat transfer. While Wheeler's original theory posited that bipedalism per se—which preceded the evolution of the *Homo* genus—increased thermal tolerance and endurance, this remains a contentious issue (see David-Barrett and Dunbar (2016) vs. Ruxton and Wilkinson (2011)). But bipedalism associated with an elongated body would certainly have provided a greater means of dissipating heat, in line with Allen's rule. Allen's rule is supported by both experimental studies of limb length and metabolism (Tilkens et al. 2007) as well as the negative association between body height and risk of heat stroke (Taylor et al. 2024).

Many other changes in the human physique, discussed by Bramble and Lieberman (2004), may have simply been associated with the elongation of the body in humans. Others such as changes in dentition and the shape of the foot (Bramble and Lieberman 2004; Zink and Lieberman 2016) have less clear evolutionary origins, but epigenetic factors may have played a role in these as well (Quinn 2012; Khalaf et al. 2022). One adaptation that is more likely to have coincided with the loss of terminal body hair is the increased melanin content of the skin, which would have offset the dangers of increased solar irradiation due to the loss of hair cover (Jablonski 2021). Without such pigmentation, folate metabolism would be seriously impaired, threatening hominin reproductive success (Jablonski 2021; Lucock

2023). Melanin synthesis is influenced by many factors, but it is ultimately dependent on tyrosine and its conversion to L-dopa and then dopaquinone (Marranduca et al. 2019), consistent with evidence that L-dopa treatment for Parkinson's disease has stimulating effects on melanogenesis (Bougea et al. 2019). In line with the hypothesized link between skin pigmentation and reduced hair cover during early *Homo* evolution, significant inverse correlations exist between skin pigmentation and hair follicle density and hair length in extant humans, with the former accounting for over 28% of the variance in follicle density (Dhugga et al. 2014).

## Implications for Human Evolution

The linkage between EN1 and associated genes and dopaminergic brain development suggests that the mutations of the EN1-enhancer ECE18 may have been a catalyst for ensuing evolutionary changes in early *Homo*. Several rationales support the view that the enormous increase in eccrine sweat glands occurred before many other evolutionary changes such as decreased hair cover and increased stature. Of the three factors unique to human thermal tolerance, elongation of the body occurred later in the period from 2.5 to 1.5 mya, based on the skeletal record (Will et al. 2017). The other factor—reduced hair cover due to a retraction of terminal hair—may have occurred secondarily as well, for in the absence of copious sweating capabilities a loss of hair cover would have exposed humans to damaging solar radiation, with mixed thermoregulatory effects (David-Barrett and Dunbar 2016). (By

contrast, the benefits of an increase in eccrine sweat glands would also have been limited without a concomitant decrease in hair cover (Lieberman 2015), but at least expanded eccrine sweating by itself would not have proven harmful). An additional reason for believing in the primacy of eccrine gland evolution is that greater eccrine activation and perhaps density is associated with hotter climates (Best and Kamilar 2018; Best et al. 2019), and the climate of the savanna was hotter at the beginning of hominin evolution than after 2.5 mya, when worldwide climate underwent a cooling trend (Stanley 1995). On the other hand, as the climate cooled and dried and forests in East Africa gave way to grassland, arboreal creatures such as the Australopithecines would have had more trouble adapting to the new climate than early *Homo*, the latter having a greater surface-to-mass area, reduced hair cover, and a more advantageous foot structure (Bramble and Lieberman 2004). Because EN1 influences both eccrine and hair follicle development, it cannot be ruled out that the eccrine increase and loss of hair cover occurred simultaneously; however, hair follicle density per se has not changed in humans relative to chimpanzees (Kamberov et al. 2018), and there is no evidence that EN1 promotes the catagen-induced loss of terminal hair.

One plausible evolutionary scenario is portrayed in Figure 1. An initial genetic adaptation involving ECE18 and the EN1 gene could have independently increased eccrine sweat gland density and dopaminergic brain innervation. The latter's elevation would then contribute to reduced human hair cover and increased peripheral vasodilation to further enhance human thermal tolerance.

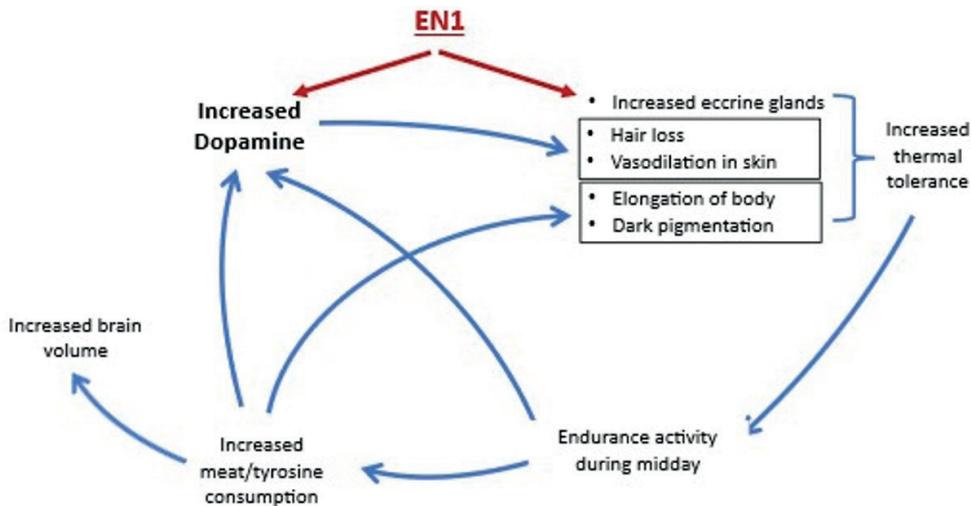


Figure 1. A hypothetical scenario for the rise of human intelligence and endurance capabilities in early human evolution. A mutation of the ECE18 enhancer to the regulatory gene EN1 could have expanded both eccrine gland density and brain dopaminergic systems. In turn, dopamine would facilitate complementary heat loss mechanisms that allowed for increased endurance capabilities and the ability of early humans to exploit the African savanna for procurement of meat. The tyrosine and other proteins contained in the more carnivorous diet would lead to an increase in brain size, height, melanization of the skin, and further increases in brain dopamine

This facilitated the greater exploitation of the savanna grasslands by permitting travel over longer distances under thermally stressful conditions to procure meat, rich in tyrosine. The increase in tyrosine would have further increased brain dopamine, physical stature, and brain size along with increasing the melanin content of the human skin to protect it against the increased solar absorption due to the loss of hair cover. Once begun, the entire cyclical process could have been a gradual one, as suggested by Jablonski (2021, Fig. 1). A gradualist scenario is consistent with evidence that dopamine levels can be altered by epigenetic mechanisms and easily traverse the placenta, steadily accumulating over generations (see Previc 2009). The gradualist

view of dopaminergic expansion is also consistent with recent re-appraisals of the cognitive capabilities of *Homo erectus* and archaic humans, given evidence of advanced lithic technology, abstract designs, food processing, and the use of fire dating back hundreds of thousands of years and, in some cases, even longer (Bednarik 1995; DeLouize et al. 2017; Clark and Henneberg 2021).

The putative rise in brain dopamine in conjunction with eccrine gland expansion and a less hairy and darkened skin is necessarily speculative and cannot yet be linked to a specific timeframe, since all scientists can currently decipher about soft tissue changes during human evolution is the difference between extant humans and chimpanzees.

That divergence is believed to have occurred about 6–7 mya, and each species has evolved since then. The presence of the ECE18 mutations in the Neanderthal genome might push its existence as far back as back as 800 kya and perhaps somewhat plausibly even to the emergence of *Homo erectus*, but in the progression from *Homo habilis* to *Homo erectus* all that can be determined from the fossil and archaeological record is that more advanced tools were used to extract meat from carcasses, elongation of the body occurred, cranial capacity increased, and dentition evolved with ingestion of softer foods (Dean and Cole 2013). Aside from some limited genetic evidence related to tapeworm mutations, suggesting meat-eating as early as ~2 mya (Hoberg et al. 2001), there is little else available to capture precisely the evolutionary past other than theoretical analyses. Chemical composition in bone—especially relative zinc isotopes ( $Z^{66}$  to  $Z^{64}$ ) and carbon and nitrogen amino acid isotopes—offers promise in determining when greater carnivory occurred (Jaouen 2016; Jaouen et al. 2022; Larsen 2022), but these measures are difficult to interpret with remains dating back millions of years. So, definitive findings concerning when the putative rise in dopamine first occurred during hominin evolution is still lacking.

According to Previc (2009), the hominin progression leading from *Homo habilis* to *Homo erectus* was a major step in establishing the “dopaminergic mind”, but it was not the final stage. Despite large migrations of *Homo erectus* to different latitudes and regions with vastly different climates along with the thermal effect of clothing wear beginning around 170 kya (Toups et al. 2011), human intelligence, brain size, meat-eating, body

height, sweat gland density, and many other distinguishing features of modern humans never retreated to pre-*erectus* levels. It may be presumed, as Previc (2009) argued, that dopamine levels in the human lineage continued to increase to the present, possibly epigenetically, as dopamine levels in individuals can be altered through diet, exercise, and psychological factors (e.g., stress) and can be easily passed on to offspring through placental transmission (Horackova et al. 2022). In the end, *Homo sapiens* acquired a large dopaminergic brain innervation and an impressive intelligence and thermal tolerance without parallel among mammals.

## Conclusion

Recent findings have confirmed three of the major tenets of Previc (1999): the key roles of dopamine in human intelligence; the expansion of dopaminergic innervation of brain areas essential to human cognitive abilities; and the criticality of dopamine in thermal tolerance. Which uniquely human traits evolved after the divergence with chimpanzees is much better understood than how and when those traits evolved. But recent findings also offer a clearer glimpse than ever before as to what might plausibly constitute the progression of events during hominin evolution from *Homo habilis* to *Homo erectus*. Almost certainly, the neurotransmitter dopamine exerts a paramount influence on that evolutionary course.

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There are no conflicts of interest associated with this paper.

**Author contribution**

Sole author responsible for conceptualization, literature synthesis, writing and editing of the manuscript.

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