Language evolution to revolution: from a slowly developing finite communication system with many words to infinite modern language

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Abstract

There is overwhelming archeological and genetic evidence that modern speech apparatus was acquired by hominins by 600,000 years ago. There is also widespread agreement that modern syntactic language arose with behavioral modernity around 100,000 years ago. We attempted to answer two crucial questions: (1) how different was the communication system of hominins before acquisition of modern language and (2) what triggered the acquisition of modern language 100,000 years ago. We conclude that the communication system of hominins prior to 100,000 years ago was finite and not-recursive. It may have had thousands of words but was lacking flexible syntax, spatial prepositions, verb tenses, and other features that enable modern human language to communicate an infinite number of ideas. We argue that a synergistic confluence of a genetic mutation that dramatically slowed down the prefrontal cortex (PFC) development in monozygotic twins and their spontaneous invention of spatial prepositions 100,000 years ago resulted in acquisition of PFC-driven constructive imagination (*mental synthesis*) and converted the finite communication system of their ancestors into infinite modern language.

1. Acquisition of modern speech apparatus from 2 million to 600,000 years ago

The articulate speech of humans is unique among primates. The vocal tract of our closest relatives, chimpanzees' is extremely limited in its ability to modulate sound and restricts the range of distinct vocalizations to between 20 to 100[1–4]. The modern human vocal apparatus can communicate tens of thousands of different words. The evolution of language is undoubtedly connected to the evolution of articulate speech and the underlying vocal tact. The modern vocal apparatus developed as a result of changes of the structure and the position of many organs that play a role in generating and modulating vocalizations: larynx, tongue, musculature of the mouth, lips, and diaphragm as well as the neurological control of the associated musculature. While cartilaginous and soft tissue is not preserved in the fossil record, we can draw conclusions about evolution of vocal apparatus from the bony structures which do survive. Three lines of converging evidence point to acquisition of modern speech apparatus by 600,000 years ago: 1) the changing hyoid bone, 2) the flexion of the bones of the skull base, and 3) the evolution of the FOXP2 gene.

1. The changing hyoid bone. This small U-shaped bone lies in the front of the neck between the chin and the thyroid cartilage. The hyoid does not contact any other bone. Rather, it is connected by tendons to the musculature of the tongue, and the lower jaw above, the larynx below, and the epiglottis and pharynx behind. The hyoid aids in tongue movement used for swallowing and sound production. Accordingly, phylogenetic changes in the shape of the hyoid provide information on the evolution of the vocal apparatus.

The hyoid bone of a chimpanzee is very different from that of a modern human. The australopith hyoid bone discovered in Dikika, Ethiopia, and dated to 3.3 million years ago closely resembles that of a chimpanzee [5]. The *Homo erectus* hyoid bone recovered at Castel di Guido, Italy, and dated to about 400,000 years ago reveal the "bar-shaped morphology characteristic of *Homo*, in contrast to the bulla-shaped body morphology of African apes and *Australopithecus"* [6]. The Neanderthal hyoid bone from about 60,000 B.C. discovered at the Kebara 2 Cave in Israel [7] is virtually identical to that of a modern human in size and shape suggesting that the last direct ancestor of both *Homo neanderthalensis* and *Homo sapiens* (namely *Homo heidelbergensis*) already possessed a nearly modern hyoid bone [8]. The similarities between Neanderthal and modern human hyoid make it likely that the position and connections of the hyoid and larynx were also similar between the two groups.

2. The flexion of the bones of the skull base. Laitman [9,10] has observed that the roof of the vocal tract is also the base of the skull and suggested that evolving vocal tract is reflected in the degree of curvature of the underside of the base of the skull (called basicranial flexion). The skull of *Australopithecus africanus* dated to 3 million years ago shows no flexing of the basicranium, as is the case with chimpanzees [11]. The first evidence of increased curvature of the base of the basicranium is displayed in *Homo erectus* from Koobi Fora, Kenya, 1.75 million years ago [9]. A fully flexed, modern-like, basicranium is found in several specimen of *Homo heidelbergensis* from Ethiopia, Broken Hill 1, and Petralona from about 600,000 years ago[12] providing converging evidence for acquisition of modern-like vocal apparatus by 600,000 years ago.

3. The evolution of the FOXP2 gene. The most convincing evidence for the timing of the acquisition of the modern speech apparatus is provided by DNA analysis. The FOXP2 gene is the first identified gene that, when mutated, causes a specific language deficit in humans. Patients with FOXP2 mutations exhibit great difficulties in controlling their facial movements, as well as with reading, writing, grammar, and understanding others [13].The protein encoded by the FOXP2 gene is a transcription factor. It regulates genes involved in the production of many different proteins. The FOXP2 protein sequence is highly conserved. There is only one amino acid difference in the chimpanzee lineage going back some 70 million years to the common ancestor with the mouse [14]. The FOXP2 proteins of chimpanzee, gorilla and rhesus macaque are all identical to each other. This resistance to change suggests that FOXP2 is extraordinarily important for vertebrate development and survival. But there is a change of two amino acids in FOXP2 that occurred over the last 6 million years, during the time when the human lineage had split off from the chimpanzee. These two amino acid substitutions predate the human-Neanderthal split. The analysis of the Neanderthal DNA extracted from two different individuals excavated from the El Sidron Cave in Asturias, northern Spain, showed that modern humans and Neanderthals have an identical FOXP2 protein sequence [15]. This indicates that *Homo heidelbergensis,* the common ancestor of *Homo sapiens* and Neanderthals, already had a FOXP2 protein sequence that was identical to that of modern humans. The comparatively fast mutation rate of FOXP2 in hominins indicates that there was strong evolutionary pressure on development of the speech apparatus before *Homo sapiens* diverged from Neanderthals over 500,000 years ago [16].

Based on these three lines of evidence — the structure of the hyoid bone, the flexion of the bones of the skull base, and the FOXP2 gene evolution — most paleoanthropologists conclude that the speech apparatus experienced significant development starting with *Homo erectus* about two million years ago and that it reached nearly modern configurations in *Homo heidelbergensis* about 600,000 year ago [17]. We will never know the extent of *Homo heidelbergensis* neurological control of their speech, however considering that chimpanzee communication system already has 20 to 100 different vocalizations [1–4], it is likely that the modern-like remodeling of the vocal apparatus in *Homo heidelbergensis* extended their range of vocalizations by orders of magnitude. In other words, by 600,000 years ago the number of distinct verbalizations was no longer a limiting factor in hominin communication.

2. Modern syntactic language arose concurrently with behavioral modernity around 100,000 years ago

Archeological records from many geographically diverse areas show that around 40,000 years ago human society has experienced a sudden emergence of four novel traits, these being: 1) figurative arts, 2) manufacturing of multitude of new types of tools, 3) improvements in design and construction of living quarters, and 4) elaborate burials. Together with 5) fast colonization of the globe and migration to Australia (presumably by boats) at around 62,000 years ago, the archeological evidence indicates an abrupt change in hominin behaviour. While extreme gradualists envisage the slow emergence of "modern" behaviors over hundreds of thousands of years [18], the majority of researchers explain this abrupt change in human behavior by a "big bang" acquisition of modern syntactic language around 100,000 years ago[19–24].

1. Figurative arts. The archeological record possesses just a few objects that can be classified as art until about 80,000 years ago. There is always heated debate on whether some ancient item, e.g., a bone or a stone with regular incisions, is a natural artifact or was produced by a hand of a hominin [25]. The first undisputed art objects include pierced marine shells, found in various locations in Africa, Asia, and Europe, which were probably used as beads. The earliest pierced shells from eastern Morocco were dated to around 82,000 years ago [26]. The famous shells from the Blombos Cave in South Africa were dated to around 70,000 years ago, and include over 65 shells that were brought from rivers located 20 km from the cave and then pierced by inserting a small bone tool through the aperture to create a "keyhole perforation." [27,28] In addition to beads, archeologists have also discovered several ochre plaques with cross-hatched patterns engraved over a smoothed surface [29]. The plaques were dated to approximately 75,000-100,000 years ago.

The earliest figurative art appears in the archeological record around 40,000 years ago. At this point it is already represented by many different forms such as cave paintings drawn using charcoal and ochre or carved into the walls, and diverse figurines, e.g., voluptuous "Venus figures," made out of bone and stone. What's interesting is that this early art appeared nearly simultaneously in hundreds of distant locations from Europe [30,31] to Indonesia [32]. Among drawings and figurines, there are composite objects such as the Lowenmensch ("lion-man") sculpture from the caves of Lone valley in Germany (dated to 37,000 years ago) [33]. The composite objects do not exist in nature and must have been imagined by the artists by first *mentally synthesizing* parts of the man and beast together and then executing the product of this mental creation in ivory or other materials. The composite artworks provide direct evidence that by this time humans were capable of purposefully imagining novel images. This constructive conscious PFC-driven [34] process of creating a new image within one's mind we will designate as a *mental synthesis* [35,36].

2. Creativity and innovation. The hominin propensity for creativity and innovation can be inferred by looking at the number and quality of the different types of tools they manufactured. Researchers have been able to observe and record an extensive list of over thirty types of tools used in the wild by chimpanzees [37–39]. Most tools, such as stones used to break nuts, are used in their natural form, but there are a few tools that are manufactured by chimpanzees. For example, chimps prepare sticks for termite-fishing by trimming twigs; they also make a sort of spear for hunting bushbabies by biting on one end of a stick [40]. Hominins expanded on the chimpanzee repertoire by adding Mode One stone choppers around 3.3 [41] to 2.5 [42] million years ago. Around 2 million years ago, *Homo ergaster* added

Mode Two handaxes [43]. Around 400,000 years ago, Neanderthals added Mode Three stone tools, which consisted of sophisticated stone-flakes and task-specific tools such as large scrapers created from flint flakes [43]. These tools were produced using soft hammer percussion, using hammers made out of materials such as bones, antlers, and wood, as opposed to hard hammer percussion, which uses stone hammers [43]. Neanderthals also manufactured wooden spears[44]. This list pretty much includes all the types of tools manufactured by primates before the arrival of *Homo sapiens.*

In comparison to the relative stasis of tool development by early hominins, tool development by modern humans seems to be lightning fast [17,45]. As early as 64,000 years ago humans introduced quartz-tipped arrows suggesting the development of the bow and arrow [46]; bone needles (dated to as early as 61,000 years ago) [47], and even musical instruments – tools for facilitating the process of producing pleasing sounds (dated as early as 43,000 years ago) [48].

3. Design and construction. There is little evidence of hominins constructing dwellings or fire hearths until the arrival of *Homo sapiens*. While Neanderthals controlled the use of fire, their hearths were usually very simple: most were just shallow depressions in the ground. There is almost a complete lack of evidence of any dwelling construction [49] . The arrival of *Homo sapiens*, on the other hand, is marked by a multitude of constructed structures including stone-lined and dug-out fireplaces, as well as unambiguous remains of dwellings, which all flourished starting around 30,000 years ago. These include foundations for circular hut structures at Vigne-Brune (Villerest) in eastern France, dating back to 27,000 years ago [50]; postholes and pit clusters at a site near the village of Dolní Věstonice in the Czech Republic, dating back to 26,000 years ago [51], and mammoth bone structures at Kostienki, Russia and Mezirich, Ukraine [52]. As early as 12,000 years ago, *Homo sapiens* introduced agriculture and started to build permanent villages [17,45].

4. Adorned burials and religious beliefs. The origin of religious beliefs can be traced by following the beliefs in the afterlife. Beliefs in the afterlife, in turn, are often associated with adorned burials. Therefore the development of religious beliefs may be inferred by studying the time period when humans started to bury their deceased in elaborate graves with accompanying "grave goods."

The oldest known human burial, dated at 500,000 years ago and attributed to *Homo heidelbergensis*, was found in the Sima de los Huesos site in Atapuerca, Spain, and consists of various corpses deposited in a vertical shaft [53]. A significant number of burials are also associated with Neanderthals: La Chapelle-aux-Saints, La Ferrassie, and Saint-Cesaire in France; Teshik-Tash in Uzbekistan; Shanidar Cave in Iraq [54]. However, whether or not these sites constitute actual burial sites is hotly disputed. Their preservation could well be explained by natural depositions [55]. Even if those burials were made deliberately, the goal may have been to simply toss the bodies away in order to discourage hyena intrusion into the caves [17]. In any case, these early burials completely lack the "grave goods" that would indicate the belief in an afterlife [17].

Human skeletal remains that were intentionally stained with red ochre were discovered in the Skhul and Qafzeh caves, in Levant and dated to approximately 100,000 years ago [56]. One of the burials contains a skeleton with a mandible of a wild boar, another contains a woman with a small child at her feet, and yet another one containing a young man with a possible offering of deer antlers and red ochre [57]. While these burials are clearly intentional, whether or not they indicate the belief in an afterlife is uncertain. The ochre by itself is inconclusive evidence. For example, ochre could have been used during lifetime to protect skin from insects and the deceased could have been buried still bearing the ochre marks. The small number of "offerings" found in these burial sites may have simply been objects that fell into the burial pit accidentally. In any case, there is not enough conclusive evidence from these early burials to judge the occupants' beliefs in an afterlife.

The number of known *adorned* burials and the sophistication of the offerings significantly increases around 40,000 years ago. To date, over one hundred graves of *Homo sapiens* have been discovered that date back to the period between 42,000 and 20,000 years ago [58]. In many cases several bodies were interred in a single grave. Burial offerings were commonplace and ochre was used abundantly. Examples include: a burial in Lake Mungo, Australia of a man sprinkled with red ochre, dating back to 42,000 years ago [59]; an elaborate burial in Sungir, Russia that includes two juveniles and an adult male wearing a tunic adorned with beads and carefully interred with an astonishing variety of decorative and useful objects, dating back to 30,000 years ago [60]; a grave in Grimaldi, Italy, which contains the remains of a man and two adolescents along with burial offerings from around 40,000 years ago [58]; and a site in Dolni Vestonice, in the Czech Republic where a woman was buried between two men and all three skulls were covered in ochre dating back to 28,000 years ago [61].

5. Fast colonization of the globe and migration to Australia. Hominins diffusing out of Africa have been colonizing the Europe and Asia long before the arrival of *Homo Sapiens*: the remains of *Homo erectus* have been found as far as in Spain [62] and Indonesia [63] and Neanderthals remains have been found in Europe and Asia [64]. However, both the extent and the speed of colonization of the planet by *Homo Sapiens* are unprecedented. Our ancestors diffusing out of Africa around 70,000 years ago quickly settled Europe and Asia and crossed open water to Andaman Islands in the Indian Ocean some 65,000 years ago [65] and Australia as early as 62,000 years ago [66]. Migration to Australia is consistent with the use of boats by early modern humans further underlying their propensity for technological innovations.

Conclusions from paleontological evidence. Evolution of figurative arts, creativity and innovation, design and construction, religious beliefs, and steadfast colonization of the planet are highly correlated with each other in time and geography and are indisputably associated with *Homo Sapiens* diffusion out of Africa around 70,000 years ago. This abrupt change toward behavioral modernity has been characterized by paleoanthropologists as the "Upper Paleolithic Revolution," [67] the "Cognitive revolution," [68] and the "Great Leap Forward" [69] (also see [17,70]) and is consistent with a single enabling process causing these multifaceted behavioral changes. This enabling process is considered by many scientists to be the acquisition of modern language [19–24].

3. What happened 100,000 years ago?

Acquisition of modern language is commonly cited as the reason that humans dramatically changed their behavior around 100,000 years ago [19–24]. However, to this day, there is vigorous scientific debate, which revolves around the following questions: what part of language was acquired 100,000 years ago and why was the language acquired so abruptly [71]? Charles Darwin envisioned the origin of language simply as an acquisition of a mechanical ability to produce sounds, which provides the basis for a communication system [72]. However, as discussed above, archeological and genetic evidence from FOX2P gene indicates that the number of distinct words could not have been a limiting factor in hominin communication system after 600,000 years ago. The hypotheses explaining the half million year gap between the acquisition of modern vocal apparatus 600,000 years ago and acquisition of modern language 100,000 years ago tend to fall into one of the two categories: some scientists prioritize the role of nurture, while others advocate the role of nature in language acquisition. The "nurture" hypothesis claims that a culturally acquired communication system enabled language acquisition [73]. Opponents of the "nurture" hypothesis argue that human syntactic language cannot be taught to animals and therefore humans must be unique in their genetic predisposition to language. Spearheading the "nature" hypothesis is Noam Chomsky who argues that a genetic mutation, which took place 100,000 years ago, enabled the innate faculty of language [74]. Both parties agree that hominin behavior changed dramatically some 100,000 years ago, but the nurture party argues that a communication system was culturally acquired at that time, while the nature party argues that a genetic mutation predisposed humans to language acquisition. Neither hypothesis, however, directly explains the dramatic and sudden change in human behavior: the appearance of figurative drawings and sculpture, displays of composite images like lion-man, unprecedented technological progress, and lightning-fast expansion of settlements to all habitable regions of the planet. From a neuroscience perspective, it is relatively easy to imagine how a single mutation could have increased the brain volume or the number of synapses or the number of glial cells by a few percentage points but it is unclear how these relatively small neurological changes could have resulted in such an abrupt change of behavior. If it was not a genetic mutation but solely the acquisition of a communication system that was acquired 100,000 years ago, then it is unclear why the communication system that had been developing for close to two million years (as evidenced by the developing speech apparatus) generated such a dramatic change in behavior at a 100,000-year mark, but not earlier.

We suggest that the nurture and nature theories are not mutually exclusive and that, in fact, both theories are correct. We call our theory the "Romulus and Remus hypothesis." Our hypothesis posits that genetically identical twins shared a mutation that slowed down their PFC development, extending their critical period [75] and predisposing them to acquisition of modern language. We argue that the parents of the twins possessed a finite non-recursive communication system with many words, but no flexible syntax or spatial prepositions. According to our analysis of children linguistically isolated until puberty, finite communication systems (called kitchensign or homesign, as opposed to a formal sign language) are unable to facilitate development of mental synthesis even in genetically modern children. In particular, these children exhibit lifelong mental synthesis disability in both verbal and nonverbal tests despite many years of focused rehabilitation attempts [36]. Our analysis shows that childhood use of infinite communication system with flexible syntax and spatial prepositions is essential for acquisition of mental synthesis. Accordingly, we propose that Romulus and Remus spontaneously invented spatial preposition around 100,000 years ago and thus converted their tribe's non-syntactic finite communication system into an infinite syntactic communication system. With just a few prepositions, their normal conversations with each other would have provided enough stimulation to acquire experience-dependent mental synthesis (see the legend to Fig. 1) and thus, a full human language. Once Romulus and Remus invented the infinite language, we can expect that each following generation expanded the repertoire of recursive elements of language and, as a result, improved their mental synthesis. The best-studied modern example of such parallel development of newly invented language and mental synthesis is found among deaf children in Nicaragua who spontaneously developed an original sign language of great complexity, with verb agreement and other conventions of grammar [76]. As newer generations of Nicaraguan sign language speakers expanded their language, they have also improved on multiple measures of mental synthesis [77–79].

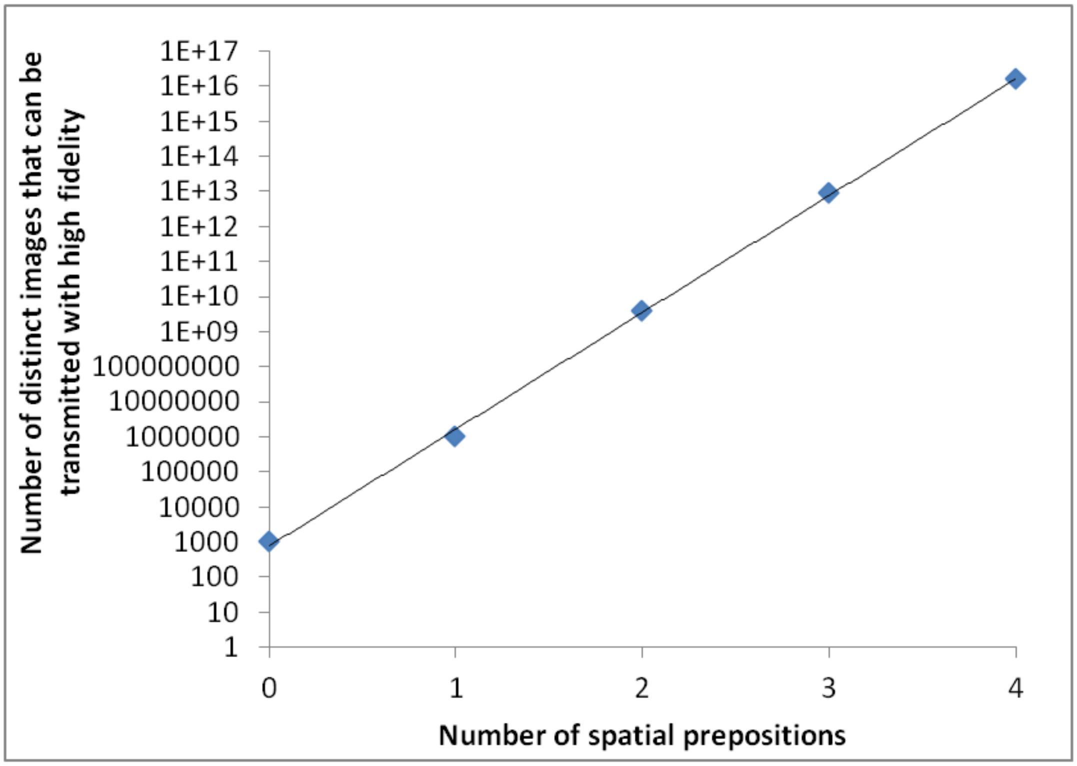

Figure 1. Flexible syntax, prepositions, adjectives, verb tenses, and other common elements of grammar, all facilitate the human ability to communicate an infinite number of novel images with the use of a finite number of words. The graph shows the number of distinct images that can be transmitted with high fidelity in a communication system with 1,000 nouns as a function of the number of spatial prepositions. In a communication system with no spatial prepositions and other recursive elements, 1000 nouns can communicate 1000 images to a listener. Adding just one spatial preposition allows for the formation of three-word phrases (such as: 'a bowl *behind* a cup' or 'a cup *behind* a bowl') and increases the number of distinct images that can be communicated to a listener from 1000 to one million (1000x1x1000). Adding a second spatial preposition and allowing for five-word sentences of the form *object-preposition-object-preposition-object* (such as: a bowl *on* a cup *behind* a plate) increases the number of distinct images that can be communicated to four billion (1000x2x1000x2x1000). The addition of a third spatial preposition increases the number of distinct images to 27 trillion (1000x3x1000x3x1000x3x1000), and so on. In general, the number of distinct images communicated by three-word sentences of the structure object-preposition-object equals the number of object-words times the number of prepositions times the number of object-words. A typical language with 1000 nouns and 100 spatial prepositions can theoretically communicate 1000^{101} x 100^{100} distinct images. This number is significantly greater than the total number of atoms in the universe. For all practical purposes, an infinite number of distinct images can be communicated by a syntactic communication system with just 1000 words and a few prepositions. Prepositions, adjectives, and verb tenses dramatically facilitate the capacity of a syntactic communication system with a finite number of words to communicate an infinite number of distinct images. Linguists refer to this property of human languages as *recursion*. The "infiniteness" of human language has been explicitly recognized by "Galileo, Descartes, and the 17th-century 'philosophical grammarians' and their successors, notably von Humboldt" [71]. The infiniteness of all human languages stand in stark contrast to finite homesign communication systems that are lacking spatial prepositions, syntax, and other recursive elements of a formal sign language.

4. The riddle of the "PFC delay" mutation

Overall, humans are born with a less mature brain and develop one and a half to two times slower than chimpanzees: molar teeth erupt three years later and humans become sexually active roughly five years after the chimps do [80]. However, the period of synaptogenesis in the human PFC is stretched out over the first 3.5–10 years of childhood, whereas in chimpanzees and macaques it is limited to several postnatal months [81,82]. Furthermore, the PFC myelination rate in human is significantly slower than in chimpanzees [83]. The delay in maturation in the PFC from a few months in chimpanzees and macaques to more than 3.5 years in humans is much more dramatic compared to this overall delay in maturation. Additionally this delay is exhibited primarily by the PFC, but not by other parts of the brain, such as the cerebellum [84]. Sometime during the past six million years a genetic mutation triggered this dramatic delay of the PFC maturation schedule. Notably, Liu *et al.* report that the delay in the PFC development occurred within the last 300,000 years, placing the "PFC delay" mutation on the radar for mutations that could have contributed to the "Great leap forward" 100,000 years ago [81].

In fact, the fixation of the "PFC delay" mutation in a human population does not make sense without a simultaneous acquisition of modern language. Universally, mutations that get "selected" for and fixed in a population are associated with some survival benefits. The "PFC delay" mutation has no such obvious survival benefit. On the opposite, this mutation carries clear disadvantages to its carriers. A significantly extended immaturity of the PFC results in a prolonged childhood when the brain is incapable of full risk assessment. For example, three-year-old chimps often venture away from their mother, but rarely come close to water, their mature PFC prohibiting them from doing so. On the contrary, among human children under 4 year of age, drowning is the leading cause of death [85]. The PFC of the four-year-old child is unable to fully assess the risk of drowning. Similarly, three-year-old children cannot be left alone near fire, near an open apartment window, near a traffic road, or in a forest. In terms of risk assessment, three year-old human children are intellectually disabled compared to any other three year-old primate.

The only clear advantage of the "PFC delay" mutation is that it prolongs the "language acquisition critical period" [75] and predisposes the carrier to the acquisition of mental synthesis [36]. But this advantage materializes only later in life and only if the mutation carrier is exposed to an infinite language during his/her childhood, which, in turn, provides the experience essential for mental synthesis acquisition [36]. It follows that the first carriers of the "PFC delay" mutation, 'Romulus' and 'Remus', must have also been the inventors and the first users of the modern infinite language. Living together during their exceptionally (among contemporaries) long childhood, the children must have done a common thing for the twins living together, they must have invented new words (the process called cryptophasia) [86]. In this case they must have stumbled upon spatial prepositions and/or other recursive elements of language. With just a few prepositions, their normal conversations and the stories they related to each other would have provided training for their PFC, which must have been essential for the acquisition of mental synthesis [36]. A mutation that would have been deleterious in the absence of a childhood exposure to syntactic communication system became a highly advantageous mutation due to the simultaneous acquisition of a syntactic language and mental synthesis.

5. Revolution in hominin cooperation

Synergy of infinite language and mental synthesis enabled an unprecedented level of cooperation between individuals previously unseen in the animal kingdom. While other primates often cooperate [87], their teamwork is severely limited by their inability to communicate *novel* ideas and negotiate plans: skills that depend on both the speaker and the listener being capable of mental synthesis. The combination of mental synthesis with infinite language converted a pre-mental-synthesis society to a modern human society, which relied on the highest level of cooperation. Groups of *Homo sapiens* became much better hunters: they could mentally plan a strategy and then use infinite language to explain the plan to their tribesmen (that is, to synthesize mental images in the minds of their peers as to where to run and how to attack a prey or an enemy). They could deceive prey animals by building a trap, make sophisticated weapons, such as atlatls and the bow and arrow [45,46], and use these weapons in novel ways, hunting from a distance therefore avoiding close range and highly dangerous encounters with large animals [17].

Could a hominin tribe with no mental synthesis build a trap? It is very unlikely. Building a sophisticated pitfall trap requires mental planning of the process. A leader has to be able to think through the plan by imagining the step-by-step process of building a trap and then communicating the plan to the tribe: "We will make a trap by digging a large pit and covering it with tree branches. A mammoth will then fall into the pit; no need to attack a mammoth head on." In fact, early modern humans are known for building traps; traps for herding gazelle, ibex, wild asses and other large animals were found in the deserts of the Near East. Some of the traps were as large as 60km (37miles) in length [88]: funnel-shaped traps comprising two long stone walls (up to 60 kilometers in length!) converging on an enclosure or pit at the apex were found around the Negev desert. Animals were probably herded into the funnel until they reached the enclosure at the apex surrounded by pits, at which point the animals were trapped and killed. Some traps date back to as early as the 7th millennium BC [88].

Just think about the level of cooperation necessary for building a 60 km long trap! The building process must have been pre-planned by a tribe leader (or several leaders) and then explained to all the workers. Each worker, in turn, would have had to understand exactly what they needed to do: collect proper stones, assemble them into a wall, and have the two walls meet at the apex 60 km away from where they started.

Mental synthesis and infinite language would also have enabled humans to become better warriors. They could command a cleverly organized attack. For example, they could plan an encirclement of the enemy hideout followed by a simultaneous attack from all sides, they could distract the enemy and then attack him from the back, or they could entice an enemy into a trap. All these strategies require mental synthesis to plan, and articulate speech to coordinate the attack between the tribesmen.

Finally, humans could have used mental synthesis to design and build protective shelters. Again, syntactic language would have greatly facilitated the cooperation between tribe members necessary for the planning and execution of construction of an effective shelter.

To-date, cooperation plays the utmost role in modern human society [89]. It allows for division of labor that provides individual contributors with an opportunity to narrow the focus of their education. Cooperation has been credited as one of the primary reasons that the modern human society has been able to advance technological progress, build cities, and travel to space [89]. This cooperation is made possible by mental synthesis along with an infinite syntactic language.

6. Behaviorally modern humans vs. Neanderthals

The advantages of the *Homo sapiens'* acquisition of mental synthesis are best appreciated when humans are compared to Neanderthals. Neanderthals spread throughout Europe between 500,000 and 200,000 years ago but were abruptly replaced by early humans about 30,000 years ago. The short time span of just 5,000 years over which the formerly ubiquitous Neanderthals were replaced by modern humans raises the question: what exactly happened to the Neanderthals? Hypotheses regarding their fate include: the failure or inability to adapt to climate change, extinction due to parasites and pathogens, competitive exclusion, genocide by early humans, or hybridization with early humans [69,90,91]. The "Romulus and Remus hypothesis" predicts that heavy-built muscular Neanderthals did not have infinite language or mental synthesis, and consequently could not cooperate to the same degree as *Homo sapiens*. They could not mentally test multiple simulations of their defense and therefore were very limited in their ability to protect themselves against a group of well-coordinated early humans who were able to strategize and share their ideas.

Furthermore, humans must have been better hunters since they could build a trap or attack from a distance using long-range weapons such as throwing spears. Neanderthals, on the other hand, likely hunted animals from a much closer distance, thrusting themselves at an animal in an attempt to simultaneously stab it with as many spears as possible. The disproportionally large number of broken bones found in Neanderthal remains is a testament of this attack technique [17].

Both early modern humans and Neanderthals used spears, but humans used stone-tipped spears that were more efficient at puncturing animal skin than the "big toothpicks" used by Neanderthals. Both early humans and Neanderthals were using animal hides, but humans were stitching those hides into better fitting clothes with the use of sophisticated bone needles (equipped with an eye for threading). Stitching clothing is indicative of the presence of mental synthesis since in order to cut and stitch an animal hide into a well-fitting garment, one needs first to mentally simulate the process:, i.e. imagine how the parts can be combined into a finished product that fits the body. It is likely that Neanderthals simply wrapped the hides around their bodies.

An analysis of the Neanderthal genome shows that about one to four percent of the genes of non-African humans come from Neanderthals[90], which indicates interbreeding between the two populations. However, this interbreeding may have been one-sided. First of all, no evidence for gene flow from modern humans to Neanderthals has been found. Secondly, although modern humans share some nuclear DNA with the extinct Neanderthals, the two species do not share any mitochondrial DNA, which is transmitted maternally [92]. Both observations are consistent with gene flow in one direction: from Neanderthal males to modern human females. Some scientists interpreted these findings to suggest that Neanderthal males mating with human females resulted in fertile offspring, while human males mating with Neanderthal females lead to infertile offspring [93]. However, there might be a simpler explanation: as Neanderthals did not possess mental synthesis, negotiations with them were impossible. As a consequence, the inter-species sex was probably non-consensual: larger and stronger Neanderthal males taking advantage of weaker and smaller human females, while weaker human males were probably not able or not willing to take on bigger and stronger Neanderthal females.

We surmise that early modern humans were not too keen on meeting a bigger and stronger competitor one-on-one. Without mental synthesis a Neanderthal must have appeared to them as a big and dangerous animal, capable of fighting, but not capable of reasoning with. It is likely that early humans played at least some role in their extinction. Humans could have outcompeted the Neanderthals in hunting, used them as a source of food, or simply used their superior mental prowess to eliminate a stronger and dangerous competitor.

7. Conclusions

In this manuscript we presented a "Romulus and Remus" hypothesis of language acquisition and proposed that recursive language elements such as spatial prepositions were acquired synergistically with mental synthesis 100,000 years ago in one revolutionary jump towards modern infinite language. Mental synthesis and modern infinite language are highly interdependent. When humans speak they use mental synthesis to describe a novel image ("My house is the second one on the left, just across the road from the red gate") and we rely on the listener to use mental synthesis in order to visualize the novel image. When we tell stories, we are often describing things that the listener has never seen before ("That creature has three heads, two tails, large green eyes, and can run faster than a cheetah") and we rely on the listener to imagine the story in their mind's eye. As Steven Pinker put it, "the speaker has a thought, makes a sound, and counts on the listener to hear the sound and to recover that thought" (Pinker, 2011). **Importantly, all human languages allow *high fidelity transmission* of *infinite* number of *novel* images with the use of a *finite* number of words**. The magic of using a finite number of words to communicate an infinite number of images depends on ability to conduct mental synthesis both by the listener and the speaker.

Crucially, though, mental synthesis is not acquired ontogenetically unless children are exposed to infinite language before puberty [36]. This observation results in the proverbial 'the chicken and the egg' problem. Neither mental synthesis nor infinite language could be acquired phylogenetically one before the other. The "Romulus and Remus" theory resolves this conundrum by proposing that the two processes – the neurologically-based mental synthesis and the culturally-transmitted infinite syntactic language – were acquired phylogenetically at the same time. The hypothesis calls for identical twins or closely-spaced siblings both carrying the "PFC delay" mutation that prolonged critical period for language acquisition and predisposed the carriers to acquisition of infinite language. The "PFC delay" mutation is currently found in all humans, but not found in Neanderthals [81,82]. The monozygotic twins Romulus and Remus would have naturally carried identical mutations, born at the same time and would have spent a lot of time together during their upbringing, which would have increased the chances of inventing the recursive elements such as spatial prepositions. With invention of a few spatial prepositions "PFC-delayed" Romulus and Remus would have converted their parents' finite communication system to infinite language and therefore train their own mental synthesis [36].

The synergistic acquisition of mental synthesis and infinite language would have dramatically increased hominin creativity and cooperation and parsimoniously explains the "Upper Paleolithic Revolution." Figurative art, hybrid sculptures, religious beliefs, and proliferation of new types of tools are easily explained by increased creativity made possible by the acquisition of ability to conduct the mental synthesis. Very fast colonization of the globe and outcompeting Neanderthals, on the other hand, are explained by vastly increased cooperation enabled by modern infinite language.

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