Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 November 2022 doi:10.20944/preprints202211.0322.v1

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The Origin of Non-biological 'Paralife' and its Coevolution with Biological Intelligence

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Key Words:life; paralife; utility-products; UP-paralife; utility-selection; UP-evolvability; coevolution; intelligence; stone tools; language-catalysis; creativity; exoplanet; intelligent life

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Abstract:When animals evolve sufficient intelligence and dexterity to be able to learn to fabricate utility products (UPs) like tools, the UP's they produce become part of an induced-reproduction system that intrinsically shares many life-like traits with biological organisms, including genome-like fabrication and operation information that is physically-encoded in the animal fabricator's neural networks. When this set of life-like traits includes a sufficient capacity for system-improving cultural evolution (UP-evolvability), the UPs become 'para-alive', i.e., nearly alive, or a form of non-biological UP-paralife that is equivalent to the life-status of biological viruses, plasmids, and transposons. In the companion paper I focus on the evolution of UP-paralife in the context of modern, language-capable humans and its predicted evolution going forward in time (Rice 2022). Here I look backward in time and focus on the origin of UP-paralife and its subsequent coevolution with human intelligence. I begin by determining the pathways leading to the evolution of large brains in the rare lineages of biological life that have sufficient intelligence to learn to fabricate tools –a critical first step in the evolution of UP-paralife. The simplest forms of these learning-based UPs, made by species like chimpanzees and New Caledonian crows, represent only proto-UP-paralife because they lack sufficient UP-evolvability. Expanded UP-evolvability required a combination of three attributes that enabled continuous niche-expansion of the animal fabricator via a new and advanced form of UP-mediated teamwork (TW): i) self-domestication that facilitated TW among low-related individuals, ii) learned volitional words (protolanguage) that represent ephemeral UPs that coordinate TW, and iii) learned fabrication of simple flaked-stone tools with cutting and chopping capabilities (a UP to make other structural UPs) that expanded teammate phenotypes and TW capabilities. This specific triad of attributes is synergistic because each one acts as a TW-enhancer that can gradually erode different components of the three major constraints on TW operation and expansion: too much selfishness, insufficient coordination signals, and insufficient physical traits of teammates. The increase in UP-evolvability was transformative and marked the origin of UP-paralife and the initiation of coevolution between UP-paralife (cultural evolution) and the intelligence of its hominin/human symbiont (genetic evolution) that fostered 2.5 million years of: i) continuous brain size increase and niche-expansion within the genus *Homo*, and ii) parallel advances in the diversity, complexity and uses of UP-paralife. This coevolution also fostered evolutionary expansion of word-based communication, and eventually language, that acted in a catalyst-like manner to facilitate the evolution of increasingly complex forms of imagination, reasoning, mentalizing, and UP-generating technology. I next focus on the evolution of creativity in the human lineage –in the form of divergent thinking and creative imagination. I conclude that the evolution of this advanced cognitive feature required a preadaptation of sufficient intelligence and is the component of human cognition that was the major causal factor generating the greatly expanded diversity and complexity of UP-paralife currently associated with modern humans. Lastly, I apply my findings to the issue of the prevalence of extraterrestrial intelligent life. I conclude that any exoplanets with detected chemical life will very rarely (e.g., probability ~10^{-5} for a planet closely matching Earth's characteristics) have evolved intelligence equalling or exceeding that of humans.

As described in the companion paper (Rice 2022), non-essential subcellular structures that reproduce semi-autonomously in biological systems (i.e., viruses, plasmids, and transposons) are intermediate between: i) animate cellular organisms that have a trait-set including self-sustaining reproduction, genomes, mutability, heritable phenotypes, and a capacity for system-improving evolution, and ii) inanimate objects like rocks, water, and gasses that lack this trait set. For this reason, I categorized transposons, plasmids and viruses as biological systems that

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are ‘para-alive’ (i.e., nearly alive, or a form of paralife) because they share many distinctive features in common with cellular life-forms (i.e., genomes, mutability, heritable phenotypes and a capacity for system-improving evolution), but they induce associated cellular life-forms to carryout at least some of their core reproductive functions, e.g., fabricate subunits via protein synthesis. Counter-intuitively, and as described more fully in the companion paper (Rice 2022), utility-products like hand tools that are fabricated by humans are also part of induced-reproduction systems that are para-alive (UP-paralife). In the following two paragraphs I briefly summarize the rationale for this conclusion.

Utility-products (UPs) include all materials humans have learned to fabricate and consider to be useful, e.g., tools, clothing, vehicles, buildings, bridges and computers. Humans’ UPs are para-alive (UP-paralife) because they share an identical set of paralife features with sub-cellular viruses, plasmids, and transposons. These features include physically-encoded production and operation information (UP-genomes), variation in this information (UP-mutations), heritable phenotypes (the structure of UP’s that is determined by their UP-genomes), and a capacity for system-improving evolution (UP-evolvability) via non-random differential-reproduction of UP variants (utility-selection). Also like sub-cellular viruses, plasmids, and transposons, UP-paralife reproduces by inducing a life-form (e.g., humans) to carry out at least some of its core reproductive functions. In the following paragraph, these UP-paralife features are described in more detail (for fuller details see the companion paper Rice [2022]) .

A UP-genome contains the instructions for its associated UP’s fabrication, operation and uses that are learned by a symbiotic life-form (e.g., a human) and physically encoded in a configuration of connections (engrams, aka memory traces) within the neural networks (NNs) of the life-form’s brain (and/or more recently, stored in documents and/or computer memory files). UP-mutations are predominantly reasoned or learned modifications of a UP’s fabrication information that are stored as modified NN-engrams in the brain of a life-form. The heritable-phenotypes of UPs are the structural characteristics of the utility products themselves that are produced by a process that is controlled/guided by their UP-genomes. Utility-selection is the analog of natural selection and occurs via nonrandom differential rates of fabrication of different UP variants by the life-form, including their associated production and operation information, due to the life-form’s preference for UP variants with perceived superior usefulness. The combination of UP-genomes, UP-mutations, UP-heritable phenotypes, and utility selection generates UP-evolvability, i.e., a form of system-improving (adaptive) evolution. Lastly, just as viruses, plasmids and transposons induce their host to reproduce them, the perceived utility of UPs stimulates the life-form to fabricate new copies of the UPs and culturally transmit their UP-genomes across generations. In the companion paper, I focus on UP-paralife in modern, language-capable humans and its expected evolution going forward in time. Here I look backward in time and focus on the origin of UP-paralife and its subsequent coevolution with hominin/human intelligence. Hominins are the lineages that intervene between modern humans and their common ancestor with the chimpanzee/bonobo lineage.

The origin of UP-paralife required a foundation of a sufficiently high intelligence in early hominins to support the learning required to fabricate and use UPs, and also to culturally propagate their genomes. For this reason, I first consider the evolutionary pathways leading to the evolution of large brains and high cognition among animal species. My second focus concerns the key features in hominin evolution that facilitated (via self-domestication), enabled (via flaked stone tools) and coordinated (via volitional words) a new and advanced form of social cooperation: UP-mediated TW including low-related individuals. As explained in later sections, this major advance in animal cooperation increased UP-evolvability and thereby fostered the origin of UP-paralife. My third focus concerns a form of self-reinforcing coevolution between UP-paralife and the intelligence of its biological symbiont: hominins in the genus *Homo*. The coevolution is directional because it leads to ever-increasing i) diversity and complexity of UP-paralife, ii) human intelligence, and iii) human TW and niche-expansion. My fourth focus concerns the catalyst-like role of protolanguage, and later language, in the evolution of advanced cognition, including conscious reasoning, expanded mentalizing ability, and complex imagination. My fifth focus concerns the special role of creativity in the evolution of the diversity and complexity of UP-paralife. Finally, I focus on the plausibility of discovering intelligent life on exoplanets once evidence for the presence of chemical-based life has been detected on them –and what the evolution of complex UP-paralife and elevated intelligence in humans on Earth can tell us about how commonly it will be found.

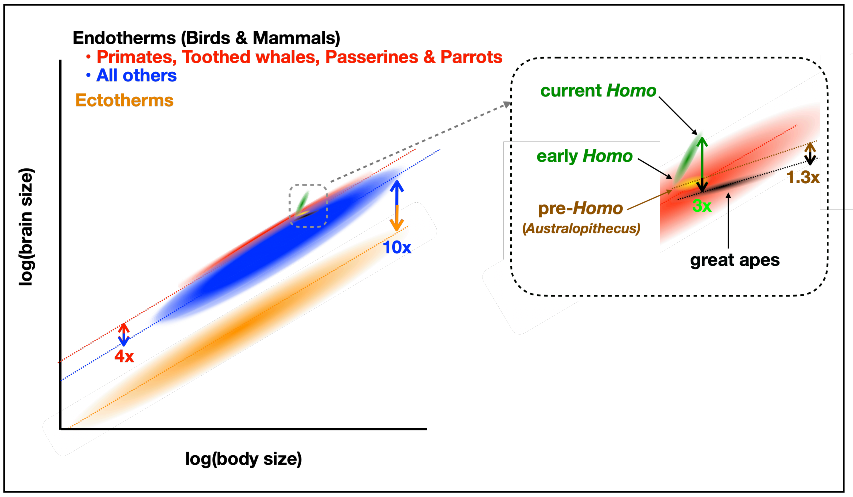

Figure 1. Large body size, endothermy, a high quality diet, and inclusion in an outlier clade with high encephalization are the major features associated with large brains and high cognition. In a log-log plot of brain size vs. body size across a wide range of taxa and body sizes (masses), the average slope is 0.67, but individuals clades can deviate substantially from this average. In general, larger animals have larger brains, but because the broad-scale log-log slope is < 1, there is a trend for lower encephalization in larger animals. Endothermy is associated with a substantial increase in brain size for a given body size (increased intercept in the graph). A few endothermic clades are outliers and shown in red (toothed whales [including dolphins], primates, and passerine and parrot birds) with substantially larger brain size for a given body size. A high quality diet is a feature contributing to higher encephalization in some taxa. **Expanded region:** Great apes do not have exceptionally large brains for their body size within the primate clade, except for the *Australopithecus* hominin lineages (elevated intercept) and hominins in the genus *Homo* (steeper slope). The colored clouds of points are illustrative representations to show patterns (not actual data points) and are based on data presented in multiple publications (Isler et al. 2013; Yu et al. 2014; Herculano-Houzel 2017; Tsuboi et al. 2018; Font et al. 2019).

Pathways to the origin of UP-paralife

Features contributing to the evolution of the high cognitive ability.

Production of UPs requires sufficient intelligence to enable the learning needed to construct, use and culturally propagate them. The few species known to be capable fabricating UPs in nature (i.e., New Caledonian crows and some great apes) are established to have unusually high intelligence, as measured by learning and problem solving abilities (Boesch et al. 2009; Rutz and St Clair 2012). What features are associated with species that have evolved high level of intelligence?

To determine the structural features associated with high intelligence, one can survey the numerous studies of cognition in animals, and search for those taxa that stand out as having exceptional abilities in general features like learning and problem solving –and what structural features they share. Many lines of evidence indicate that larger brains (ideally measured as the number of neurons and synapses; Herculano-Houzel 2009; Olkowicz et al. 2016, but usually measured more crudely by volume or weight) typically have increased learning and problem-solving ability (Deaner et al. 2007; MacLean et al. 2014), although encephalization in combination with large brain size may also contribute to intelligence (Benson-Amram et al. 2016). Broad-scale comparisons across the animal taxa on Earth (Figure 1) indicate that the general features leading to large brain size are: large body size (Isler et al. 2013; Tsuboi et al. 2018; Font et al. 2019), endothermic homeothermy (Yu et al. 2014), a high quality diet (DeCasien et al. 2017), and given these three traits, inclusion in an outlier clade that for unresolved reasons have higher than average encephalization, e.g. passerine song birds (Herculano-Houzel 2017). Increased brain size is costly due to the high energetic demand of brain tissue (Aiello and Wheeler 1995), but despite this cost, larger brains can be selectively favored when increased cognitive ability generates a net fitness increase.

Most animal species have not undergone tests of their cognitive ability (as measured by learning and problem-solving ability), but there is nonetheless a strong consensus among numerous reviews of animal intelligence that some of the most capable taxa include the great apes, toothed whales, and large bodied members of the corvids (jays, crows, magpies, and ravens) and parrots (true parrots, cockatoos, and New Zealand parrots) (Manger et al. 2013; Yu et al. 2014; Osvath et al. 2014; Mitchell 2016; Gunturkun et al. 2017; Herculano-Houzel 2017; Krasheninnikovaet al. 2019). These taxa are endothermic and have higher than average encephalization, i.e., their brain mass values lie at the upper edge of the cloud of points for endotherms when log brain size is plotted against log body size (colored red in Figure 1; Yu et al. 2014; Herculano-Houzel 2017). The brain sizes of the parrots and corvids are smaller in volume and mass than those of the other high-cognition taxa, but they also have double the density of neurons (and plausibly also higher synapse densities per neuron) and a higher proportion of brain neurons located in the primary part of the brain used in problem solving (pallial telencephalon) compared with other birds, primates, toothed whales and other mammals (Olkowicz et al. 2016). An additional indication of the association between brain size and intelligence is the weak but highly significantly positive correlation between brain size and IQ in humans ($r=0.24$, $R^2=0.06$, $P \ll 0.001$; meta analysis of 128 samples with total $N > 8{,}000$; Pietschnig et al. 2015).

In sum, one trait shared by all taxa established to have exceptionally high cognitive ability (learning and problem solving), and forming a foundation for the evolution of UP fabrication ability, is large brain size. The evolutionary pathway leading to large brain size includes the evolution of large body size, endothermy, a high quality diet, and inclusion in an outlier clade with high encephalization. But among these exceptional taxa with large brains, only the human lineage evolved an exceptionally high level of intelligence and the corresponding ability to fabricate complex UP-paralife –so additional features were required to lead to this evolutionary end point. One such feature is self-domestication which facilitates sharing and social cooperation, in the form of teamwork beyond the family level, as described in the next section.

Self-domestication opened a pathway facilitating the evolution of teamwork among low-related individuals.

As described more fully in later sections, the origin of UP-parlife was dependent on a high level of teamwork that was mediated by UPs and included low-related individuals. Hereafter I will abbreviate teamwork by ‘TW’ and low-related by ‘low-r’. Teammates that have low-r are required because the combination of large body size and endothermy found in taxa with high cognition is generally associated with low fecundity and small family size –so TW including even moderately-large numbers of teammates requires cooperation including non-family members. Self-domestication is a process that reduces aggression and increases social tolerance within social groups and would thereby facilitate TW that includes low-r individuals (Hare et al. 2007; Bednarik 2008).

Domestication syndrome is a suite of traits, originally identified by Darwin (1868), that are shared by many domesticated mammals that have reduced aggression compared to their wild counterparts –including traits that fossilize, like reduced brain and tooth size and shorter snout length. A substantial body of evidence indicates that this set of shared traits among domesticated mammals is caused by polygenic mutations that reduce the number of neural crest cells that migrate throughout the body during ontogeny (Wilkins et al. 2014). Studies that applied experimental selection for reduced aggression in rats, mink and red fox have all led to the evolution of the domestication syndrome as a correlated effect (reviewed in Trut et al. 2009).

Self-domestication occurs when there is natural selection for reduced aggression and the domestication syndrome traits evolve as a correlated response to the reduction in aggression (Hare et al. 2007). I found no evidence for documented examples of self-domestication in animals other than vertebrates. It is rare in primates and other taxa like Carnivora and has been especially well documented, outside the context of symbiosis with humans, only in bonobos (Hare et al. 2012), marmosets (Ghazanfar et al. 2020) and hominins (Bednarik 2008; Hare 2017). Both theory and experimental evidence (Hare et al. 2007, 2012; Hare 2017) indicate that self-domestication increases the potential for cooperative TW that includes low-r individuals –a social trait that I later show is causally associated with the origin of UP-paralife.

Many lines of evidence indicate that a substantial level of self-domestication evolved prior to the first use of stone tools in hominins (Griffin 2019), and therefore could have acted as a preadaptation facilitating the later evolution of low-r TW and UP-paralife. *Ardipithecus ramidus* is the oldest fossil hominin (fossils from ~4.5 million years ago [mya]) for which there is substantial evidence that it is ancestral to modern humans (Mongle et al. 1995). This small-brained (compared to humans) and bipedal ancestor provides strong evidence for the early evolution of self-domestication in hominins: compared to chimpanzees and bonobos, the canines of *A. ramidus* are greatly reduced in size, there is low sexual dimorphism,

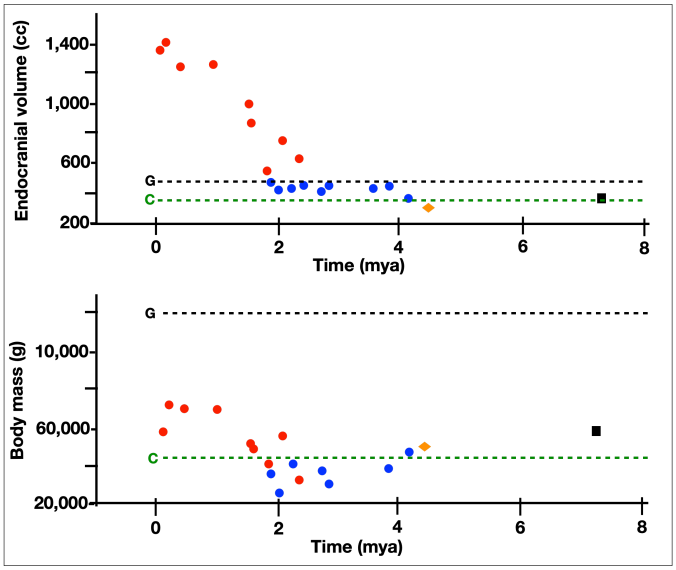

Figure 2. Average hominin brain and body sizes vs. time (based on data in Supplementary Tables 2-3 in Püschel et al. 2021). The time points for the average brain and body size data point are the averages for the time intervals that fossils for each hominin taxa have been recorded. The red circles represent taxa in the genus Homo, blue circles for taxa in the *Australopithecus*-like genera including *Australopithecus*, *Paranthropus* or *Kenyanthropus*, the orange triangle depicts *Ardipithecus ramidus*, and the black square depicts *Sahelanthropus tchadensis*. The black dotted lines are the averages for present-day gorillas (G) and the green dotted lines are the averages for present-day chimpanzees (C).

and there are other structural features, like reduced prognathism, that are associated with domestication syndrome (Clark and Henneberg 2015, 2017; Griffin 2019). The evidence for a substantial level of self-domestication from the fossils of *A. ramidus* indicate that reduced aggression evolved early in hominin evolution (≥ 4.5 mya) after the split from the chimpanzee/ bonobo lineage –far in advance of the evolution of the first flaked stone tools (~2.6 mya) and a sustained and rapid expansion of brain size (beginning at ~2.5 mya; Püschel et al.. 2021).

In addition to its early occurrence in *A. ramidus*, additional episodes of increased self-domestication plausibly occurred later within the hominin lineage leading to modern humans (Hare et al. 2017). These additional occurrences of self-domestication may have facilitated the continued evolution of low-r TW. The observation that bonobos evolved substantial self-domestication but rarely fabricate tools or engage in low-r TW in nature (Furuichi et al. 2015), and did not evolve to fabricate UP-paralife, indicates that although reduced aggression facilitates low-r TW (Hare et al. 2007, 2012; Hare 2017), it was not a sufficient condition, in combination with large brain size, to trigger the evolution of UP-paralife and human's high intelligence. Learning to fabricate flaked-stone tools, in addition to the influence of preexisting self-domestication, would be expected to substantially increase the capacity for new forms of TW in hominins and facilitate niche-expansion, as described in the next section.

Flaked stone tools opened a pathway to increased UP-evolvability, new forms of TW and UP-mediated niche expansion.

The cutting and chopping ability of flaked-stone tools causes them to be 'tools-to-make-tools' and thereby increases UP-mutability. As described in more detail in a later section, this expanded fabrication capacity was essential in increasing UP-evolvability and the origin of UP-paralife.

The initial time point for the persistent use of flaked stone tool technology is controversial. A possible form of simple flaked-stone tools (Lomekwian technology) may date back to ~3.3 mya (Harmand et al. 2015), but this date has been called into question (e.g., see Domínguez-Rodrigo and Alcala 2016). Even if this dating is accurate, there is no fossil evidence that the technology spread and persisted across space and time (Domínguez-Rodrigo and Alcala 2016). For this reason, I will not use ~3.3 mya as the time-point for the origin of the persistent and widespread use of flaked-stone tools by hominins. Substantial fossil evidence indicates that hominins first learned to fabricate Oldowan flaked-stone tools at ~2.6 mya (Braun et al. 2019; see also the reviews in Toth and Schick 2006). This technology spread across space and persisted through time and marks the beginning of the continuous and widespread use of flaked-stone tool technology by hominins.

The oldest evidence for persistent butchery of large herbivores closely matches the earliest dated Oldowan flaked-stone tools (also ~2.6 mya; reviewed in Domínguez-Rodrigo and Pickering 2017; Ben-Dor et al. 2020). The close timing of these two first occurrences of Oldowan flaked-stone tools and persistent butchery indicates that an important early use of Owdowan flaked-stone tools was butchery.

The near simultaneous onset of Oldowan stone tools and butchery at ~2.6 mya and the oldest fossil evidence for the genus *Homo* at ~2.4 mya (reviewed in Antón et al. 2014) marks a major transition point in hominin evolution at which time brain size begins to increase continuously until the modern era (Figure 2, data from Püschel et al.

2021). Between ~2.5 to ~2.0 mya, the occurrence of stone tools, long-distance stone transport, and cut-marked/percussion-marked bones increased from episodic to ubiquitous (reviewed in Antón et al. 2014) –indicating a major transition from the frugivore/herbivore guild of *Australopithecus* lineages to the large-carnivore guild (hereafter abbreviated LgCar-guild) during the early evolution of lineages within the genus *Homo*.

Among the early lineages of the genus *Homo*, there is a strong consensus that the *H. erectus* lineage is the one that is ancestral to modern humans –including their closest relatives like Neanderthals and Denisovans (reviewed in Anton 2003; Antón et al. 2014). The earliest date for a fossil of *H. erectus* is ~2 mya (Anton 2012; Herries et al. 2020). Early fossils of this long-lived lineage (it persisted almost 2 million years) had a body size that averaged ~35% larger than its inferred ancestor (*A. afarensis*), and a brain size that was ~75% larger than this species (reviewed in Antón et al. 2014). Other important changes compared to *Australopithecus* lineages include: i) a major reduction in upper body strength and ankle structures required for the rapid arboreal climbing ability (and access to outer branches) that would be needed to use trees as an escape in space from pursuing predators (DeSilva 2009; Ruff et al. 2016; but see Kraft et al. 2014 showing that substantial but slow and trunk-proximate tree climbing ability persisted), ii) a major increase in both stone tool use, butchery, and consumption of meat (Ben-Dor et al. 2020), iii) a major increase in terrestrial locomotion ability that included endurance running (Bramble and Lieberman 2004), iv) a more gracile skull and many other body structures, including a major reduction in prognathism (Bramble and Lieberman 2004; Zink and Lieberman 2016), v) a substantial decrease in sexual dimorphism (Ben-Dor et al. 2020), vi) a substantial increase in stone tool complexity (Oldowan ➔ Acheulean) during the early stages of the evolution of *H. erectus* (at about 1.7 mya, Antón et al. 2014), and vii) a substantially increased capacity for overhand throwing (Roach and Richmond 2014). Collectively, this pulse of multifarious phenotypic changes in the *H. erectus* lineage, that evolved during the first 0.6 million years after the the onset of Oldowan flaked-stone tools, indicates that these fabricated tools plausibly facilitated an adaptive peak-shift to the LgCar-guild and the initiation of a protracted period of continuous niche expansion and brain size increase. This expansion of a small ape, that lacked fast running speed and lethal anatomical weapons, into the guild of much larger and faster-running predators, with highly lethal anatomical weapons, would have been highly dangerous. Exploitation of cached leopard kills provides a plausible transition pathway to enter this dangerous and highly competitive LgCar-guild.

Utilization of cached prey-carcasses from leopards provides a plausible transition pathway from the frugivore guild to the LgCar-guild.

Although there is insufficient evidence in the fossil recored to reliably determine the pathway by which the early *Homo* hominins transitioned into the LgCar-guild, there is nonetheless a simple and plausible pathway that could be achieved with TW and simple flaked stone tools. I focus on this pathway not because there is sufficient evidence to show that it is correct, but to show that a simple and plausible UP-mediated pathway did exist for the counterintuitive entrance of a small, slow-moving, frugivorous and anatomically weakly protected ape into the large-bodied, fast-moving, highly-lethal and competitive LgCar-guild.

Leopards commonly abandon partially eaten carcasses that are cached in trees for prolonged periods of time, especially during daylight. This behavior would have generated a substantial protein-rich resource for tree-climbing hominins to exploit opportunistically (Cavallo and Blumenschine 1989). These cached leopard-prey carcasses would have been: i) more predictably located, ii) less well protected and less kleptoparasitized by other large carnivores, iii) less prone to seasonal fluctuations in abundance, and iv) required lower search effort and no pursuit effort, compared to terrestrial carcasses produced by other LgCar-guild members (Cavallo and Blumenschine 1989). Initially, large discarded bones taken from beneath abandoned leopard-prey carcasses (and processed elsewhere) would have been a relatively safe resource that could be broken with stones to access fat-rich marrow (reviewed in Ben-Dor et al. 2020) –in a manner similar to current-day chimpanzees and capuchins that use hammer-&-anvil stones to extract nut meats from their shells (Visalberghi et al. 2015). Breaking the bones would sometimes fortuitously generate stone flakes, as occurs in current-day chimpanzees and capuchins when breaking nuts with hammer-&-anvil stones (Visalberghi et al. 2015). These flakes could be used to cut small amounts of residual meat from bones discarded from cached leopard-killed carcasses, as well as to cut larger pieces of meat from the cached carcass itself. Bonobos trained to make simple flaked-stone tools have been observed to spontaneously make new stone flakes when needed to cut leather or rope bindings that surrounded puzzle boxes that contained interior food (Schick et al. 1999) –so early hominins plausibly would have had the cognitive ability to learn to use accidentally generated stone flakes to cut meat from cached leopard-prey carcasses. Using stone flakes to cut meat from cached carcasses would substantially increase the ability of early, socially-domesticated hominins to share a valuable resource. But while foraging on this resource, especially while cutting meat from a cached carcass, the hominins would expose themselves to potentially lethal leopard predation.

Because of the smaller size of leopards (similar, or only slightly larger, in weight to early *Homo*), compared to most other members of the LgCar-guild, and because of the solitary hunting style commonly used by leopards, hominins could plausibly learn to steal their cached prey. Leopard-killed carcasses are an unusual resource because in current-day Africa the carcasses are rarely foraged on by vultures (Kendall et al. 2012), nor kleptoparasitized by larger species like lions and pack-hunters like hyenas, that cannot reach these tree-cached carcasses. Current-day field studies (Oconnell et al. 1988; Nakamura et al. 2019) indicate that small groups of hominins with simple clubs, fashioned from tree branches via flaked stone tools, plausibly would have been able prevent a detected solitary leopard from displacing them when foraging on a leopard's abandoned tree-cached prey carcass that they had discovered. But a single leopard stealthily returning from an unknown direction (or a female leopard accompanied by her nearly full-grown offspring approaching from multiple directions) could readily kill or severely injure hominins that were foraging on a cached carcass unless there was an impenetrable perimeter defense, as described in the following section. When nearby trees were sufficiently close, this perimeter defense could occur passively via sentries perched in the safety of trees. But in a more open setting, the perimeter defense would require terrestrial sentries with suitable weapons for their defense. Given that early hominins could learn to produce such a terrestrial perimeter defense, learning to i) produce and use increasingly effective weapons, and ii) increasingly coordinate their defensive behaviors, could be used to gradually expand kleptoparasitism of cached leopard prey to include terrestrial prey-carcasses of progressively more dangerous members of the LgCar-Guild.

Terrestrial UP-mediated butchery requires a mobile perimeter defense

When predators kill large herbivores in an open or savanna habitat, the newly generated kill site can potentially attract numerous large kleptoparasites like lions or hyenas. Current field studies in the African savanna indicate that newly killed carcasses typically attract large kleptoparasites within ~30 minutes, even at night when vultures are not flying (Valkenburgh 2001; Hunter et al. 2006). This information from current field studies indicates that opportunities for any substantive level of terrestrial butchery by early *Homo* hominins like *H. erectus* (i.e., beyond occasionally and fortuitously finding a kill-site with sufficient nearby trees for a passive defense) would have been very low without an effective defense against large and dangerous kleptoparasites. Such a defense would have to be a perimeter defense because many kleptoparasites would be group hunters (e.g., lions and spotted hyenas) that could attack from many directions simultaneously, and because newly-arriving solitary predators could approach from any direction at any time (Figure 3). The defense would also need to be mobile because great apes have poor night vision (Dunbar 2014; Koga et al. 2017) and any group of butchering hominins would need to move to a safe sheltering location prior to nightfall –requiring movement through nearby dangerous predators in the

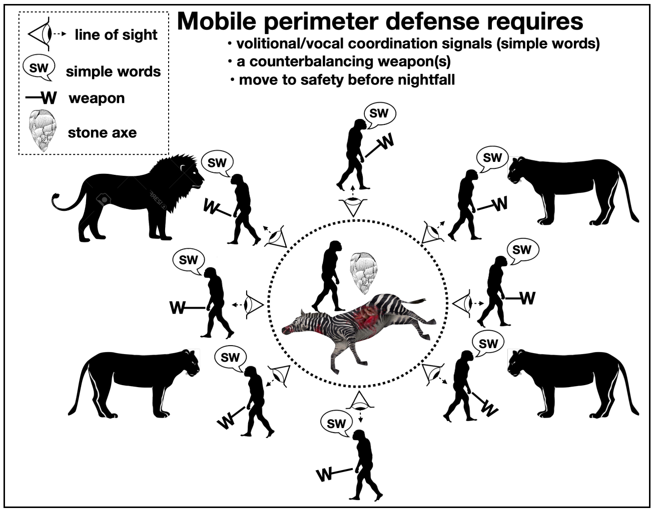

Figure 3. When hominins entered the LgCar-guild and began to butcher large herbivores, they required a mobile perimeter defense, as described in detail in the main text. There was a need for a perimeter defense because large and lethal kleptoparasites could attack butchers from many directions. The defense needed to be mobile to enable the butchers, with poor night vision, to move to safety before night-fall. Simple words (SW) were needed to coordinate fast-action responses among hominin defenders who were out-of-sight from one another (line of sight symbols) and needed to communicate a complex assessment of dynamic dangers. A suitable weapon (—W, plausibly 'weapons-of-fear', see Supplemental Figures S2-S3) was needed that could counterbalance the large asymmetry in size, speed and anatomical weapons between the hominin butchers and their kleptoparasites. Flaked-stone axes were used to butcher the carcass.

process. Early *Homo* hominins were also small (< 40 kg; Püschel et al.. 2021) relative to most of the kleptoparasites (e.g., male lions > 200 kg) and this size disparity would mean that even an occasional single claw-strike or bite could produce a lethal wound –so any defense would need to be highly persistent and consistently effective. Only coordinated TW by these small hominins could produce such a defense.

The requisite mobile perimeter defense would necessarily be mediated by a non-anatomical weapon (e.g., a UP) because early *Homo* hominins lacked large canines or any other suitable anatomical weaponry. The identity of the defense weapon(s) is unknown but neither an Oldowan stone axe nor its flakes would have been suitable (Kortlandt 1980; Guthrie 2007) –so some weapon fabricated with flaked-stone tools was used because tools fabricated using hands and/or mouth, like simple tree-branch clubs or spears, would not suffice (Kortlandt 1980; Guthrie 2007). Given the size disparity between the hominins and many of the potential kleptoparasite (e.g., lions or cave hyenas), it is difficult to imaging a suitable weapon, e.g., the bone-crushing jaw strength of a cave hyena, or the weapon-wrenching strength of a lion's limbs and claws, would strongly constrain a suitable weapon (Kortlandt 1980; Guthrie 2007).

One plausible solution to this extreme size/strength asymmetry between meat-consuming early *Homo* hominins and their kleptoparasites is the 'weapon of fear' (Supplemental Figure S2-S3; see also Kortlandt 1980; Guthrie 2007), which is used by a large diversity of animals with small size and slow speed against much larger and faster predators. Field experiments by Kortlandt (1980) demonstrated that lions have a strong fear of thorn branches and that when these were attached to flimsy cages surrounding tethered sheep, the sheep were completely protected from lion predation. He also found that mechanically swinging thorn branches produced a substantially exaggerated fear response in the lions. Both wear patterns (Lemorini et al. 2014) and Acacia resin deposits (Domínguez-Rodrigo et al. 2001) on early forms of flaked-stone tools indicate that they were used to cut wood. So even though any stone-tool-generated wooden weapons used during a mobile perimeter defense by early *Homo* hominins would not be preserved in the fossil record, we can nonetheless use fossil evidence to show that: i) flaked stone tools were used to cut wood, and ii) at least imagine a simple 'weapon of fear' that would have been sufficient to offset the predator-hominin size/strength disparity and would have been capable of being fabricated with simple flakes-stone tools. The skins of porcupines (with spines attached) that had been clubbed to death and then attached to the ends of wooden branches would be an alternative to thorn branches as a weapon of fear (Supplemental Figure S3).

Guthrie (2007) provides an extensive discussion of the efficacy of thorn branch weapons against the predators and kleptoparasites likely to have been encountered by early *Homo* hominins. Cut thorn bushes and branches are also used by current-era African humans to: i) protect caches of meat butchered from a large herbivore when there is too much meat to transport in a single trip (Lee 1979 -cited in Guthrie 2007), and ii) make corrals (bomas) to protect livestock from large carnivores (Isbell et al. 2018). Boma-like enclosures, made using simple flaked-stone tools, also would plausibly have provided safe shelters for early hominins like *H. erectus* that had substantially reduce climbing ability, agility and speed (DeSilva 2009; Ruff et al. 2016) –and consequently would have been susceptible to leopard predation if they used trees as nighttime shelters. However, suitable weapons alone would be insufficient for an effective perimeter defense. As described in the next few sections, a UP to coordinate TW during mobile perimeter defense, especially among teammates that were facing different directions, would also be required. Volitional vocal words represent such an UP.

Spoken volitional words are transient UPs.
Spoken volitional words (hereafter 'words') are sounds that have symbolic meaning and are initiated due to an internal decision and motivation rather than external stimulation –unlike involuntary and instinctive alarm calls that are made in response to a perceived predator. Words are not intuitively classified as physical 'utility-products', like a fabricated wheelbarrow or a flaked-stone axe, but they nonetheless conform to this categorization. Spoken words are fabricated physical structures (modified parcels of air that propagate sound waves) that are used as ephemeral transportation implements that move information between individuals: the speaker fabricates and transmits a sound sequence (i.e., a physically-encoded array of one or more symbols) in order to modify the mental state of one or more recipients that decode the symbol(s) embedded within the sound sequence that they perceive. Spoken word fabrication and perception are controlled by: i) non-neural sound-producing/perceiving anatomical structures like the vocal cords and ear drums, and ii) information encoding/decoding neural networks in the brain that compose and interpret the sound-encoded

signals. In the more complex context of language, the encoding/decoding neural networks in the brain generate and interpret the vocabulary, syntax, and pragmatics that underly the functional structure of word arrays with multiple words. Just as some early hominins eventually learned to make simple utility products like Oldowan flaked-stone tools, they also eventually learned to produce simple utility products in the form of spoken volitional words and word combinations (word-UPs). A prerequisite to this learning, however, was the evolution of a capacity for volitional phonation.

Volitional control of phonation was highly evolvable and the only feature preventing early hominins from learning to use word-UPs. All extant great apes except humans lack a capacity for volitional control of phonation (voluntarily engaging the vocal cords to initiate a vocalization) that is required to communicate via learned vocal words (Fitch 2018). Nonetheless, other patterns among the great apes indicate that all additional features needed for communicating with learned words are ubiquitous in this clade.

Besides volitional control of phonation, learning to use vocal words to communicate requires a cognitive capacity for vocal learning and volitional control of the lips, tongue, vocal cords, and the musculature generating airflow through the vocal tract (Hopkins 2013). All great apes are capable of learning simple sign language words (but not syntax-based sign language) and using them to communicate with humans, and to a lesser extent with each other (Lyn 2011; Hopkins 2013; Perlman 2017). In the case of chimpanzees, learned sign language words have been shown to be culturally passed on between generations (Fouts et al. 1989). Volitional control of breathing, lips, and tongue that is needed for vocal word production are also shared by all great ape species (reviewed in Lameria 2017; Perlman 2017). Volitional control of the tone of vocalizations also has been documented in all great apes (Slocombe & Zuberbuhler 2007; Clay et al. 2015; Perlman & Clark 2015; Lameira et al. 2016). Collectively these shared traits among all great apes strongly support the conclusion that the only missing requisite feature for the production of learned spoken words in non-human great apes, including early hominins, is the volitional control of phonation.

Volitional control of a vocalization requires monosynaptic connections between neurons in the motor cortex and primary motor neurons controlling the laryngeal musculature (Fitch 2018). Among the great apes, this neural circuitry has been studied most extensively in chimpanzees. Behavioral studies demonstrate that chimpanzees have volitional control over the tone of some of their involuntary vocalizations (e.g., Slocombe and Zuberbuhler 2007), as do all other great apes (Perlman 2017; Lameria 2017; Lameira and Call 2020). This inference from behavioral studies is corroborated at the neural level by the finding that chimpanzees have monosynaptic connections between neurons in their motor cortex and laryngeal motor neurons controlling tone within the anterior nucleus ambiguus of the medulla (Kuypers 1958). However, in chimpanzees (Kuypers 1958), and many other primates (Simonyan and Jürgens 2003), such monosynaptic connections were found to be missing within the posterior nucleus ambiguus that innervates the laryngeal muscles controlling phonation. The neural tracing procedures used in chimpanzees are highly destructive and, for ethical reasons, will probably never be done in other great apes. Nonetheless, because behavioral studies indicate that all great apes have volitional control of tone, it is reasonable to assume that the monosynaptic connections experimentally found in chimpanzees between neurons in the motor cortex and the anterior nucleus ambiguus are also found in other great apes –and would have been present in early hominins.

A simple route to evolving volitional control of phonation in early hominins would be an expansion of the monosynaptic connections that already occur between the motor cortex and the anterior nucleus ambiguous (controlling tone via the vagus nerve) to the adjacent posterior nucleus ambiguus (controlling phonation). Genetic analysis of such expansions of a nerve to adjacent regions has been studied in model organisms like *Drosophila melanogaster* (Winberg et al. 1998). Here it was shown that the extension of nerve tracts to adjacent regions was controlled polygenically by gene products that generate "*attractive and repulsive forces*" (via different forms of netrins, semaphorins, and IgCAMs) that guide the growth cones of nerves as they probe neighboring regions. Different combinations of hypomorphic and hypermorphic mutations residing at contributing loci were able to expand the innervation by a nerve to include adjacent regions. Genes homologous to those analyzed in this study of flies have also been found to guide neurons during ontogeny in mammals, including humans (Ackley and Jin 2004; Sanes and Yamagata 2009). Because different combinations of hypermorphic and hypomorphic alleles can generate the same phenotype (Winberg et al. 1998), and because there appear to be many contributing loci (Winberg et al. 1998; Sanes and Yamagata 2009), mutation selection balance alone would be expected to maintain non-trivial levels of heritable variation for neuron expansion to adjacent areas. Recombination among these loci would further expand the level of phenotypic variation for the expansion of a nerve to an adjacent region. This work on nerve targeting indicates that selection for volitional phonation (the only features that would have prevented early hominins from learning to communicate with vocal words) would represent directional selection on a polygenic quantitative trait, and hence would be expected to lead to a response to selection far more rapidly than would occur if the trait were oligogenic and required mutations with a large effect size.

Collectively, all of the studies described in this section demonstrate that: i) volitional phonation is highly evolvable, and therefore could evolve at a nontrivial rate in great apes once favored by natural selection, and ii) early hominin lineages would have been pre-adapted to readily evolve a capacity to learn and use words once selection favored this phenotype. However, words do not generate fossils and the indirect fossil evidence for a capacity for volitional phonation (e.g., skull endocast data indicating an expansion of language centers within the brain, like Broca's area [Beaudet 2021]), is highly disputed (Ponce de Leon et al. 2021). So the point in time when volitional phonation and word use originated is generally considered to be ambiguous. Nonetheless, we can deduce from fossil evidence that simple word use (but not syntax-based language) must have been established in the lineage leading to modern humans by ~2 mya when fossils of *H. erectus* first appeared, as described in the following section.

Use of simple spoken words (protolanguage) must have evolved by the time of the emergence of *H. erectus* at ~ 2 mya

As described in detail in Supplemental Text S1, the first use of learned vocal/volitional words plausibly evolved as early 4.5 mya during the transition between late *Ardipithecus* lineages and early *Australopithecus* lineages. Despite the plausibility of vocal words evolving quite early during hominin evolution, this line of abductive reasoning cannot produce –with high confidence– a time point for the initial evolution of the use of volitional vocal words. However, one can deduce with high confidence that such vocal/volitional words had necessarily evolved by the time of the emergence of *H. erectus* at ~2 mya. This deduction is based on two features of *H. erectus* that have been described in earlier sections: i) a combination of fossil and other diverse forms of evidence unambiguously demonstrates that the early forms of *H. erectus* had transitioned substantially into the LgCar-guild and butchered large herbivores at substantial frequency (reviewed in Brantingham 1998; Antón et al. 2014; Ben-Dor et al. 2020), and ii) irrespective of how these large herbivores were obtained (hunting vs. confrontational scavenging/kleptoparasitism), such a transition would have required a mobile perimeter defense to protect butchers from the numerous large kleptoparasites that rapidly accumulate at fresh terrestrial kill sites (Van Valkenburgh 2001; Hunter et al. 2006), and to transport the butchers to a safe site prior to nightfall.

A mobile perimeter defense against much larger and highly lethal members of the LgCar-guild required coordinated and rapid-response actions among *H. erectus* teammates, many of which needed to be facing in opposite directions and were necessarily out of view from each other –so vocal coordination signals were unequivocally required (Figure 3). These vocal signals must have been volitional because they i) would have required an integrated assessment of the complex and dynamic situation confronting different teammates (via higher-order cognitive processing in the cerebral cortex), that was subsequently ii) used to encode this information in vocal signals (simple symbolic words) given to out-of-sight teammates (via the motor cortex) who could not evaluate this complex information directly. Such vocal/volitional signals would need to include simple vocal/volitional words or short word combinations like 'I-see' nouns and adjectives that identify different threat types that require different TW responses, e.g., "lion", "cobra", "buffalo" or "hyena many". They would also need to include simple words or word combinations like 'do-action' verbs and adverbs, e.g., "stop", "forward", "reverse" or "help fast" to coordinate group movement.

Condensing all the points in the above paragraph: the mobile perimeter defense of early hominins required volitional vocal words because this group behavior cannot function without coordination signals that are: i) formulated in response to information that is available to only part of the group but must be shared rapidly with the whole group to coordinate their joint actions, ii) volitional because their production requires integration of complex sensory inputs to formulate an appropriate 'what to do or know' signal, and iii) vocal because they needed be perceived by out-of-view teammates. In Supplemental Text S2, I contrast the deduced mobile perimeter defense of early hominins with the peripheral defenses of animals like muskoxen and with the complex hunting behavior of chimpanzees and dolphins.

To summarize the complete deductive argument: we have convincing evidence that: i) *H. erectus* is ancestral to modern humans, ii) by the time of the emergence of early *H erectus* (~2 mya), this lineage had entered substantially into the LgCar-guild, iii) entrance into the LgCar-guild required a mobile perimeter defense, iv) simple vocal words (a form of protolanguage) were required to achieve a mobile perimeter defense, and therefore by deduction v) by the time of the emergence of *H. erectus*, the use volitional/vocal words had become established in the lineage leading to modern humans.

Simple learned words and short word combinations, as described in the above paragraphs, are far less cognitively demanding than language –a complex phenotype that requires syntax to avoid ambiguity within more complicated arrays of words. In humans: i) simple words develop by 1-1.5 years old, ii) word combinations by 1.5-2.5 years old, iii) the simplest form of syntax-requiring sentences (e.g., that depend on simple syntax rules like word order e.g., subject 1st, verb 2nd, and object 3rd) do not develop until 2.5-4 years old (Tager-Flusberg et al. 2009), and iv) full syntax ability does not emerge until the syntax-specific neural networks of brain-area BA 44 (Broca's area of the frontal lobe) and its connection to area pSTC (posterior superior temporal cortex, aka Wernicke's area) fully matures at ~10 years old (Friederici et al. 2017). The long delay (~2 years) between first words and first syntax-requiring sentences (i.e., the simple language of young children), and the much longer delay until fully developed hierarchical syntax develops (complex language by age 10), demonstrates the substantial additional cognitive development that was required to expand the simple word-using capabilities deduced here to be present in early *H. erectus* (and also capable of being taught to non-hominins like large parrots [Pepperberg 1981, 2002], great apes (sign language words; Perlman 2017) and dolphins [Richards et al. 1984]) to the complex language of modern humans. The long delay also supports the conclusion that use of simple learned/phonation-requiring words plausibly evolved, once selectively favored, far in advance of language in the lineages leading to modern humans.

Once the use of simple learned and volitional-phonation-requiring words evolved, it would generate selection for longer word-arrays that communicated more complex information. Attempts to use simple word combinations is observed in great apes that have been taught sign language words, but without syntax these word combinations lack substantive structure and are highly ambiguous (Rivas 2005; Yang 2013). Word-capable hominins using vocal word-arrays greater than one word long would be prone to generating ambiguity and consequently produce selection for the gradual evolution of an ability to learn syntax rules that enabled the production of unambiguous word-arrays and language.

As a final point, the conclusion that hominins were capable of using spoken volitional words by ~2 mya can be made by another and simpler line of deductive reasoning. There is high confidence that the defense of terrestrial butchery sites would intrinsically and strongly select for spoken volitional words in order to communicate complex appraisals of (or responses to) potential dangers detected by individuals that needed to be looking in different directions (or focused on butchering an animal). Many lines of indirect evidence indicate that volitional phonation is: i) highly evolvable in great apes, and therefore will evolve at a nontrivial rate once selectively favored, and ii) the only feature preventing great apes from using volitional spoken words. For these reasons, strong selection for spoken volitional words would be expected to result in the evolution of volitional phonation at a nontrivial rate. Butchery would have generated this strong selection over a period lasting at least 0.5 million years before the emergence of *H. erectus* (~2.0 mya): more than ample time for a response to selection by a highly evolvable trait like vocal volitional words.

Volitional words are ‘tools-to-make-tools’

In an earlier section I categorized flaked-stone tools as tools-to-make-tools because their cutting and chopping capabilities greatly expanded the ability of hominins to fabricate new forms of structural-UPs, especially those made from wood. Using the same logic, simple volitional words are also tools-to-make-tools because their potential to be combined to greatly expanded the ability of hominins to fabricate new and more complex types of word-UPs (word-arrays) in the form of phrases, sentences and longer narratives. To be unambiguous, most word-arrays require learned semantic and syntax rules that can gradually evolve into language. As described more fully in later sections, word-UPs in the form of language also enabled the fabrication and use of social rules that expanded TW by reducing the interfering influence of selfishness on cooperation and coordination among low-r teammates.

The origin of UP-paralife

Simple fabricated tools are the most basic form of utility products (UPs). Tool use is a rare phenomenon in the animal kingdom. A summary of published evidence indicates that it occurs in less than 1% of all genera of animals and that tool fabrication is much rarer (McGrew 2004; Visalberghi et al. 2017). UP-paralife requires learning-based tool fabrication and I was able to find evidence for this trait in nature (in the form of modified plant stems) in only some great ape species (e.g., chimpanzees; Boesch et al. 2009) and one crow species (New Caledonian crow; Rutz and St Clair 2012). Some other bird species (summarized in Lefebvre et al. 2002; Roelofs 2015) and all great ape species (McGrew 2004) show some tool fabrication ability in captivity. Although the modified plant stems made by chimpanzees and New Caledonian Crows represent fabricated UPs, they do not represent UP-paralife because they are based on simple hand/mouth or beak/foot fabrication that produces UPs with trivial UP-evolvability, and hence they have too little scope for system-improving evolution to be para-alive. I will refer to simple UPs with learned fabrication but highly stunted UP-evolvability as proto-UP-paralife (region-2 in Figure 4).

The highly stunted capacity for the evolution of UPs began to change when hominins learned to produce a form of simple flaked-stone technology that persisted through time (Oldowan stone tool technology at ~2.6 mya; Braun et al. 2019; the technology is reviewed in Toth and Schick 2006). Because of their cutting and chopping capabilities, flaked-stone tools represented a UP that can be used to fabricate many other forms of UPs, like tree branches cut into sharpened spears or digging sticks (Figure 5, top-left). Put another way, flaked stone tools represented a quantum leap in UP-mutability because they could be used to fabricate an open-ended diversity of modified plant stems, many of which have utility and can function as UPs. This expanded tool fabrication ability substantially enhanced the beneficial 'UP-mutation rate' and thereby increased UP-evolvability (Figure 5, top-left).

A second feature expanding the capacity for UPs to evolve is an expanded scope for favorable UP-mutations, i.e., new UP variants that have increased utility and are therefore favored by utility-selection (a cultural evolution analog to

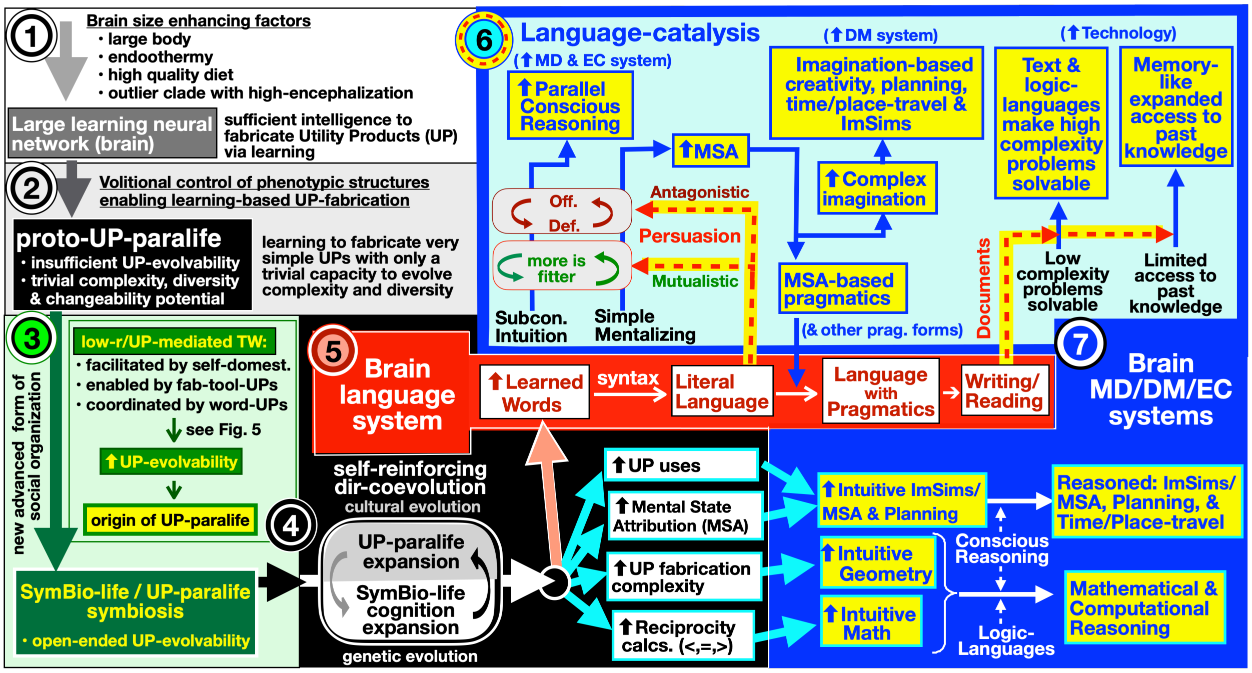

Figure 4. Major features associated with the origin of UP-paralife and its subsequent coevolution with hominin/human intelligence. Sections 1-3 illustrate the sequence of events leading to the origin of UP-paralife, and section 4 illustrates its subsequent coevolution with human cognition. Expanded details of sections 1-4 are illustrated in Figure 4. Section 5 illustrates the evolution of word-UPs from simple, unstructured protolanguage to complex language with syntax and pragmatics. Section 6 illustrates how language indirectly expands cognitive ability via 'language-catalysis.' Section 7 illustrates how conscious reasoning and logic languages generated via language-catalysis expands cognition beyond intuitive thinking (MD = multiple demand; DM = default mode; EC = executive control).

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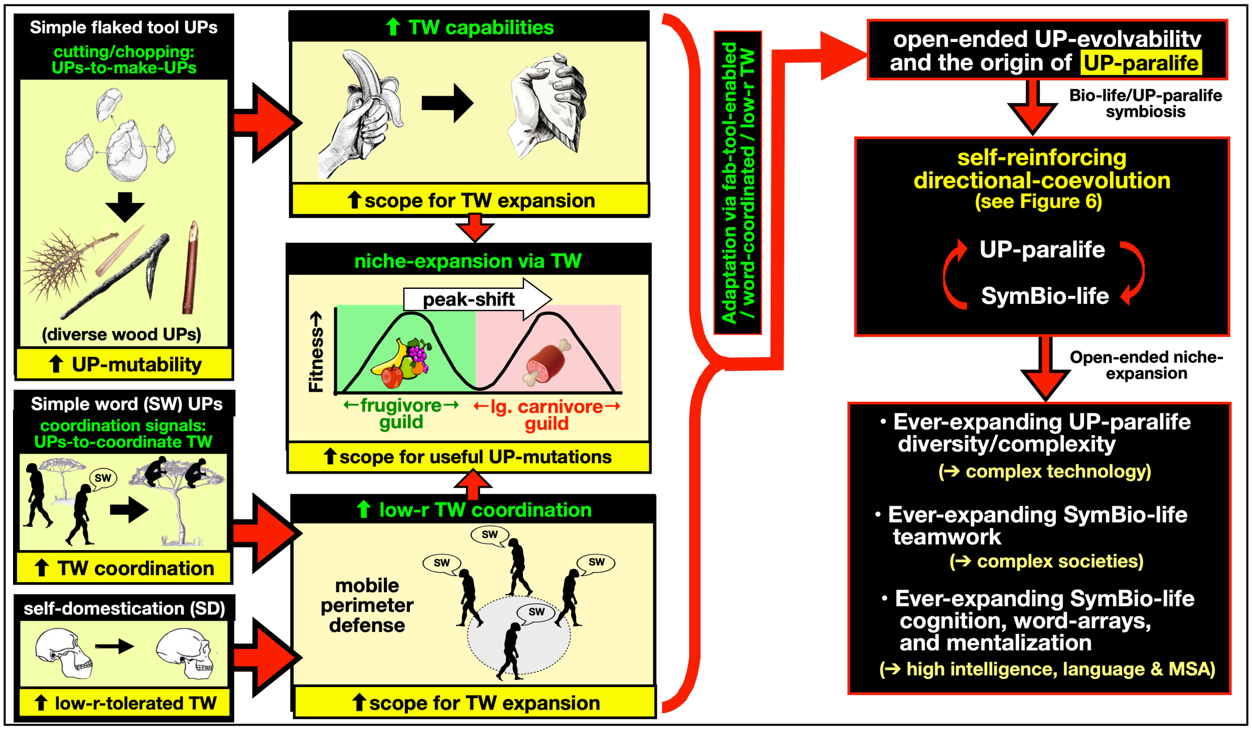

Figure 5. Major features contributing to the origin of UP-paralife near the time when Oldowan flaked-stone tool technology originated (~2.6 mya; Braun et al. 2019), and its directional coevolution with the intelligence of its symbiotic biological life-form (SymBio-life, or more specifically, hominins in the genus *Homo*). Self-domestication (left-bottom) initially evolved in the hominin lineages far in advance of the origin of Oldowan flaked-stone tool technology and was evident in *A. ramidus* at ~4.5 mya (*Clark and Henneberg 2015, 2017; Griffin 2019*), but there is also evidence for additional self-domestication near the time when *H. erectus* emerged at ~2.0 mya (Hare 2017). The use of learned simple words (protolanguage; left-middle) plausibly began in *Australopithecus* lineages (~ 4 mya; see Supplemental Text S1) far before the first use of flaked-stone tools, but it can be deduced to necessarily have been present by the emergence of *H. erectus* at 2.0 mya, as explained in the main text. The combination of self-domestication and simple words (middle-bottom) enabled expansion of TW coordination that included low-r individuals. When hominins first learned to fabricate Oldowan flaked-stone tools at ~ 2.6 mya, (left-top) there was a large increase in UP-mutability due to the cutting and chopping capabilities of these tools in the context of making wood-based UPs. These tools also expanded the phenotypes of hominins and thereby generated an expansion of hominin TW capabilities. The combination of self-domestication, learned words, and learning-based flaked-stone tool fabrication enabled niche-expansion due to adaptation via word-coordinated/fab-tool-enabled/low-r-tolerated TW (middle-middle). This process generated an increased scope for useful UP-mutations, open-ended UP-evolvability, and the origin of UP-paralife (right-top). Once formed, UP-paralife coevolved with the intelligence of its symbiotic biological life-form (hominins/humans; right-middle and right-bottom of figure) and produced ever-expanding: i) complexity and diversity of UP-paralife (advancing technology), and ii) hominin intelligence, language, MSA, and sociality (right-bottom of figure).

natural selection in biological life; Rice 2022). An increased scope for favorable UP-mutations occurred when hominins learned to fabricate two new types of UPs and use them to enable ever-expanding UP-mediated TW ➔ open-ended niche-expansion (Figure 4, region 3, and Figure 5, top-right). One of these forms of UPs was already described in the previous paragraph: flaked-stone tools and the modified plant stems they were used to produce. These structural-UPs (that I will also refer to as fabricated tools, abbreviated by 'fab-tools') generated new teammate phenotypes (like wood-based weapons) that expanded TW capabilities and thereby facilitated hominins' entry into the LgCar-guild (as described in a previous section). The other form of UP was volitional vocal words (word-UPs) that enabled expanded TW via increases in the social coordination of TW actions –like a mobile perimeter defense (as described in a previous section; Figure 5, middle-left). The combination of word-coordinated TW and fab-tool-enabled TW fostered continuous niche expansion that generated open-ended opportunities for new beneficial UP-mutations (Figure 5, middle-middle). As described in a previous section, self-domestication that generated aggression-

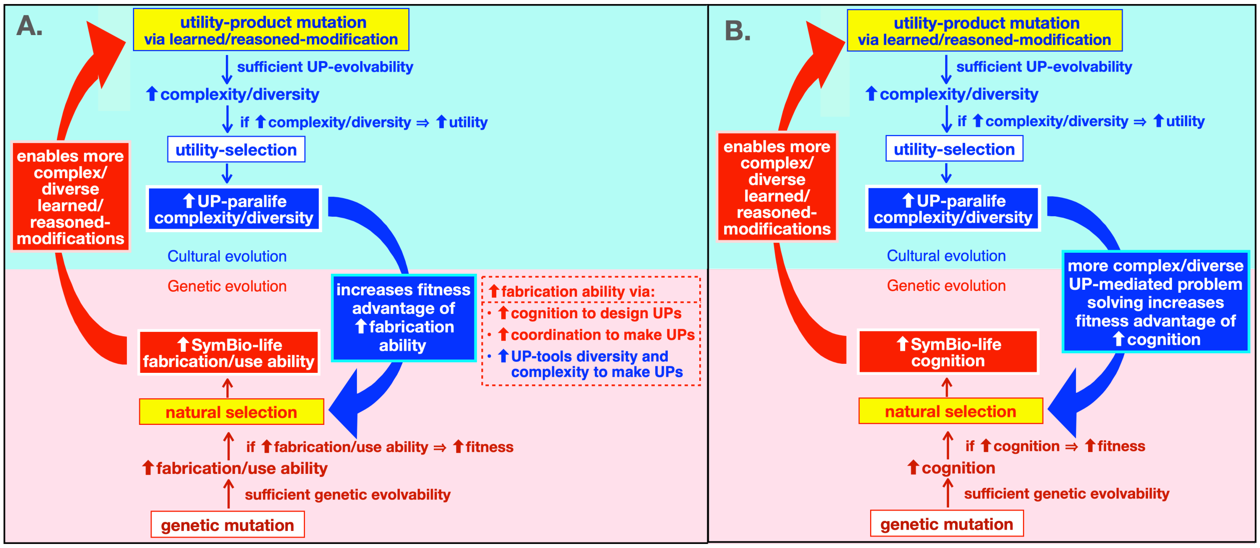

Figure 6. The positive feedback loop that generated i) ever-expanding UP-paralife diversity and complexity, and ii) ever-expanding intelligence in its hominin/human host species (SymBio-life). **A.** A general feedback loops between a hominin's UP fabrication ability and UP diversity and complexity. **B.** A more specific positive feedback loop between a hominin's intelligence and UP diversity and complexity.

suppression and increased social tolerance (Hare et al. 2007, 2012; Hare 2017) was an important pre-adaptation enabling increased levels of word-coordinated/fab-tool-enabled/low-r-tolerated TW (Figure 5, bottom-left).

In sum, the combination of i) an expanded UP-mutability via flaked stone tools and ii) an increased scope for favorable UP-mutations via word-coordinated/fab-tool-enabled/low-r tolerated TW, greatly expanded the evolutionary potential of proto-UP-paralife. As a consequence, the UPs of early *Homo* lineages transitioned to UP-paralife due to its expanded capacity for system-improving evolution (adaptation), i.e., due to increased UP-evolvability. In the Discussion section I will explain why the combination of self-domestication, word-coordination of TW, and fabricated-tool expansion of teammate attributes was so transformative with respect to UP-evolvability. In brief, each of these traits acts as a TW enhancer process that eroded different parts of the trio of features that constrains TW operation and expansion: too much selfishness, insufficient coordination signals, and insufficient physical traits.

Self-reinforcing directional coevolution between UP-paralife and the intelligence of its biological host

Just as subcellular biological paralife (transposons, plasmids and viruses) coevolves with its biological host(s), so too did UP-paralife with its early symbiotic biological host: hominins in the genus *Homo*, and especially their intelligence. During this coevolution, UP-paralife evolved via cultural evolution and the hominins' intelligence (and other features influencing UP fabrication ability, such as hand-eye coordination) evolved via genetic evolution (Figure 6). The coevolution was directional because it led to: i) ever-increasing UP diversity and complexity, and ii) ever-increasing intelligence of the biological host that enables more complex and diverse UP to be fabricated and used in new ways (Figure 6). The coevolution was self-reinforcing due to a positive feedback loop between the complexity and diversity of UP-paralife and the the intelligence of its biological symbiont (SymBio-life, see Figure 6B).

To understand the positive feedback loop generating self-reinforcing directional coevolution (Figure 6), consider a starting point in which the hominins learn to fabricate a new UP, e.g., Oldowan flaked-stone tools. The cutting and chopping ability of this new UP would enable the hominins to produce a greater diversity (and more complex) UPs as modified plant stems, like sharpened spears and digging sticks, although not all new UPs would have this feature of expanding the hominins' fabrication capacity. The presence of any new UP itself, however, would also necessarily increase the number, and sometimes the complexity, of UPs that are available, and thereby increase the potential for more diverse and/or complex ways to use and combine UPs to solve problems influencing fitness. This increased potential for UP-mediated problem solving would intrinsically generate an advantage for higher intelligence because more intelligence enables the discovery of new and more complex fitness-increasing uses for the UPs –especially if the new UPs enable niche-expansion (Figure 6A,B, right-most blue box). Increased intelligence would only be expected to evolve, however, when its benefit outweighs its metabolic costs. Increased intelligence would in turn intrinsically enable UP expansion because more complex and diverse UPs could be designed and fabricated (i.e., it would increase the beneficial UP-mutation rate to new UP forms with increased utility; Figure 6A,B, left-most red box), and the positive feedback loop is completed. This positive feedback loop would generate perpetual directional coevolution between UP-paralife (ever-increasing diversity and complexity) and its symbiotic biological host (ever increasing intelligence), assuming the cost of increasing intelligence is sufficiently counterbalanced by the benefits of expanded UP uses, diversity and complexity. The UPs encompassed with this positive feedback loop include words, simple word-arrays and eventually language (ephemeral word-UPs) and also structural UPs like hand tools, weapons and eventually vehicles like rafts and boats (persistent structural-UPs). A second feature generating expanded hominin intelligence, in addition to the positive feedback loop described in this section, is a catalyst-like interaction between the use of words, word-arrays and language and the development of complex forms of intelligence, as described in the next section.

Language-catalysis

I will define vocal word-arrays to be strings of one or more symbolic vocal signals that are volitional and learned. Their purpose is to change the mental state (MSC = mental state change) of one or more recipient individuals who hear the signal by transferring information to them. They can vary from single words, or groups of a few words that lack both syntax and pragmatics, to child-like language with simple nonhierarchical syntax, to the more the complex language of current human adults with both hierarchical syntax and pragmatics. Vocal word-arrays are unique UPs because of their extremely short persistence and because they are produced in a manner that is independent of any need for manual dexterity. Instead, these ephemeral word-UPs require coordinated activity of breathing, vocal cords, tongue and lips as well as specialized regions of the brain for their composition (e.g., Broca's area in the frontal lobe of the cerebral cortex) and interpretation (e.g., Wernicke's area in the temporal lobe of the cerebral cortex).

Although the language composition/interpretation regions of the brain may contribute in an indirect way to humans' problem-solving ability (intuition and reasoning) by enabling different pieces of information to be organized (as in a sentence), neuroimaging studies do not support a functional linkage between the fluid intelligence used during many forms of complex problem solving (e,g., activating the multiple demand system) and the language processing regions of the brain (Woolgar et al. 2018). Despite this lack of direct linkage between brain regions controlling language and complex problem-solving, and as described in the following sections, I will conclude that the evolution of language has nonetheless acted to facilitate, in a catalyst-like manner, the expansion of human intelligence. I will also conclude that written language generated a pathway to learning new forms of language, like mathematics and computer code, that are used to enhance quantitative deduction and induction rather than functioning for communication. These new forms of language greatly expanded the potential to design and fabricate complex forms of UP-paralife.

Although one can deduce that the use of at least simple words (protolanguage) was present by ~ 2 mya when *H. erectus* first occurs in the fossil record (as described in a previous section), the timespan for the gradual transition from syntax-less words and simple word-arrays to syntax-dependent language is less clear. The long lag (~2 years; Tager-Flusberg et al. 2009) between current-day human children's first words and first syntax-containing language indicates that substantial neurological development was required for the protolanguage-to-language transition in hominins, and hence language may have evolved much later than the use of simple words. In the following sections, when I use the word 'language' I will assume that at least child-like simple syntax language has already evolved, although some features described below may have begun to evolve earlier during the transition from simple word-arrays to language.

Persuasion and human intelligence

The idea that language can generate persistent selection for increased intelligence was previously proposed by Pinker and Bloom (1990). They argued that language, in the context of persuasion, can lead to an evolutionary 'arms-race' in which persuasion generates persistent antagonistic coevolution between a deception phenotype expressed in individuals trying to deceive others and a resist-deception phenotype in potentially gullible individuals trying to avoid being deceived. In this context, a deceptive person-D tries to persuade a potentially gullible person-G to do something that increases person-D's fitness at the expense of person-G's fitness. Assuming that increased intelligence enhances

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both the capacity to deceive and to resist deception, this arms-race between offense (deceptive persuader) and defense (potentially gullible victim) is predicted to continually generate increasing intelligence unless counterbalancing selection, like the metabolic cost of increased intelligence, stops the expansion.

Similar logic can be applied to mutualistic persuasion in which two individuals try to persuade each other to do alternative actions that they think will be mutually beneficial. Here the two interacting phenotypes are persuasion ability and evaluation ability. Each individual is selected to evaluate their own and the other's arguments and choose the best one, i.e., the alternative that most increases the pair's fitness. Assuming that higher intelligence increases both persuasion ability (so a superior alternative is more convincingly presented) and evaluation ability (so superior alternatives are more commonly chosen), higher intelligence will always be favored (more intelligence is fitter) unless counterbalancing selection, such as the high metabolic cost of brain tissue, stops the upward trend. Here I move beyond these generic types of arguments for increased intelligence and show why persuasion can act as a 'language-catalyst' that facilitates the evolution of conscious reasoning and more complex levels of problem-solving, logic-languages, mental state attribution (MSA) and imagination Figure 4, region 6).

Parallel conscious reasoning. In modern humans, problem-solving can occur via fast-acting and subconscious intuition or slower and conscious reasoning (Evans 2010). Reasoning can be further decomposed into deduction (from general to specifics), induction (from specifics to general), and abduction (plausible general conclusions based on incomplete/insufficient specific information). While there is debate about the qualitative capacity of non-humans to use at least simple forms of conscious reasoning, there is no debate concerning the conclusion that humans markedly exceed all other species in their conscious reasoning ability (reviewed in Frankish 2010). Language, and more specifically language-mediated persuasion, has plausibly had a strong facilitating role (language-catalysis; Figure 4, section 6) in the evolution of this distinction. To see why, I will consider a hypothetical persuasion 'debate' between two individuals.

Consider a group of hominins with at least a simple form of syntax-based language that are deciding about a planned activity. Similar logic could possibly be applied to a combination of simple words and gestures when they can covey alternatives for a planned activity and why one alternative is superior. Individual-A proposes action-A, individual-B proposes action-B and the group (individuals A and B and any other listening teammates) have to decide which alternative to choose. Further suppose that one action (arbitrarily selected to be action-A) is the better choice because it leads to higher fitness for all individuals within the group. Without conscious reasoning, both of the proposed actions would be based on the proposer's intuition, as would be the evaluation process of all individuals. For example, one intuitive evaluation process would be based on a group-wide favorable opinion of individual-B based on past experiences in which individual-B had a much lower mistake rate compared to individual-A –so all else being equal, choose action-B. Another evaluation process would be to choose the action that matched your own intuition –but this option prevents one from benefiting from other individuals with more experience and/or superior intuitive intelligence.

Next suppose that individual-A appended a 'why-explanation' to his/her proposed action that was based on reasoning –even if action-A was initially developed by individual-A entirely via intuition and the 'why' reasoning was generated subsequently to bolster individual-A's argument. The why-explanation would increase the level of persuasion for individual-A's proposed action whenever it was convincing to the listeners. In this way, the superior action-A could be chosen by the group despite individual-A's higher past mistake rate, and even if it did not match the intuition of most group members. If both individuals A and B appended why-explanations to their proposed actions, the reasoning component of their arguments would benefit both debating individuals because individual-B could now understand why his/her proposed action was inferior and change their mind. In this example, why-explanations mutualistically benefited all group members. So mutualistic persuasion generates selection for an expanded capability for conscious reasoning (Figure 4, area-6, left-region, 'more is fitter' feedback loop). However, participants in the context of antagonistic persuasion would also benefit from why-explanations when it: i) enabled a deceiver to better persuade others by using reasoned arguments designed to dupe vulnerable individuals, and ii) enabled potentially duped individual to evade deception when they detected less convincing why-explanations (Figure 4, area-6, left-region, 'offense/defense' feedback loop).

Why-explanations would also be expected to have an important role in pedagogy. Pedagogy can be considered to be a form of persuasion because one individuals coaxes another individual to do something (an outcome) by showing them a pathway to that outcome. For example, consider a more experienced individual (teacher) instructing a less experienced individual (pupil) to fabricate a flaked-stone tool. The simplest procedure would not require why-explanations: simply allow the pupil to observe the teacher making the tool, and then the pupil remembers the steps used to make it. However, for a complex tool, requiring numerous and/or complex fabrication steps, the why-explanation can be especially effective. To see why, consider an an analogy: just as the metaphor 'a picture is worth a thousand words' illustrates the substantially expanded information content possible with a single picture, a parallel metaphor is 'a why-explanation is worth a thousand how-to instructions.' This second metaphor illustrates the utility of why-explanations in the context of pedagogy. Why-explanations are exceptionally information-rich because they allow the pupil to 'deduce from understanding' rather than remembering the many and/or complex steps required to fabricate the complex tool. Because why-explanations require rational thinking, they promote (catalyze) the development of conscious reasoning in the context of pedagogy.

The above scenarios illustrates why persuasion generates selection for why-explanations that are produced via conscious reasoning –even when most ideas are generated initially by intuition. Better reasoning ability enables better evaluation of reasoned why-explanations of others and they also enable an individual to be more persuasive. In this way language, via the process of persuasion, acts as a catalyst for the evolution of increased conscious reasoning ability (Figure 4, left area of region 6).

Mental State Attribution (MSA) A feature in addition to why-explanations that can augment an individual's persuasion ability is mental state attribution (MSA). During the transition of simple words and word-arrays (protolanguage) to syntax-based language, combining single words into short word-arrays would generate ambiguity. For example 'hit Mary John' could mean John hit Mary, Mary hit John, Mary and John were both hit by something else, Mary and John both hit something else, or Mary and John exchanged hits. Syntax removes this ambiguity. Early in the development of language, this type of ambiguity could be reduced by learning to restrict word-arrays to those word combinations that are not ambiguous like "cat big", "run fast" or only using longer word-arrays that are intrinsically not ambiguous like a noun and two adjectives: "lion two far". The early use of simple word-arrays would have selected for MSA to determine if a spoken word-array signal was informative to the recipient (MSA: Did the receiver perceive a meaningful message?) or if the intended message was perceived (MSA: Did the recipient perceive the desired meaning?). So the early development of language would have intrinsically selected for increased MSA capability. But language-based persuasion expands this selection for increased MSA ability.

MSA is an intrinsic component of persuasion because it provides real-time feedback concerning the success of the mental state changes (MSCs) that the persuader is trying to achieve, i.e., has the persuasion generated the desired MSC? –if not try an alternative argument. MSA can also be used to plan the structure of a persuasive language to make it more effective. To illustrate this feature again consider the hominin example from the previous section in which individual-A proposes action-A, individual-B proposes action-B and the group has to decide which alternative to choose. Again suppose that action-A is the better choice and that individual-A has the poorer past mistake rate. Besides using why-explanation to persuade the group to choose action-A, individual-A could use MSA to make his message more persuasive. For example, he/she could ascertain whether or not some group members were: i) potentially offended if a junior member had a new and better idea, ii) were egotistical, iii) angry with him/her due to past mistakes, iv) had low openness to new ideas, and so forth. Using this MSA information, individual-A could add MSA-based pragmatics to his language by: i) being tactfully polite to prevent offending more senior group members, ii) self-deprecating to appease egotistical group members, iii) interject humor to make the group more receptive, frame his/her argument as minor extensions of established behaviors to seem less radically different than the usual procedures, and so forth. This example involves mutually beneficial persuasion but the same logic apples to antagonistic persuasion where MSA and MSA-based pragmatics could be used to better deceive vulnerable individuals or better detect deceiving individuals, e.g., detecting lies. In this way, selection for better persuasion ability would catalyze the expansion of both MSA capability and pragmatics ability (Figure 4, area-6, MSA boxes and linkages).

MSA is an intrinsically complex form of imagination because one must imagine something that has never been directly observed:

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the thinking and perspectives of another's mind. It requires an individual to imagine how the world appears to each of many different individuals based on current observations and also a memory dossier of different individuals' past behavior. As language expanded the MSA ability of hominins, it also expanded the ability for imagination, as described in the following section (Figure 4, area-6, imagination boxes and linkages).

Imagination As described more fully in the section on creativity below, experimental evidence indicates that imagination is not unique to humans (reviewed in Mullally and Maguire 2014; Blaisdell 2019). However, language, especially in the context of persuasion, requires highly complex and abstract imagination –so language-based persuasion generated selection for exceptionally complex imagination. Consider someone planning to make a persuasive argument. The simplest plan would be to rely on real-time intuition and trust that whatever contingencies arise during the persuasive interaction, a rapid intuitive response will be sufficient. However, modern humans commonly plan out anticipated persuasive episodes by imaginative simulations (hereafter ImSims) in which various 'what-if' contingencies are simulated using episodic memories (Schacter et al. 2012; Mullallyand Maguire 2014; Schacter and Addis 2020).

ImSims used for planning can be quite complex because they can include both place- and time-travel as well as complicated dialogs. Such ImSims represent a type of imagined alternative to actual trial-and-error because different alternatives can be simulated and then evaluated for effectiveness using intuition, reasoning and predicted MSA. The accuracy, and hence the utility, of ImSims for planning will depend on the accuracy of imagination –so highly realistic ImSims plausibly would be selectively favored. For these reasons, language-based persuasion acted as a catalyst that facilitated the evolution of highly complex imagination in context of planning persuasion episodes (Figure 4, area-6, imagination box, and area-7, reasoned box).

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Written documents influence on reasoning and the diversity and complexity UP-paralife

When humans learned to write and read language, written documents substantially expanded the capacity for increased problem-solving ability and thereby enabled UP-paralife to evolve increased diversity and complexity (Figure 4, region-7, right-top). The simplest way that documents expanded human's capacity to make more complex and diverse UPs was to reduce the constraints of limited working memory. Working memory is a specific form of short-term memory – the limits of which constrain the number of items that can be simultaneously integrated or manipulated during the reasoning process (Chai et al. 2018). Working memory is estimated to be be able to process only 3-5 items or 'chunks' of information simultaneously during reasoning (reviewed in Cowan 2010). Written documents allow many more items to be logically integrated or manipulated in the form of lists, sequential steps, plans/protocols and diagrams –and thereby enable more complex problems to be solvable. As a consequence, more complex UPs can be designed and more diverse UPs can be integrated into systems.

Written documents also created a pathway for the development of logic languages like mathematics and computer code (Figure 4, region-7, right-bottom). The purpose of these languages is to expand reasoning ability rather than transfer information between individuals in the context of communication. Geometry is a logic language that expands our ability to quantify and make inference about the shape of objects and the spatial relationships among different objects. Deterministic variable mathematics, like algebra and calculus, is a logic language that expands our ability to carry out quantitative deduction (from the general to the specific). Stochastic variable mathematics, like inferential statistics, is a logic language that expands our ability to carry out quantitative induction (from the specifics to the general). Computer language enables rapid quantitative calculations and the ability to solve many mathematically intractable problems via quantitative iteration. Computer language in the form of artificial intelligence (AI) enables UPs in the form of machines to independently learn from experience and reasoning, and thereby expands the limits of human cognition. Collectively, these logic languages generated a form of 'cognitive leverage' (like the mechanical advantage of a lever and fulcrum in the context of physics) that greatly expanded our quantitative reasoning ability and enabled more complex problems to be solvable, and as a consequence, more complex UPs could be designed and more diverse UPs could be fabricated and integrated into systems.

Documents also expand the capacity to build an archive of cumulative knowledge. This accumulated knowledge enabled scientific disciples like physics, chemistry and biology to develop and expand continuously with time. The accumulation of scientific knowledge and understanding enable technology to continuously

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expand, and as a consequence, so too did the diversity and complexity of UP-paralife.

Creative imagination

Creativity requires an expanded form of imagination that fossil evidence indicates evolved relatively recently in the human lineage (as described below). Creativity may be unique to humans because of the complexity of the thought processes that it requires (a combination of convergent and divergent thinking; Lumsden and Findlay 1988; Blaisdell 2019; Zhang et al. 2020). Imagination, however, is not unique to humans. Early experimental studies in animal behavior indicated that some vertebrates are able to imagine the rotation of images (pigeons) and to imagine items in their environment that are blocked by an intervening visual barrier (rats; these studies are reviewed in Blaisdell 2019). More direct evidence comes from research in neuroscience using optogenetics to measure neuron firing. These studies have shown that rats, learning to find a food reward in a maze that they have previously learned to navigate, activate pairs of previously learned navigation engrams (neural network configurations of simultaneously firing neurons containing at least one 'place cell' neuron) while paused immediately prior to deciding which way to turn at bifurcation points within the maze (reviewed in Josselyn and Tonegawa 2020). Earlier experiments had shown that one of the pair of engrams activates when the rat navigates through the right arm of the maze and the other activates when it moves through the left arm. As the rats learned to navigate to the food reward, the prevalence of the correct-turn navigational engram increased relative to the incorrect alternative, while paused immediately prior to deciding which way to turn.

Further evidence for imagination in rats comes from studies in which a rat navigates an unfamiliar maze and is stopped by a transparent barrier that enables it to see that a food reward is located at the end of one side of a bifurcation point but not the other side. In response, the rats generated a new navigational NN engram that led through the bifurcation pathway leading to the food reward and not to the other pathway (Olafsdottir et al. 2015). Collectively these studies with model organisms clearly demonstrated that imagination occurs in vertebrate species with far less cognitive ability compared to humans –and therefore imagination would have been plausibly present in the hominin lineages leading to modern humans.

Creative imagination is the foundation for creativity. It requires two types of thinking: i) divergent thinking to generate novel ideas, and ii) convergent thinking to use the novel ideas to solve a specific problem using fluid and/or crystalized intelligence (Karwowski et al. 2016; Zhang et al. 2020). Convergent thinking is the ability to determine the correct or best solution to a narrowly focused problem, while divergent thinking is the ability to determine the greatest diversity of solutions to an open-ended problem. Intelligence tests like Raven's matrix test for fluid intelligence measure convergent thinking ability, and tests like the alternative use test (containing questions like: name as many nonconventional uses as possible for a common object like a brick or spoon) measure divergent thinking ability. Divergent thinking is generally considered to be the primary limitation for creativity because it requires that something new, original and valuable is formed and this outcome necessarily requires some form of divergent thinking (Karwowski et al. 2016; Zhang et al. 2020).

Convergent thinking is a basal form of thinking that is shared by many forms of animal life. This form of thinking enables an organism to generate a best cognitive solution to a problem that influences fitness, i.e., learning and intuitive insight are used instead of genetically evolved adaptations (like an instinctual behavior) to solve a problem in order to increase fitness. For example, a bird species could evolve to instinctively avoid eating a form of green, unripe berry that, post consumption, produced abdominal pain and vomiting: a genetic adaptation solution to the fitness-influencing problem –instinctively avoid green fruit. Alternatively, the bird could learn via trial-&-error to avoid the green berries because they have an unpleasant aftereffect: a convergent thinking solution to a fitness-influencing problem –learn to avoid green fruit because of its associated painful aftereffects.

Divergent thinking usually requires an organism to ignore the convergent-thinking answer to a problem (e.g., use bricks conventionally by stacking them vertically to make walls or place them side-by-side horizontally to make paved surfaces) and replace it with many new alternative answers (e.g., use bricks unconventionally to do something new and different, like: i) cut it in half, hollow it out, and make a storage container, or ii) grind it up, mix it with clear oil, and make red paint. Such short-circuiting of the convergent thinking process may require sufficiently high intelligence and empirical studies within humans show a strong correlation between divergent

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thinking ability and general intelligence level (meta analysis by Karwowski et al. 2016). For this reason divergent thinking may be restricted to higher-cognition species and possibly also to higher intelligence individuals within a species. A corollary conclusion is that creativity plausibly may have been restricted to only those hominin lineages that had evolved sufficient cognitive ability to be capable of divergent thinking.

Substantial empirical evidence confirms that divergent and convergent thinking abilities are not independent. Many studies have used bivariate regression between measures of divergent thinking as the dependent variable and measures of convergent thinking (e.g., IQ) as the independent variable. These studies consistently found a steep positive regression (meta analysis by Karwowski et al. 2016; and also Weiss et al. 2020), and collectively provide strong support for the conclusion that sufficient intelligence (i.e., near or above average) is a necessary but not a sufficient condition for the creative imagination that underlies creativity in modern humans –at least as it is measured by divergent thinking instruments (Karwowski et al. 2016).

A second factor, besides intelligence, that empirical data indicate strongly influences divergent thinking ability is the personality trait ‘openness to experience’ (hereafter abbreviated by OtoE) –one of the big-five personality traits (see DeYoung et al. 2005 and Nekljudova 2019 for a review of this personality trait). OtoE has six sub-categories including a penchant for: fantasy, sensitivity to emotions, appreciation of art and beauty, seeking novel experiences, intellectual curiosity, and questioning conventional norms (Nekljudova 2019). McCrae (1987) combined data from many different studies and found a consistent and strong positive association between OtoE and divergent thinking ability. Wang et al. (2022) used structural equations modeling to compare the joint influences of OtoE and divergent thinking ability on creative achievement. This study found that OtoE was the stronger predictor of creative achievement (a correlation coefficient twice as strong), despite the fact that divergent thinking is generally considered to be the foundation for creative imagination (Karwowski et al. 2016; Zhang et al. 2020).

Other studies have found empirical evidence for a strong interaction between intelligence and OtoE in their influence on divergent thinking ability. For example, Shi et al. (2016) analyzed a sample of N = 831 12-13 year old school children. Each child was scored for three features: i) Intelligence (sorted into bins of low [< {mean - 1 SD}], middle [within the mean ± 1 SD], and high [> {mean + 1 SD}]), ii) OtoE (sorted into the same bins of low, middle, and high), and iii) a composite measure of divergent thinking. As had been found in many previous studies (reviewed in Karwowski et al. 2016), low intelligence was associated with very low levels of divergent thinking. But this study also found that the level of OtoE had no measurable influence on divergent thinking ability at low levels of intelligence. In sharp contrast, at middle and high intelligence levels, higher OtoE markedly increased divergent thinking ability, with the highest divergent thinking found in the combination of high intelligence and high OtoE. Overall, the steep increase in divergent thinking ability with increasing intelligence that had been reported in numerous past studies (reviewed in Karwowski et al. 2016) only occurred when there was a combination of both middle to high OtoE and also middle to high intelligence. With low OtoE there was only a small gain in divergent thinking ability as intelligence increased from low to middle and high levels. These results were corroborated by a study of adults that measured creative achievement rather than divergent thinking ability (Harris et al. 2019). Collectively these studies indicate that higher intelligence is only associated with a substantial gain in divergent thinking ability when there is at least a middle level of OtoE, and higher OtoE was only associated with a substantial gain in divergent thinking ability when there is at least a middle level of intelligence.

A simple model that is consistent with the effects of intelligence, OtoE, and their interaction on divergent thinking ability and creativity has three components. First, intelligence generates the ‘potential’ for divergent thinking, with higher intelligence generating higher potential. Second, OtoE enables the ‘expression’ of an individual’s potential for divergent thinking ability, with higher OtoE producing higher expression of the potential ability. Third, the interaction between intelligence and OtoE results from OtoE not being able to increase divergent thinking ability when the potential for this trait is too low due to insufficient intelligence, and intelligence not being able to increase divergent thinking ability when its expression is too strongly reduced due to insufficient OtoE. Supplemental Figure S5 expresses this hypothesis graphically as a creative-solutions landscape model.

Collectively, the findings described up to this point in this section indicate that: i) in modern humans, at least near-average intelligence and near-average OtoE are both necessary conditions for substantive divergent thinking ability (and the

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creative imagination and achievement it enables) and that the combination of at least near-average levels of both features is a sufficient condition for substantive divergent thinking ability, and ii) human creativity evolved only after hominins evolved the necessary level of intelligence due to expanded brain size, and plausibly also due to increased connections between different cortical regions via white matter tracts like the arcuate fasciculus (Neubauer et al. 2018). This increased computation ability made divergent thinking possible –and hence generated a potential for creativity. But creativity also required a high level of a major personality trait –OtoE– for this potential to be expressed. OtoE has substantial heritability in present day humans (estimated to be ~0.4-0.5 by Bergeman et al. 1993; and 0.59 in young adults and 0.69 in older adults by Kandler et al. 2020), indicating that it could be rapidly increased by natural selection once such selection occurred.

The earliest fossil evidence for creative imagination in humans dates back to only 0.05-0.1 mya, as inferred from the presence of musical instruments (Conard et al. 2009), figurative cave art (Brumm et al. 2021), and carved figurines (Kind et al. 2014). The figurines and cave art unequivocally demonstrate creative imagination because they depict nonexistent hybrids that are part human and part animal, like the 'lion man' figurine (Kind et al. 2014). The complexity of Acheulean stone technology indicates that hominins as early as 1.7 mya had the dexterity needed to make creative structures that could be preserved in the fossil record, but extant archeological evidence indicates that these indicators of creative imagination nonetheless were only produced within the last 50-100,000 years.

The very recent first occurrence of fossil evidence for creative imagination (Conard et al. 2009; Brumm et al. 2021; Kind et al. 2014), in combination with the strong reduction in divergent thinking ability and creative achievements in humans with intelligence lower than one standard deviation below the mean (irrespective of the OtoE level; Karwowski et al. 2016; Shi et al. 2016; Harris et al. 2019; Weiss et al. 2020), supports the conclusion that creativity evolved in humans only after sufficient cognitive ability had developed during the ~2.5 million years of continuous expansion in hominin brain size and shape (and plausibly also connectivity, Neubauer et al. 2018).

The earliest archeological evidence for creative imagination is also associated with a sudden burst in the rate of advances and innovations in technology. Prior to evidence for creative imagination, technological advance was slow, e.g., the initial Oldowan flaked-stone technology persisted for ~0.9 million years and its successor, Acheulean flaked-stone technology, lasted for ~1.5 million years (Antón et al. 2014). But in only the last 0.05 million years since the first evidence for the presence of creative imagination, humans transitioned between at least two new stone tool technologies and then to copper, then bronze, then iron, then steel technologies, as well as transitioning to moving-parts technologies like the bow and arrow and atlatl. Later in this same 0.05 million year period, humans also transitioned to agriculture, large cities with expansive infrastructure and complex social structure, the writing/reading revolution, the steam-driven industrial revolution, the electricity revolution, and most recently the information revolution. Most of what are considered to be uniquely human capabilities, like numerous forms of art, mathematics and complex technologies all became established only after we find fossil evidence that the human lineage had evolved creative imagination.

The advent of creative imagination in the hominin lineage was a pivotal transition point in the evolution if UP-paralife when its full potential for UP-mutability and UP-evolvability developed and enabled its diversity and complexity to become fully open-ended. Just as the transition from unicellular to multicellular life was a pivotal transition point in the potential for increased complexity and diversity of biological life (Szathmary and Maynard-Smith 1995), the evolution of creative imagination in UP-paralife's symbiotic biological host (hominins/humans) was a quantum leap in the potential for the complexity and diversity of UP-paralife.

Discussion

The foundation for this paper is the realization that useful structures that animals learn to fabricate and use to increase their fitness (utility products = UPs) share many characteristics with biological life and become nearly alive (UP-paralife) when they develop sufficient UP-evolvability, as summarized in Box-1. Once UP-paralife originated, a biological-life/UP-paralife symbiosis formed that enabled a new and advanced form of social cooperation: word/tool-mediated teamwork that includes low-related individuals. This symbiosis initiated self-reinforcing and directional coevolution between UP-paralife (cultural evolution) and the intelligence of its biological fabricator (genetic evolution) that caused ever-increasing diversity and complexity of UP-paralife, and also ever-

Box-1 Succinct summary of the origin UP-paralife and its coevolution with human intelligence.

Once animals evolve sufficient intelligence and dexterity, they can potentially learn to fabricated utility products (UPs), like tools, and culturally transmit the information (I) required for their production, operation and uses across generations. These UPs are intrinsically part of an induced-reproduction system when the perceived benefit of a UP stimulates the animal to reproduce it, including its production and operation information (I) that is physically-encoded in the animals' neural network (UP-genome). Learning can modify the information in UP-genomes (UP-mutations) and cause the production of new UP variants (UP-heritable-phenotypes). When UPs develop sufficient UP-evolvability (a capacity for system-improving cultural evolution) due to nonrandom differential reproduce favoring UP-variants with perceived higher usefulness (utility-selection), the UPs become 'para-alive', i.e., nearly alive, or a form of UP-paralife. This non-biological paralife is equivalent to the life-status of biological viruses, plasmids, and transposons that have genomes, mutability, heritable phenotypes and a capacity for adaptive evolution, but must induce a life-form to assist in at least some of their core reproductive functions, e.g., protein synthesis.

UP-evolvability increased substantially when hominins learned to fabricate and use flaked-stone tools. This type of tool increased UP-evolvability in two ways by: i) increasing UP-mutability, and ii) increasing the scope for new beneficial UP-mutations. The cutting and chopping ability of flaked-stone tools made them 'tools-to-make-tools' and this fabrication-enabling feature markedly increased the UP-mutation rate, especially for wood-based UPs. An increased scope for beneficial UP-mutations developed when hominins combined flaked-stone tool fabrication with the use of learned spoken words (a transient form of UP for volitional communication) and self-domestication. Fossil evidence indicates that a substantial level of self-domestication evolved in the hominin lineages far in advance of their learning to fabricate flaked-stone tools. Studies of extant species with self-domestication demonstrates that it facilitates social cooperation, food-sharing, aggression-suppression, and social tolerance among low-related (low-r) teammates. The timing of first word-use by hominins is less certain, but it can be deduced to have necessarily evolved by the time they entered the large-carnivore guild (between 2.6 and 2 mya). This entry required spoken volitional words to coordinate the actions of out-of-sight teammates during a mobile perimeter defense of butchery sites.

The triad of words, fabricated-tools, and self-domestication fostered the origin of UP-paralife because it produced an open-ended scope for new beneficial UP-mutations by enabling hominins to engage in a new, advanced, and expandable form of UP-mediated teamwork (TW) that was coordinated by volitional spoken words, enabled by fabricated tools, and tolerated by low-r teammates. The triad of traits is synergistic because it enables the joint erosion of all of the three major barriers to increased levels of TW: too much selfishness, insufficient coordination signals, and insufficient physical traits. Advances in UP-mediated TW enabled continuous niche-expansion of hominins and initiated coevolution between UP-paralife (via cultural evolution) and the cognition of its biological symbiont (via genetic evolution). The coevolution was self-reinforcing because: i) increased intelligence enables the design and fabrication of more diverse and complex UPs, and ii) more complex and diverse UPs select for increased intelligence to better use them to solve problems that influence fitness. The coevolution was directional because it generated ever-increasing diversity and complexity of UPs, and ever-increasing hominin intelligence.

The expansion of both intelligence and the diversity and complexity of UP-paralife was further accelerated due a catalyst-like influence of word-based communication (language-catalysis) in the context of persuasion, written documents, and logic languages like mathematics and computer code. Word-based communication also enabled the fabrication of social rules that augmented self-domestication in counteracting the intrinsic selfishness that constrains TW including low-r teammates. As intelligence expanded, it eventually reached a threshold that enabled creativity via divergent thinking and creative imagination. Just as multicellularity marked a pivotal transition that increased the diversity and complexity of biological life, the evolution of creativity in the human lineage marked a crucial transition in the evolution of UP-parlife that greatly expanded its diversity and complexity –and opened a pathway to the evolution of UP-life, as described in the companion paper (Rice 2022).

increasing intelligence of its symbiotic biological fabricator (Box-1).

What event triggered the origin of UP-paralife and the expansion of hominin intelligence?

Identifying the 'triggering' event for origin of UP-parlaife and it coevolution with hominins requires a knowledge of the timing of the three phenotypes that collectively enabled word-coordinated/fab-tool-enabled/low-r-tolerated TW. This complex form of TW expanded the scope for beneficial UP-mutations (and thereby increased UP-evolvability) and caused the transformation UPs ➔ UP-paralife. The three phenotypes were: i) self-domestication, ii) flaked-stone tools, and iii) volitional vocal words. Fossil evidence for substantial self-domestication dates back to at least the time of *A. ramidus* (~4.5 mya; Clark and Henneberg 2015, 2017; Griffin 2019), a time far in advance of the start of a persistent increase in hominin brain size at ~2.5 mya (Figure 2, data from Püschel et al. 2021) –so self-domestication alone does not appear to be the triggering event. The *Australopithecine* lineages that evolved immediately after A. *ramidus* did have brains that were 40% larger, despite having body sizes that averaged ~25% smaller (Püschel et al.. 2021). However, this increase in brain size represented a short pulse of small-scale expansion rather than the long-term and large-scale expansion that occurred in the *Homo* lineages (Figure 2).

Persistent use of flaked-stone tools (Oldowan technology) first appear in the fossil record at ~2.6 mya (Braun et al. 2019), and this time point roughly coincided with the beginning of the rapid

Box-2 The major factors constraining TW.

Teamwork is limited by three major features that interfere with its operation and its expansion to higher levels: i) too much selfishness, ii) insufficient coordination signals, and iii) insufficient physical traits (Figure 7-top). First consider selfishness. Unless teammates have identical genotypes, there are intrinsic conflicts of interest among teammates that can favor selfishness that substantially interferes with cooperative TW –especially when some teammates have very low relatedness (Hamilton 1964). Most TW in nature occurs among family members, and this close relatedness among teammates reduces the intrinsic benefits of selfishness and facilitates cooperation and TW (Hamilton 1964). Self-domestication is a rare phenotype in nature that reduces aggression and increases social tolerance and thereby facilitates TW despite the presence of low-r teammates (Hare et al. 2007, 2012; Hare 2017). TW including low-r teammates is important because brains that are sufficiently large to be able to learn to fabricate tools require a combination of endothermy and large body size (Figure 1), and animal species with these traits tend to have small families that preclude complex TW that requires many teammates. When self-domestication evolved in the hominin lineage in *Ardipithecus ramidus* (fossils from ~4.5 mya), far in advance of evidence for flaked stone tool use by hominins, it reduced a major constraint on the potential for TW expansion: too much selfishness (Figure 7). Additional episodes of self-domestication may have further erode this constraint (Hare 2017). As word-UPs expanded in complexity during the transition from protolanguage to language, they enabled the fabrication, use, and enforcement of social rules that further enhanced the potential for expanding UP-mediated TW by further eroding the negative influence of selfishness on this cooperative behavior.

Next, consider coordination signals. TW is intrinsically limited by the capacity of teammates to coordinate their joint behavior via communication signals because more complex TW requires more information exchange among teammates. Coordination-enhancing communication signals among teammates reduces this constraint. For example, communication signals in the form of pheromones are associated with substantially enhanced TW in taxa like social insects (Ali and Morgan 1990; Queller and Strassman 1998), and communication signals in the form of context-specific alarm calls in social mammals like meerkats and dwarf mongoose also are associated with enhanced TW (Manser et al. 2014). TW coordination via learning-based words (and later language) represents a 'quantum leap' over instinct-based coordination signals, like pheromones and alarm calls, because complex sensory information can be rapidly integrated in the cerebral cortex and used to produce context-dependent volitional word-signals that substantially enhance the speed, flexibility and adaptability of complex TW. Words, and later language, also enable the development of more complex TW via planning. When hominins learned to fabricate and use simple words to coordinate TW, expansion of this trait enabled a gradual erosion of one of the three major constraints on TW expansion: insufficient coordination signals (Figure 7).

Lastly, consider physical traits. TW is intrinsically limited by the structural attributes of teammates. For example, TW by terrestrial predators with running/walking locomotion, like lions, can not readily be expanded via genetic evolution to exploit prey living in non-terrestrial habitats, like deep water. Learning to fabricated UPs like flaked-stone tools, with an open-ended capacity to continually expanded UP diversity and complexity, represented a 'quantum leap' in the capacity to expand TW to new domains. The increase in TW capabilities occurs because the UPs expand the physical traits of teammates (via cultural evolution) and thereby opens a pathways to learn to expand the scope for TW activities. When hominins learned to fabricate and use flaked-stone tools with cutting and chopping capabilities, this feature enabled them to expand teammate phenotypes and extend TW capabilities (Figure 7). For example, UPs like simple rafts and spears would allow terrestrial hominins to exploit deep water aquatic species like fish. Expansion of the diversity and complexity of fabricated structural UPs enabled a gradual erosion of one of the three major constraints on TW expansion: insufficient coordination signals (Figure 7).

The confluence of the three traits of self-domestication, word-coordination of TW and expanded teammate phenotypes due to fabricated structural UPs was transformative because it enabled all three of the major major TW constraints to begin to erode simultaneously (Figure 7). A a consequence, TW began to continuously expand, which enabled continuous niche-expansion that favored new and more complex UPs and the intelligence to design, fabricate, and use them. This process gradually lead to a new and far more complex form of social cooperation: UP-sociality (Figure 7, left-bottom).

increase in hominin brain size (Figure 2) and evidence for ever-increasing levels of butchery of large herbivores (Domínguez-Rodrigo and Pickering 2017; Ben-Dor et al. 2020). The close timing between the first fossil evidence for flaked-stone tools, and the beginning of brain size expansion and butchery (requiring fab-tool-enabled/word-coordinated/low-r-tolerated TW), suggests that this feature was plausibly the 'trigger' for the the origin of UP-paralife.

Use of TW-coordinating volitional words may have evolved much earlier than the persistent use of flaked-stone tools (Supplemental Text S1), or it may have evolved soon after this event due to its high potential for evolution once selectively favored (as described earlier). However, volitional words do not fossilize, so we cannot say with certainty when the use of volitional words first evolved. Nonetheless they must have evolved by the time of early *H. erectus,* when it can be deduced that these hominins were using a mobile perimeter defense that required (or at least

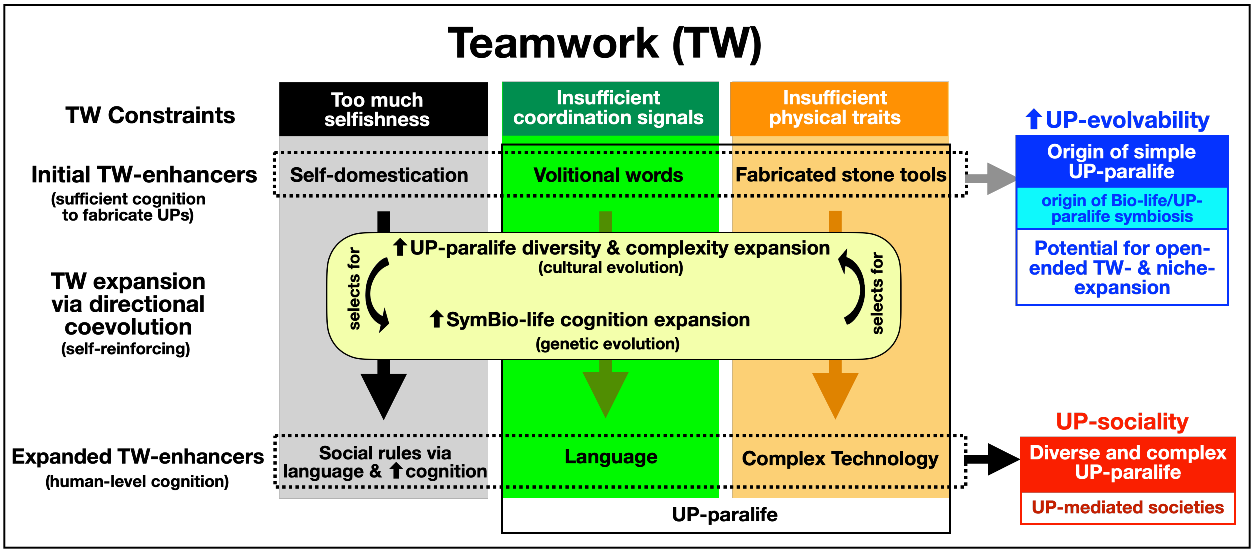


Figure 7. A flow diagram illustrating of the relationships between expanding teamwork (TW) and the erosion of its three major constraints via TW-enhancers that are generated due to UP-paralife/SimBio-life coevolution. See Box-2 for a more detailed description.

strongly selected for) coordination of TW via volitional vocal words (Figure 3).

UP-mediated TW was pivotal in the evolution of UP-paralife and human intelligence.

UP-mediated TW provides a pathway to ever-more diverse and complex UPs because of its influence on the self-reinforcing positive feedback loop that operated during the coevolution between the diversity and complexity of UP-paralife and the intelligence of its biological host (Figure 6B). This positive feedback loop requires that: i) increased intelligence enables the design and fabrication of more diverse and complex UPs, and ii) more complex and diverse UPs select for increased intelligence to better use them to solve problems that influence fitness. The positive feedback loop, however, further requires that the benefits of increased intelligence outweigh its intrinsic high metabolic cost (Aiello and Wheeler 1995). The combination of self-domestication, simple volitional words and simple flaked-stone tools can generate the requisite high benefit of increased intelligence because they acted as enhancers that continuously eroded each of the three major barriers to TW (too much selfishness, insufficient coordinations signals, and insufficient teammate physical traits) so that it could continually expand to levels never before achieved in nature (see Box-2 and Figure 7 for details). This expanding TW enabled continuous niche-expansion that fueled selection for ever-increasing UP diversity and complexity, and the intelligence required to produce and use these UPs.

The potential for niche-expansion due to elevated levels of TW is supported by the exceptional success of the order *Hymenoptera* in colonizing new and diverse habitats. The *Hymenoptera* clade (sawflies, wasps, bees, and ants) has many colonial species (eusociality) with exceptionally high levels of TW, including a division of labor, cooperative breeding, overlapping generations, and very large team sizes. These advanced TW features are associated with the evolution of at least 150,000 described species (and plausibly as many as one million total species) that have colonized nearly all terrestrial habitats on Earth (Peters et al. 2017). The other major taxa of eusocial insects, termites (that lack some of *Hymenoptera's* idiosyncracies, like haplodiploidy), also has high species diversity and an exceptionally wide geographic distribution, at least within tropical habitats that most species require (Von Hagen 1942). One might argue that because other non-social orders of insects –like flies and beetles– are also highly speciose, *Hymenoptera's* high diversity is not remarkable. However, eusocial insects are functionally large-bodied super-organisms because they form reproductive colonies that are composed predominantly of numerous sterile workers and soldiers. From this perspective, *Hymenoptera* are exceptionally diverse compared to other large-bodied animal taxa. For example, all orders of the class *Mammalia* combined constitute only ~6,500 species (Burgin et al. 2018). Also, the combined biomass of all ant species alone exceeds the combined biomass of all wild bird and mammal species combined (Schultheiss et al 2022). The extreme diversity, biomass and wide global distributions of eusocial insects supports the conclusion that increased levels of TW increase the potential for niche-expansion. The word-coordinated/fab-tool-enabled/low-r-tolerated TW of hominins is expected to surpass the niche-expansion capabilities of eusocial insects because it continually erodes all of the barriers constraining TW and thereby leads to ever-expanding TW and the niche-expansion it enables (Box-2, Figure 7).

For all of the reasons summarized in this section, UP-mediated TW is uniquely capable of expanding UP-evolvability and thereby leading to the origin of UP-paralife and its continuous expansion in diversity and complexity. Other pathways to the origin of simple forms of UP-paralife may exist, but if they did not also eventually lead to UP-mediated TW, then the diversity and complexity of the UP-paralife would be expected to stall at very low levels. The stalling would occur because the diverse and complex forms of UPs associated with current-era humans can only be achieved when there is UP-mediated TW that includes very large numbers of individuals and high levels of specialization in the context of a complex and diverse division of labor.

UP-paralife caused a major evolutionary transition in the complexity of life.

The evolution of biological life on Earth has been punctuated by major evolutionary transitions that led to increased complexity, like the transition from prokaryotes to eukaryotes, unicellular protists to muticellular plants, animals and fungi, and solitary multicellular individual to colonies with sterile castes (Szathmary and Maynard-Smith 1995). The origin of UP-paralife represents the most recent and most advanced evolutionary transition to increased complexity that produced symbiosis between biological life and UP-paralife (Supplementary Figure S4). This symbiosis initiated a form of self-reinforcing directional coevolution that eventually led to the evolution of sufficient human intelligence to enable the creativity that caused the transition from simple word-coordinated/fab-tool-enabled/low-r-tolerated TW to complex societies with language, culture, art and complex technology (UP-sociality; Figure 7-bottom-right). These UP-mediated societies are based on biological-life/UP-paralife symbiosis that far surpasses the level of TW that evolved in small-brained eusocial insects, and also the TW found in much larger brain-sized carnivores and non-human primates, and have the potential to eventually generate non-biological UP-life (Supplementary Figure S4-top-right), as described in the companion paper (Rice 2022).

Simple UPs plausibly prevailed during most of UP-paralife/Biolife coevolution

After the origin of UP-paralife, flaked-stone tool technology changed very slowly, with only two technology transitions within the initial ~2.4 million years of UP-paralife/SymBio-life coevolution (Oldowan ➜ Achulean at ~1.7 mya, and Achulean ➜ Mousterian at ~0.2 mya). This slow change is in sharp contrast to the rapid changes in flaked-stone tool technology (and also bone-based and metal-based technologies) detected in the archeological record within the most recent ~0.05 million years of coevolution (Ambrose 2001). Other forms of persistent-structural UPs, like modified wooden plant stems that do not fossilize, may have changed faster than flaked-stone tools. Nonetheless, if early hominins in the genus *Homo* were rapidly advancing the structural complexity of wood-based UPs, it seems implausible that there would not be more concomitant changes in the structural complexity of flaked-stone tools. For this reason, the exceptionally slow pace of advances in flaked-stone tool technology indicates, more generally, that the complexity of structural UPs plausibly evolved slowly during most of the first 2.4 million years of continuous brain size expansion observed in fossil hominins within the genus *Homo*. This pattern indicates that coevolution between structural UP-paralife and human intelligence was mediated primarily by learning new ways to use simple forms of these structural UPs –rather than due to the fabrication of ever-more complex forms.

Indirect evidence indicates that protolanguage, in the form of simple words and very short word-arrays without syntax, also increased in complexity very slowly after its origin sometime before the emergence of *H. erectus*. Studies with chimpanzees indicate that when they were taught sign language words, they learned vocabularies in the range ~100 words (Beran and Heimbauer 2015). For comparison, young adults of modern humans have English language vocabularies of ~10,000 words (Miltonand Treffers-Daller 2013). The limited chimpanzee vocabulary was used to form simple word-arrays that were usually only 1-2 words long, and rarely ≥ 3 words long (Rivas 2005). The word combinations made by chimpanzees showed no syntax structure and only minimal semantic structure that was far less than observed in young children (Rivas 2005; Yang 2013). As described earlier in the case of human children, there is a long delay (~2 years) between a child's first words and his/her first simple-syntax sentences (Tager-Flusberg et al. 2009). These empirical findings in chimpanzees and human children indicate that substantial cognitive development would have been needed during the transition between the use of simple words and unstructured short word-arrays (protolanguage) and the simplest forms of syntax-based language. This long ontogenetic delay and substantial neurological development separating first words and first simple sentences supports the conclusion that a substantial period of evolution was required to evolve brains capable of even the simplest form of syntax-requiring language. The pattern also indicates that much of the early coevolution between word-UP-paralife (words and word-arrays) and human intelligence was plausibly mediated by learning new ways to use simple forms of these word-UPs (protolanguage) –and not due to the fabrication of ever-more complex forms of word-UPs, like language.

The slow technical advance of stone tool technology documented in the fossil record, and the inferred slow transition between protolanguage and language described in the above paragraph, indicates that much of the early coevolution between UP-paralife and human intelligence was via learning to use simple structural and signal UPs to advance TW. Evidence for an ever-expanding capacity for UP-mediated TW, despite little evidence for rapid advances in structural or signal UPs, can be found in the plausible impact of early hominins on other members of the LgCar-guild.

Studies by Werdelin and Lewis (2013) and Faurby et al. (2020) indicate that during the first 2.4 million years of increasing brain size in the human lineage, there is a strong correlation between increasing brain size of hominins and an increasing extinction rate of sympatric large carnivores –but not sympatric small carnivores nor allopatric large carnivores. The authors conclude that these extinctions cannot be explained by non-anthropomorphic features like climate change. This inferred impact of increasing human intelligence on extinctions within the LgCar-guild, despite the near stagnation in stone tool technology advance (and also the plausible slow advance in protolanguage), indicates that human intelligence was largely expanding the coordination and capabilities of hominin TW via learning to make better use of simple protolanguage and simple tools.

Social rules complemented self-domestication. As described in earlier sections, self-domestication was the major feature contributing to low-r-tolerated TW early-on during the coevolution between UP-paralife and the intelligence of its hominin/human biological symbiont. However, as increased intelligence and language capabilities developed, these features generated an additional pathway for low-r-tolerated TW that was based on learning and UPs. Increasing intelligence and language skills enabled humans to learn to fabricate, use and enforce social rules that counteract the intrinsic selfishness-based tension that arrises during TW that includes low-r teammates (see Box-2 and Figure 7). Social rules have the advantage of expanding via cultural evolution, and can therefore evolve to become more effective at a faster rate than self-domestication that is based on slower genetic evolution. Social rules might also facilitate the evolution of increased self-domestication because it increases the capacity to comply with these rules.

UP-paralife/SymBio-life Symbiosis produces a Red-Queen advantage.
Because UP-mutations are learned or reasoned modifications of a UP, they are directional (toward anticipated higher utility, unlike non-directional genetic mutations in biological life and paralife) and therefore more likely to be favored by UP-selection. Additionally, UP-selection can completely replace an old UP variant with a newly modified one on a time scale of years or decades –unlike the more gradual process of genetic change via natural selection that spans at least many generations (polygeneic trait with high heritability), and sometimes many hundreds of generations (single gene trait). For both of these reasons, the speed of non-random system-improving evolution of UP-paralife (nonrandom cultural evolution) is expected to be far faster than that of biological life and paralife (nonrandom genetic evolution). As a consequence, the rate of adaptive advance of a biological-life/UP-parlife duo can be far faster than genetic adaptation by other forms of biological life when much of the duo's adaptive advance accrues via the cultural evolution of the forms, diversity, complexity, and uses of UPs.

The rapid adaptive potential of symbiotic UP-paralife/SymBio-life would be expected to produce a large Red-Queen (antagonistic coevolution of a species with its competitors and enemies; Van Valen 1977) advantage whenever UPs can be used to mediate the interaction between the biological life form and its enemies and/or competitors. In modern humans the vaccine-based eradication of the disease small pox caused by the viruses *Variola major* and *V. minor* (and near-eradication of Polio, caused by the poliovirus, a serotype of *Enterovirus C)* illustrates this advantage. In earlier hominins, again consider the studies by Werdelin and Lewis (2013) and Faurby et al. (2020) that indicated that

Box-3 Rough estimate of the probability of intelligent life on an Earth-like exoplanet.

The patterns seen on Earth will be used to calculate a point estimate of the probability of intelligent life evolving on an exoplanet matching Earth's characteristics, including its age, star type and so on. First, I assume that if all of the taxonomic families that express a rare trait (in at least one of its constituent species) are missing during evolution (because by chance all such families failed to evolve), then that trait fails to evolve and persist on the exoplanet – and so too does any composite trait that requires the component trait. I also assume that large brain size evolves independently among families, and given that large brain size has evolved in a subset of families, the presence of the traits self-domestication, learning-based tool fabrication, and learning-based word fabrication also evolve independently among and within these families with large brains. For example, I assume that learning-based tool fabrication evolved independently in the large-brained crow and great ape families, and similarly that learning-based tool fabrication and learning-based word fabrication evolved independently within the great ape family.

Large brain size may be a synapomorphy for some or all of the 13 cetacean families, which would invalidate my independence assumption. However, this lack of independence would inflate my estimated probability of a family with large-brained species evolving on an Earth-like exoplanet. As a consequence, my estimated probability of intelligent life evolving on an Earth-like exoplanet would be an overly-optimistic upper-bound for the true probability.

With these assumptions, the probability of a family evolving sufficient intelligence to potentially fabricate tools is estimated by the number of families on Earth with this cognitive capacity (20) divided by the total number of animal families (~5,500). However 13 of these families are cetaceans that lack the manual dexterity to potentially fabricate tools of even modest complexity. As a consequence, when I delete these 13 cetacean families, the estimated probability of evolving a family containing at least one large-brained species, and having sufficient dexterity to fabricate tools, the proportion of families is the remaining 7 families divided by the total 5,500 families = 0.0013. Given that a family has evolved at least one species with sufficient cognitive and dexterity capabilities to fabricate tools, the conditional probability of further evolving the three traits required for the word-coordinated/fab-tool-enabled/low-r-tolerated TW that I assume is needed for UP-paralife to originate and evolve is (1/7)(2/7)(1/7). This product of three proportions estimates the conditional probability because of the 7 families with sufficient dexterity and cognition to fabricate tools, there are 1, 2, and 1 families on Earth that have evolved self-domestication (Hominidae), learning-based tool fabrication (Hominidae and Corvidae) and learning-based use of words (Hominidae), respectively. The probability of evolving all of the four rare traits required for the evolution of intelligent life is therefore estimated to be (7/5,500)(1/7)(2/7)(1/7) = 7.4 x 10^{-6}, or ~10^{-5}.

during the first 2.4 million years of increasing brain size in the human lineage, there is a strong correlation between increasing brain size of hominins and an increasing extinction rate of sympatric large carnivores (but not sympatric small carnivores nor allopatric large carnivores) that these authors conclude cannot be explained by non-anthropomorphic features like climate change. This pattern in the fossil record supports the conclusion that UP-paralife/SymBio-life symbiosis produces a large Red-Queen advantage. Other intelligent species like killer-whales have split into different sub-types (fish-eating vs. mammal-eating) via cultural evolution (e.g., see Moura et al. 2014): indicating a substantial influence of cultural evolution during the process of adaptation. But the cultural evolution of UP-paralife within the hominin lineages took this process to a new and much higher level by enabling continuous niche-expansion and adaptation via word-coordinated/fab-tool-enabled/low-r-tolerated TW.

The paradox of a low average OtoE in modern humans. The strong positive influence of higher levels of OtoE on divergent thinking, and the creative imagination that it enables, makes it paradoxical that the average value of OtoE in present-day humans is low enough to cause a strong reduction in creativity in a substantial proportion of individuals (Shi et al. 2016; Harris et al. 2019). The high heritability of OtoE indicates that it could rapidly increase in response to natural selection if a higher OtoE were favored (Kandler et al. 2020). These observations indicate that elevated levels of OtoE plausibly have costs that offset its benefit with respect to divergent thinking and creativity.

There are many plausible costs and benefits of OtoE that have been described in other contexts within earlier published studies. As examples, I next describe a few of these possibilities. Because individuals with high OtoE are more receptive to new ideas, a social cost of elevated OtoE may be increased gullibility in the context of antagonistic persuasion (Pinker and Bloom 1990). A self-evident potential cost of too little OtoE would be resistance to new beneficial ideas due to a person being overly conservative. An overly conservative personality could plausibly also contribute to an increased propensity for motivated reasoning (Kunda 1990; Westen et al. 2006) and some forms of self-deception (Smith et al. 2017). Because high OtoE is associated with a propensity for vivid imagination, it might also lead to the confounding of reality and fantasy when trial-&-error is simulated via imagine-&-error in the context of ImSims –although sufficiently high cognition might prevent such confounding. All of these possibilities are vague and speculative. Nonetheless, because OtoE is expected to influence many traits besides creativity, balancing the costs and benefits of all of these influences could plausibly maintain a moderate average level of OtoE, despite the fact that this mean value suppresses creativity in a substantial proportion of the population.

Plausibility of intelligent life on exoplanets with detected life

The work presented here indicates that the elevated level of intelligence found in modern humans (hereafter 'intelligent life') came about due to the origin of UP-paralife and its subsequent coevolution with the intelligence of early hominins. This origin required a brain with sufficient intelligence (crudely measured by volume or mass) to be able to learn to design, fabricate, use, and culturally propagate UPs. This elevated level of cognition is established to have evolved only in the lineages including cetaceans (13 families), crows/ravens (1 family), parrots (5 families), and great apes (1 family), that comprise ~0.3% of the ~5,500 *Animalia* families (Mora et al. 2011). This list might also include elephants (Nissani 2008; Byrne and Bates 2009) but most (97.5%) of the large brain mass of elephants is within the cerebellum rather than the cerebrum (Herculano-Houzel et al. 2014). The small number of families that have evolved large brains indicate that even the first step toward evolving sufficient computing power to initiate the evolution of intelligent life was a rare event during the evolution of life on Earth –that would plausibly be missing entirely during evolution on an exoplanet.

Given that a sufficiently intelligent brain evolves to fabricate and culturally propagate simple UPs, the pathway to intelligent life on Earth indicates that there would need to be three additional co-occurring features to establish simple UP-paralife: self-domestication, learned tool fabrication (plausibly requiring the inclusion of tools-to-make-tools), and learned use of volitional words. This triad is required to enable the continuous erosion of all three of the major constraints on TW that are needed to generate sufficient UP-evolvability to transform the UPs of species like chimpanzees and New Caledonian crows to simple UP-paralife (Box-2, Figure 7). Once formed, simple UP-paralife would have the potential to initiate low-r-tolerated/UP-mediated TW, and consequently, the open-ended niche expansion that created a pathway for the evolution of high intelligence in hominins. Self-domestication, outside the context of adaptation to symbiosis with humans, is only established to have evolved in two families of primates (great apes [bonobos and hominins/humans] and marmosets), indicating that only ~0.04% of animal families are established to have evolved this trait. Learned tool fabrication is also rare and has been established to have evolved in only two families (Corvidae and Hominidae) or ~0.04% of animal families. Volitional words are established to have evolved in only one lineage (hominins) of one family (Hominidae), so this is the rarest of the triad of traits (~0.02% of families). The probability of bringing together all four rare traits in a single lineage would be expected to be smaller than the probability of the rarest trait: one in 5,500 or < 0.02%. In Box-3, I calculate a rough estimate of this probability on an Earth-like planet. Irrespective of the accuracy of this estimate, the requisite combination of rare features that led to intelligent life on Earth indicates that evolution on other planets with chemical life will rarely lead to a species matching or exceeding a human-like level intelligence. As a consequence, it is predicted that the vast majority of any life-bearing planets detected by astronomers (e.g., those with an atmospheric chemical signature of life) in the future will not harbor intelligent life –even when they closely match all of the characteristics of life on Earth.

Acknowledgments

I thank K. Schoenrock for copy-editing assistance.

References

Ackley, B. D., & Jin, Y. (2004). Genetic analysis of synaptic target recognition and assembly. *Trends in neurosciences*, *27*(9), 540-547.

Aiello, L. C., & Wheeler, P. (1995). The expensive-tissue hypothesis: the brain and the digestive system in human and primate evolution. *Current anthropology*, *36*(2), 199-221.

Ali, M. F., & Morgan, E. D. (1990). Chemical communication in insect communities: a guide to insect pheromones with special emphasis on social insects. *Biological Reviews*, *65*(3), 227-247.

Ambrose, S. H. (2001). Paleolithic technology and human evolution. *Science*, *291*(5509), 1748-1753.

Antón, S. C. (2003). Natural history of Homo erectus. American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists, 122(S37), 126-170.

Antón, S. C. (2012). Early Homo: who, when, and where. *Current Anthropology*, *53*(S6), S278-S298.

Antón, S. C., Potts, R., & Aiello, L. C. (2014). Evolution of early Homo: An integrated biological perspective. *science*, *345*(6192), 1236828.

Beaudet, A. (2021). The enigmatic origins of the human brain. *Science*, *372*(6538), 124-125.

Bednarik, R. G. (2008). The domestication of humans. *Anthropologie (1962-)*, *46*(1), 1-18.

Ben-Dor, M., Sirtoli, R., & Barkai, R. (2021). The evolution of the human trophic level during the Pleistocene. *American journal of physical anthropology*, *175*, 27-56.

Benson-Amram, S., Dantzer, B., Stricker, G., Swanson, E. M., & Holekamp, K. E. (2016). Brain size predicts problem-solving ability in mammalian carnivores. *Proceedings of the National Academy of Sciences*, *113*(9), 2532-2537.

Beran, M. J., & Heimbauer, L. A. (2015). A longitudinal assessment of vocabulary retention in symbol-competent chimpanzees (Pan troglodytes). *PLoS One*, *10*(2), e0118408.

Berg, K. S., Delgado, S., Cortopassi, K. A., Beissinger, S. R., & Bradbury, J. W. (2012). Vertical transmission of learned signatures in a wild parrot. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1728), 585-591.

Bergeman, C.S., Chlpuer, H.M., Plomin, R., Pedersen, N.L., McClearn, G.E., Nesselroade, J.R., Jr Costa, P.T. and McCrae, R.R.. (1993). Genetic and environmental effects on openness to experience, agreeableness, and conscientiousness: An adoption/twin study. *Journal of personality*, *61*(2), 159-179.

Blaisdell, A. P. (2019). Mental imagery in animals: Learning, memory, and decision-making in the face of missing information. *Learning & Behavior*, *47*(3), 193-216.

Boesch, C. (2002). Cooperative hunting roles among Tai chimpanzees. *Human Nature*, *13*(1), 27-46.

Boesch, C., Head, J., & Robbins, M. M. (2009). Complex tool sets for honey extraction among chimpanzees in Loango National Park, Gabon. *Journal of Human Evolution*, *56*(6), 560-569.

Bramble, D. M., & Lieberman, D. E. (2004). Endurance running and the evolution of Homo. *nature*, *432*(7015), 345-352.

Brantingham, P. J. (1998). Hominid–carnivore coevolution and invasion of the predatory guild. *Journal of Anthropological Archaeology*, *17*(4), 327-353.

Braun, D. R., Aldeias, V., Archer, W., Arrowsmith, J. R., Baraki, N., Campisano, C. J., ... & Reed, K. E. (2019). Earliest known Oldowan artifacts at> 2.58 Ma from Ledi-Geraru, Ethiopia, highlight early technological diversity. *Proceedings of the National Academy of Sciences*, *116*(24), 11712-11717.

Brumm, A., Oktaviana, A. A., Burhan, B., Hakim, B., Lebe, R., Zhao, J. X., ... & Aubert, M. (2021). Oldest cave art found in Sulawesi. *Science Advances*, *7*(3), eabd4648.

Burgin, C. J., Colella, J. P., Kahn, P. L., & Upham, N. S. (2018). How many species of mammals are there?. *Journal of Mammalogy*, *99*(1), 1-14.

Byrne, R. W., Bates, L. A., & Moss, C. J. (2009). Elephant cognition in primate perspective. *Comparative Cognition & Behavior Reviews*.

Cavallo, J. A., & Blumenschine, R. J. (1989). Tree-stored leopard kills: expanding the hominid scavenging niche. *Journal of Human Evolution*, *18*(4), 393-399.

Chai, W. J., Abd Hamid, A. I., & Abdullah, J. M. (2018). Working memory from the psychological and neurosciences perspectives: a review. *Frontiers in psychology*, *9*, 401

Clark, G., & Henneberg, M. (2015). The life history of “Ardipithecus ramidus”: a heterochronic model of sexual and social maturation. *Anthropological Review*, *78*(2), 109-132.

Clark, G., & Henneberg, M. (2017). Ardipithecus ramidus and the evolution of language and singing: An early origin for hominin vocal capability. *Homo*, *68*(2), 101-121.

Clay, Z., Archbold, J., & Zuberbühler, K. (2015). Functional flexibility in wild bonobo vocal behaviour. *PeerJ*, *3*, e1124.

Clutton-Brock, T. H., O'riain, M. J., Brotherton, P. N., Gaynor, D., Kansky, R., Griffin, A. S., & Manser, M. (1999). Selfish sentinels in cooperative mammals. *science*, *284*(5420), 1640-1644.

Clutton-Brock, T. (2009). Cooperation between non-kin in animal societies. *Nature*, *462*(7269), 51-57.

Colonnesi, C., Stams, G. J. J., Koster, I., & Noom, M. J. (2010). The relation between pointing and language development: A meta-analysis. *Developmental Review*, *30*(4), 352-366.

Conard, N. J., Malina, M., & Münzel, S. C. (2009). New flutes document the earliest musical tradition in southwestern Germany. *Nature*, *460*(7256), 737-740.

Cowan, N. (2010). The magical mystery four: How is working memory capacity limited, and why?. *Current directions in psychological science*, *19*(1), 51-57.

Darwin, C. R. (1868). Variation of plants and animals under domestication.

Deaner, R. O., Isler, K., Burkart, J., & Van Schaik, C. (2007). Overall brain size, and not encephalization quotient, best predicts cognitive ability across non-human primates. *Brain, behavior and evolution*, *70*(2), 115-124

DeCasien, A. R., Williams, S. A., & Higham, J. P. (2017). Primate brain size is predicted by diet but not sociality. *Nature ecology & evolution*, *1*(5), 1-7

DeSilva, J. M. (2009). Functional morphology of the ankle and the likelihood of climbing in early hominins. *Proceedings of the National Academy of Sciences*, *106*(16), 6567-6572.

DeYoung, C. G., Peterson, J. B., & Higgins, D. M. (2005). Sources of openness/intellect: Cognitive and neuropsychological correlates of the fifth factor of personality. *Journal of personality*, *73*(4), 825-858.

Domínguez-Rodrigo, M., Serrallonga, J., Juan-Tresserras, J., Alcala, L., & Luque, L. (2001). Woodworking activities by early humans: a plant residue analysis on Acheulian stone tools from Peninj (Tanzania). *Journal of Human Evolution*, *40*(4), 289-299.

Domínguez-Rodrigo, M., & Alcalá, L. (2016). 3.3-million-year-old stone tools and butchery traces? More evidence needed. *PaleoAnthropology*, *2016*, 46-53

Font, E., García-Roa, R., Pincheira-Donoso, D., & Carazo, P. (2019). Rethinking the effects of body size on the study of brain size evolution. *Brain, Behavior and Evolution*, *93*(4), 182-195.

Dominguez-Rodrigo, M., & Pickering, T. R. (2017). The meat of the matter: an evolutionary perspective on human carnivory. *Azania: Archaeological Research in Africa*, *52*(1), 4-32.

Dunbar, R. I. (2014). How conversations around campfires came to be. *Proceedings of the National Academy of Sciences*, *111*(39), 14013-14014.

Evans, J. S. B. (2010). Intuition and reasoning: A dual-process perspective. *Psychological Inquiry*, *21*(4), 313-326.

Faurby, S., Silvestro, D., Werdelin, L., & Antonelli, A. (2020). Brain expansion in early hominins predicts carnivore extinctions in East Africa. *Ecology Letters*, *23*(3), 537-544.

Fitch, W. T. (2018). The biology and evolution of speech: a comparative analysis. *Annual review of linguistics*, *4*, 255-2

Font, E., García-Roa, R., Pincheira-Donoso, D., & Carazo, P. (2019). Rethinking the effects of body size on the study of brain size evolution. *Brain, Behavior and Evolution*, *93*(4), 182-195.

Fouts, R. S., Fouts, D. H., & Van Cantfort, T. E. (1989). The infant Loulis learns signs from cross-fostered chimpanzees. *Teaching sign language to chimpanzees*, 280-292.

Friederici, A. D., Chomsky, N., Berwick, R. C., Moro, A., & Bolhuis, J. J. (2017). Language, mind and brain. *Nature human behaviour*, *1*(10), 713-722.

Furuichi, T., Sanz, C., Koops, K., Sakamaki, T., Ryu, H., Tokuyama, N., & Morgan, D. (2015). Why do wild bonobos not use tools like chimpanzees do?. In *Bonobo Cognition and Behaviour* (pp. 179-214). Brill.

Gazda, S. K., Connor, R. C., Edgar, R. K., & Cox, F. (2005). A division of labour with role specialization in group–hunting bottlenose dolphins (Tursiops truncatus) off Cedar Key, Florida. *Proceedings of the Royal Society B: Biological Sciences*, *272*(1559), 135-140.

Ghazanfar, A. A., Kelly, L. M., Takahashi, D. Y., Winters, S., Terrett, R., & Higham, J. P. (2020). Domestication phenotype linked to vocal behavior in marmoset monkeys. *Current Biology*, *30*(24), 5026-5032.

Griffin, W. E. (2019). The vocal precursor of protolanguage and self-domestication in early hominid evolution. *Biological Theory*, 1-22.

Güntürkün, O., Ströckens, F., Scarf, D., & Colombo, M. (2017). Apes, feathered apes, and pigeons: differences and similarities. *Current Opinion in Behavioral Sciences*, *16*, 35-40.

Guthrie, R. (2007) Haak en Steek – The tool that allowed hominins to colonize the African savannah and flourish there. In: Roebroeks W, editor. Guts and brains an integrative approach to the hominin record. Leiden: Leiden University Press. pp. 133–164.

Hamilton, W. D. (1964). The genetical evolution of social behaviour. II. *Journal of theoretical biology*, *7*(1), 17-52.

Hare, B., Melis, A. P., Woods, V., Hastings, S., & Wrangham, R. (2007). Tolerance allows bonobos to outperform chimpanzees on a cooperative task. *Current Biology*, *17*(7), 619-623.

Hare, B., Wobber, V., & Wrangham, R. (2012). The self-domestication hypothesis: evolution of bonobo psychology is due to selection against aggression. *Animal Behaviour*, *83*(3), 573-585.

Hare, B. (2017). Survival of the friendliest: Homo sapiens evolved via selection for prosociality. *Annual review of psychology*, *68*, 155-186

Harmand, S., Lewis, J. E., Feibel, C. S., Lepre, C. J., Prat, S., Lenoble, A., ... & Roche, H. (2015). 3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya. *Nature*, *521*(7552), 310-315.

Harris, A. M., Williamson, R. L., & Carter, N. T. (2019). A conditional threshold hypothesis for creative achievement: On the interaction between intelligence and openness. *Psychology of Aesthetics, Creativity, and the Arts*, *13*(3), 322.

Herculano-Houzel, S. (2009). The human brain in numbers: a linearly scaled-up primate brain. *Frontiers in human neuroscience*, 31.

Herculano-Houzel, S., Avelino-de-Souza, K., Neves, K., Porfírio, J., Messeder, D., Mattos Feijó, L., ... & Manger, P. R. (2014). The elephant brain in numbers. *Frontiers in neuroanatomy*, *8*, 46.

Herculano-Houzel, S. (2017). Numbers of neurons as biological correlates of cognitive capability. *Current Opinion in Behavioral Sciences*, *16*, 1-7.

Herries, A. I., Martin, J. M., Leece, A. B., Adams, J. W., Boschian, G., Joannes-Boyau, R., ... & Menter, C. (2020). Contemporaneity of Australopithecus, Paranthropus, and early Homo erectus in South Africa. *Science*, *368*(6486), eaaw7293.

Hopkins, W. D. (2013). Apes, Language, and the Brain. In *Animal Models of Speech and Language Disorders* (pp. 263-288). Springer, New York, NY.

Hunter, J. S., Durant, S. M., & Caro, T. M. (2007). Patterns of scavenger arrival at cheetah kills in Serengeti National Park Tanzania. *African Journal of Ecology*, *45*(3), 275-281.

Isbell, L. A., Bidner, L. R., Van Cleave, E. K., Matsumoto-Oda, A., & Crofoot, M. C. (2018). GPS-identified vulnerabilities of savannah-woodland primates to leopard predation and their implications for early hominins. *Journal of human evolution*, *118*, 1-13.

Isler, K. (2013). Brain size evolution: how fish pay for being smart. *Current Biology*, *23*(2), R63-R65.

Josselyn, S. A., & Tonegawa, S. (2020). Memory engrams: Recalling the past and imagining the future. *Science*, *367*(6473), eaaw4325.

Kandler, C., Bratko, D., Butković, A., Hlupić, T. V., Tybur, J. M., Wesseldijk, L. W., ... & Lewis, G. J. (2020). How genetic and environmental variance in personality traits shift across the life span: Evidence from a cross-national twin study. *Journal of Personality and Social Psychology*.

Karwowski, M., Dul, J., Gralewski, J., Jauk, E., Jankowska, D. M., Gajda, A., ... & Benedek, M. (2016). Is creativity without intelligence possible? A necessary condition analysis. *Intelligence*, *57*, 105-117.

Queller, D. C., & Strassmann, J. E. (1998). Kin selection and social insects. *Bioscience*, *48*(3), 165-175.

Kendall, C. J. (2012). Alternative strategies in an avian scavenger guild and their conservation implications (Doctoral dissertation, Princeton University).

Kind, C. J., Ebinger-Rist, N., Wolf, S., Beutelspacher, T., & Wehrberger, K. The Smile of the Lion Man. Recent Excavations in Stadel Cave (Baden-Württemberg, south-western Germany) and the Restoration of the Famous Upper Palaeolithic Figurine.

King, S. L., Sayigh, L. S., Wells, R. S., Fellner, W., & Janik, V. M. (2013). Vocal copying of individually distinctive signature whistles in bottlenose dolphins. *Proceedings of the Royal Society B: Biological Sciences*, *280*(1757), 20130053.

Kingston, J. D. (2007). Shifting adaptive landscapes: progress and challenges in reconstructing early hominid environments. *American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists*, *134*(S45), 20-58.

Koga, A., Tanabe, H., Hirai, Y., Imai, H., Imamura, M., Oishi, T., ... & Hirai, H. (2017). Co-opted megasatellite DNA drives evolution of secondary night vision in Azara's owl monkey. *Genome biology and evolution*, *9*(7), 1963-1970.

Kortlandt, A. (1980). How might early hominids have defended themselves against large predators and food competitors?. *Journal of human Evolution*, *9*(2), 79-112.

Kraft, T. S., Venkataraman, V. V., & Dominy, N. J. (2014). A natural history of human tree climbing. *Journal of Human Evolution*, *71*, 105-118.

Krasheninnikova, A., Berardi, R., Lind, M. A., O'Neill, L., & von Bayern, A. M. (2019). Primate cognition test battery in parrots. *Behaviour*, *156*(5-8), 721-761.

Krause, M. A., Udell, M. A., Leavens, D. A., & Skopos, L. (2018). Animal pointing: Changing trends and findings from 30 years of research. *Journal of Comparative Psychology*, *132*(3), 326.

Leavens, D. A., & Bard, K. A. (2011). Environmental influences on joint attention in great apes: implications for human cognition. *Journal of Cognitive Education and Psychology*, *10*(1), 9-31.

Kunda, Z. (1990). The case for motivated reasoning. *Psychological bulletin*, *108*(3), 480.

Kuypers, H. G. (1958). Some projections from the peri-central cortex to the pons and lower brain stem in monkey and chimpanzee. *Journal of Comparative Neurology*, *110*(2), 221-255.

Lameira, A. R., Hardus, M. E., Mielke, A., Wich, S. A., & Shumaker, R. W. (2016). Vocal fold control beyond the species-specific repertoire in an orang-utan. *Scientific reports*, *6*(1), 1-10.

Lameira, A. R. (2017). Bidding evidence for primate vocal learning and the cultural substrates for speech evolution. *Neuroscience & Biobehavioral Reviews*, *83*, 429-439.

Lee, R. B. (1979). The !Kung San: Men, women and work in a foraging society. Cambridge University Press.

Lefebvre, L., Nicolakakis, N., & Boire, D. (2002). Tools and brains in birds. *Behaviour*, *139*(7), 939-973.

Lemorini, C., Plummer, T. W., Braun, D. R., Crittenden, A. N., Ditchfield, P. W., Bishop, L. C., ... & Potts, R. (2014). Old stones' song: use-wear experiments and analysis of the Oldowan quartz and quartzite assemblage from Kanjera South (Kenya). *Journal of Human Evolution*, *72*, 10-25.

Lent, P. C. (1988). Ovibos moschatus. *Mammalian species*, (302), 1-9.

Lumsden, C. J., & Findlay, C. S. (1988). Evolution of the creative mind. *Creativity Research Journal*, *1*(1), 75-91.

Lyn, H. Apes and the Evolution of Language: Taking Stock of 40 Years of Research. In *The Oxford Handbook of Comparative Evolutionary Psychology*.

MacLean, E. L., Hare, B., Nunn, C. L., Addessi, E., Amici, F., Anderson, R. C., ... & Zhao, Y. (2014). The evolution of self-control. *Proceedings of the National Academy of Sciences*, *111*(20), E2140-E2148.

Manger, P. R., Spocter, M. A., & Patzke, N. (2013). The evolutions of large brain size in mammals: the 'over-700-gram club quartet'. *Brain, behavior and evolution*, *82*(1), 68-78.

Manser, M. B., Jansen, D. A., Graw, B., Hollén, L. I., Bousquet, C. A., Furrer, R. D., & Le Roux, A. (2014). Vocal complexity in meerkats and other mongoose species. In *Advances in the Study of Behavior* (Vol. 46, pp. 281-310). Academic Press

McCrae, R. R. (1987). Creativity, divergent thinking, and openness to experience. *Journal of personality and social psychology*, *52*(6), 1258.

McGrew, W. C. (2004). Primatology: advanced ape technology. *Current Biology*, *14*(24), R1046-R1047.

Milton, J., & Treffers-Daller, J. (2013). Vocabulary size revisited: the link between vocabulary size and academic achievement. *Applied Linguistics Review*, *4*(1), 151-172.

Mitchell, C. (2016). The evolution of brains and cognitive abilities. In *Evolutionary biology* (pp. 73-87). Springer, Cham.

Mongle, C. S., Strait, D. S., & Grine, F. E. (2019). Expanded character sampling underscores phylogenetic stability of Ardipithecus ramidus as a basal hominin. *Journal of Human Evolution*, *131*, 28-39.

Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G., & Worm, B. (2011). How many species are there on Earth and in the ocean?. *PLoS biology*, *9*(8), e1001127.

Moura, A. E., Kenny, J. G., Chaudhuri, R. R., Hughes, M. A., Reisinger, R. R., De Bruyn, P. J. N., ... & Hoelzel, A. R. (2015). Phylogenomics of the killer whale indicates ecotype divergence in sympatry. *Heredity*, *114*(1), 48-55.

Mullally, S. L., & Maguire, E. A. (2014). Memory, imagination, and predicting the future: a common brain mechanism?. *The Neuroscientist*, *20*(3), 220-234.

Nakamura, M., Hosaka, K., Itoh, N., Matsumoto, T., Matsusaka, T., Nakazawa, N., ... & Zamma, K. (2019). Wild chimpanzees deprived a leopard of its kill: implications for the origin of hominin confrontational scavenging. *Journal of Human Evolution*, *131*, 129-138.

Nekljudova, S. V. (2019). Six aspects of openness to experience. *Journal of Psychology and Clinical Psychiatry*, *10*(2).

Nelson, S. V. (2013). Chimpanzee fauna isotopes provide new interpretations of fossil ape and hominin ecologies. *Proceedings of the Royal Society B: Biological Sciences*, *280*(1773), 20132324.

Neubauer, S., Hublin, J. J., & Gunz, P. (2018). The evolution of modern human brain shape. *Science advances*, *4*(1), eaao5961.

Nissani, M. (2008). Elephant cognition: a review of recent experiments. *Gajah: Journal of the IUCN/SSC Asian Elephant Specialist Group*, *28*, 44-52.

O'Connell, J. F., Hawkes, K., & Jones, N. B. (1988). Hadza scavenging: Implications for Plio/Pleistocene hominid subsistence. *Current Anthropology*, *29*(2), 356-363.

Ólafsdóttir, H. F., Barry, C., Saleem, A. B., Hassabis, D., & Spiers, H. J. (2015). Hippocampal place cells construct reward related sequences through unexplored space. *Elife*, *4*, e06063.

Olkowicz, S., Kocourek, M., Lučan, R. K., Porteš, M., Fitch, W. T., Herculano-Houzel, S., & Němec, P. (2016). Birds have primate-like numbers of neurons in the forebrain. *Proceedings of the National Academy of Sciences*, *113*(26), 7255-7260.

Osvath, M., Kabadayi, C., & Jacobs, I. (2014). Independent evolution of similar complex cognitive skills: the importance of embodied degrees of freedom. *Animal Behavior and Cognition*, *1*(3), 249-264.

Pepperberg, I. M. (1981). Functional vocalizations by an African Grey parrot (Psittacus erithacus). *Zeitschrift für Tierpsychologie*, *55*(2), 139-160.

Pepperberg, I. M. (2006). Cognitive and communicative abilities of Grey parrots. *Applied Animal Behaviour Science*, *100*(1-2), 77-86.

Perlman, M., & Clark, N. (2015). Learned vocal and breathing behavior in an enculturated gorilla. *Animal Cognition*, *18*(5), 1165-1179.

Perlman, M. (2017). Debunking two myths against vocal origins of language: language is iconic and multimodal to the core. *Interaction Studies*, *18*(3), 376-401.

Peters, R. S., Krogmann, L., Mayer, C., Donath, A., Gunkel, S., Meusemann, K., ... & Niehuis, O. (2017). Evolutionary history of the Hymenoptera. *Current Biology*, *27*(7), 1013-1018.

Pietschnig, J., Penke, L., Wicherts, J. M., Zeiler, M., & Voracek, M. (2015). Meta-analysis of associations between human brain volume and intelligence differences: How strong are they and what do they mean?. *Neuroscience & Biobehavioral Reviews*, *57*, 411-432.

Pinker, S., & Bloom, P. (1990). Natural language and natural selection. *Behavioral and brain sciences*, *13*(4), 707-727.

Poole, J. H. & P. Granli. (2011). “Signals, Gestures, and Behavior of African Elephants.” in J., Croze, H., & Lee, P. C. (Eds.) The Amboseli Elephants: A Long-Term Perspective on a Long-Lived Mammal. Moss, C. University of Chicago Press, Chicago, Illinois: 109–127.

Ponce de León, M. S., Bienvenu, T., Marom, A., Engel, S., Tafforeau, P., Alatorre Warren, J. L., ... & Zollikofer, C. P. (2021). The primitive brain of early Homo. *Science*, *372*(6538), 165-171.

Püschel, H. P., Bertrand, O. C., O’reilly, J. E., Bobe, R., & Püschel, T. A. (2021). Divergence-time estimates for hominins provide insight into encephalization and body mass trends in human evolution. *Nature Ecology & Evolution*, *5*(6), 808-819.

Rendell, L., & Whitehead, H. (2001). Culture in whales and dolphins. *Behavioral and brain sciences*, *24*(2), 309-324.

Rice, W. R. (2022). Non-biological ‘paralife’ and its ongoing transition to a new form of mechanical life. *Preprints* **2022**, doi: xxxx/preprints2022xxxxxxxx).

Richards, D. G., Wolz, J. P., & Herman, L. M. (1984). Vocal mimicry of computer-generated sounds and vocal labeling of objects by a bottlenosed dolphin, Tursiops truncatus.. *Journal of Comparative Psychology*, *98*(1), 10.

Rilling, J. K., Scholz, J., Preuss, T. M., Glasser, M. F., Errangi, B. K., & Behrens, T. E. (2012). Differences between chimpanzees and bonobos in neural systems supporting social cognition. *Social cognitive and affective neuroscience*, *7*(4), 369-379.

Rivas, E. (2005). Recent use of signs by chimpanzees (Pan Troglodytes) in interactions with humans. *Journal of comparative psychology*, *119*(4), 404.

Roach, N. T., & Richmond, B. G. (2015). Clavicle length, throwing performance and the reconstruction of the Homo erectus shoulder. *Journal of Human Evolution*, *80*, 107-113.

Roelofs, Y. C. (2010). Tool use in birds: An overview of reported cases, ontogeny and underlying cognitive abilities. *Unpublished MSc thesis, University of Groningen, Biological Centre, The Netherlands*.

Ruff, C. B., Burgess, M. L., Ketcham, R. A., & Kappelman, J. (2016). Limb bone structural proportions and locomotor behavior in AL 288-1 (" Lucy"). *PloS one*, *11*(11), e0166095.

Rutz, C., & St Clair, J. J. (2012). The evolutionary origins and ecological context of tool use in New Caledonian crows. *Behavioural Processes*, *89*(2), 153-165

Sanes, J. R., & Yamagata, M. (2009). Many paths to synaptic specificity. *Annual Review of Cell and Developmental*, *25*, 161-195.

Schacter, D. L., Addis, D. R., Hassabis, D., Martin, V. C., Spreng, R. N., & Szpunar, K. K. (2012). The future of memory: remembering, imagining, and the brain. *Neuron*, *76*(4), 677-694.

Schacter, D. L., & Addis, D. R. (2020). Memory and imagination: Perspectives on constructive episodic simulation. *The Cambridge handbook of the imagination*, 111-131.

Schick, K. D., Toth, N., Garufi, G., Savage-Rumbaugh, E. S., Rumbaugh, D., & Sevcik, R. (1999). Continuing investigations into the stone tool-making and tool-using capabilities of a bonobo

(Pan paniscus). *Journal of Archaeological Science*, *26*(7), 821-832.

Schultheiss, P., Nooten, S. S., Wang, R., Wong, M. K., Brassard, F., & Guénard, B. (2022). The abundance, biomass, and distribution of ants on Earth. *Proceedings of the National Academy of Sciences*, *119*(40), e2201550119.

Shi, B., Dai, D. Y., & Lu, Y. (2016). Openness to experience as a moderator of the relationship between intelligence and creative thinking: A study of Chinese children in urban and rural areas. *Frontiers in psychology*, *7*, 641.

Simonyan, K., & Jürgens, U. (2003). Efferent subcortical projections of the laryngeal motorcortex in the rhesus monkey. *Brain research*, *974*(1-2), 43-59.

Sinclair A. R. E. 1977. The African buffalo. Chicago: University of Chicago Press.

Slocombe, K. E., & Zuberbühler, K. (2007). Chimpanzees modify recruitment screams as a function of audience composition. *Proceedings of the National Academy of Sciences*, *104*(43), 17228-17233.

Smith, M. K., Trivers, R., & von Hippel, W. (2017). Self-deception facilitates interpersonal persuasion. *Journal of Economic Psychology*, *63*, 93-101.

Szathmáry, E., & Maynard-Smith, J. (1995). The major evolutionary transitions. *Nature*, *374*(6519), 227-232.

Tager-Flusberg, H., Rogers, S., Cooper, J., Landa, R., Lord, C., Paul, R., ... & Yoder, P. (2009). Defining spoken language benchmarks and selecting measures of expressive language development for young children with autism spectrum disorders.

Tomasello, M., Carpenter, M., & Liszkowski, U. (2007). A new look at infant pointing. *Child development*, *78*(3), 705-722.

Toth, N.P. and Schick, K.D. eds. (200)6. The Oldowan: case studies into the earliest stone age. Bloomington: Stone Age Institute Press.

Trut, L., Oskina, I., & Kharlamova, A. (2009). Animal evolution during domestication: the domesticated fox as a model. *Bioessays*, *31*(3), 349-360.

Tsuboi, M., van der Bijl, W., Kopperud, B. T., Erritzøe, J., Voje, K. L., Kotrschal, A., ... & Kolm, N. (2018). Breakdown of brain–body allometry and the encephalization of birds and mammals. *Nature Ecology & Evolution*, *2*(9), 1492-1500.

Van Valen, L. (1977). The red queen. *The American Naturalist*, *111*(980), 809-810.

Van Valkenburgh, B. (2001). The dog-eat-dog world of carnivores: a review of past and present carnivore community dynamics. *Meat-eating and human evolution. Oxford University Press, Oxford*, 101-121.

Visalberghi, E., Sirianni, G., Fragaszy, D., & Boesch, C. (2015). Percussive tool use by Taï Western chimpanzees and Fazenda Boa Vista bearded capuchin monkeys: a comparison. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1682), 20140351.

Visalberghi, E., Sabbatini, G., Taylor, A. H., & Hunt, G. R. (2017). Cognitive insights from tool use in nonhuman animals. In *APA handbook of comparative psychology: Perception, learning, and cognition, Vol. 2* (pp. 673-701). American Psychological Association.

Von Hagen, V. W. (1942). Natural History of Termites: I. *The Scientific Monthly*, *54*(6), 489-498.

Wang, X., Zhuang, K., Li, Z., & Qiu, J. (2022). The functional connectivity basis of creative achievement linked with openness to experience and divergent thinking. *Biological Psychology*, *168*, 108260

Weiss, S., Steger, D., Schroeders, U., & Wilhelm, O. (2020). A reappraisal of the threshold hypothesis of creativity and intelligence. *Journal of Intelligence*, *8*(4), 38.

Werdelin, L., & Lewis, M. E. (2013). Temporal change in functional richness and evenness in the eastern African Plio-Pleistocene carnivoran guild. *PLoS One*, *8*(3), e57944.

Westen, D., Blagov, P. S., Harenski, K., Kilts, C., & Hamann, S. (2006). Neural bases of motivated reasoning: An fMRI study of emotional constraints on partisan political judgment in the 2004 US presidential election. *Journal of cognitive neuroscience*, *18*(11), 1947-1958.

Wilkins, A. S., Wrangham, R. W., & Fitch, W. T. (2014). The “domestication syndrome” in mammals: a unified explanation based on neural crest cell behavior and genetics. *Genetics*, *197*(3), 795-808.

Winberg, M. L., Mitchell, K. J., & Goodman, C. S. (1998). Genetic analysis of the mechanisms controlling target selection: complementary and combinatorial functions of netrins, semaphorins, and IgCAMs. *Cell*, *93*(4), 581-591.

Woolgar, A., Duncan, J., Manes, F., & Fedorenko, E. (2018). Fluid intelligence is supported by the multiple-demand system not the language system. *Nature Human Behaviour*, *2*(3), 200-204.

Yang, C. (2013). Ontogeny and phylogeny of language. *Proceedings of the National Academy of Sciences*, *110*(16), 6324-6327.

Yu, Y., Karbowski, J., Sachdev, R. N., & Feng, J. (2014). Effect of temperature and glia in brain size enlargement and origin of allometric body-brain size scaling in vertebrates. *BMC evolutionary biology*, *14*(1), 1-14.

Zhang, W., Sjoerds, Z., & Hommel, B. (2020). Metacontrol of human creativity: The neurocognitive mechanisms of convergent and divergent thinking. *NeuroImage*, *210*, 116572.

Zhu, W., Shang, S., Jiang, W., Pei, M., & Su, Y. (2019). Convergent thinking moderates the relationship between divergent thinking and scientific creativity. *Creativity Research Journal*, *31*(3), 320-328.

Zink, K. D., & Lieberman, D. E. (2016). Impact of meat and Lower Palaeolithic food processing techniques on chewing in humans. *Nature*, *531*(7595), 500-503.

Zuberbühler, K. (2008). Gaze following. *Current Biology*, *18*(11), R453-R455.

Supplementary Figures and Text on on the following pages

Supplemental text S1. A plausible pathway for simple words to have evolved far in advance of the emergence of the genus *Homo*

Because, as detailed in the main text, all great apes have all the prerequisite traits needed to communicate with spoken words except volitional phonation, word-based communication may have evolved very early in the hominin lineage –far in advance of the use of flaked-stone tools and the emergence of the genus *Homo*. I begin by focusing on pointing as a form of joint attention that can lead to the use of spoken words.

Pointing is a form of communication that commonly precedes the use of words in infant humans, but only by one or a few months – pointing typically begins at age 11-12 months (Tomasello et al. 2007; Colonnesi et al. 2010). Pointing generates joint attention when it is unambiguous what feature the pointer is pointing toward, and joint attention may be a prerequisite for communicating with learned words (Tomasello et al. 2007). Pointing can also generate a need for words to identify the target of pointing when it is ambiguous. Field studies have found few examples of pointing in wild populations of great apes, while studies of captive animals, especially those with substantial interactions with humans, report many examples across all great ape species (Krause et al. 2018). This observation, and many other lines of evidence reviewed in Leavens and Bard (2011), clearly demonstrate that all great apes are capable of learning to point, despite rarely doing so in nature. As a consequence, there is substantial confidence that the cognitive ability to learn to point and understand its meaning would have been present in the hominin lineage at the time that they diverged from the chimpanzee/bonobo lineage.

When early hominins began using open woodlands and savannas after their split from the chimpanzee/bonobo lineage (estimated to be sometime between 5-8 mya based on fossil evidence; Kingston 2007), the field of view from positions within trees would have expanded substantially. It would have been, at most, a narrow region immediately beneath a tree in a dense, multi-tiered forests, but expanded to a much wider panorama in open woodlands and savannas.

To understand the significance of this change in arboreal view, consider a troop of hominins foraging at a savanna or open-woodland location where most resources are located near the ground (Supplemental Figure S1). Early hominins, based on data from *A. ramidus* at ~4-5 mya, had greatly reduced canines, no stone tools and slow running speed: so their major defense against large predators would necessarily have been an arboreal 'escape in space' (Clark and Henneberg 2015; Nelson 2017; Mongle et al. 2019). When foraging on the ground in an open savanna habitat, resource acquisition rate would be increased but so too would predation risk. Once the acquired resources of an individual reach a point where the benefit of continued foraging near the ground was less than the increased cost of predation, a troop member would be expected to retreat to a safe position within a proximate tree. This repositioning would lead to some troop members (sufficiently sated) being located in trees while the others (not sufficiently sated) remained foraging on the ground (Supplemental Figure S1). As a consequence, a troop would be partitioned into safe arboreal individuals with a panoramic 'lookout' view and unsafe ground-foragers with a substantially more restricted view. Put another way, the common occurrence of a 'lookout' phenotype would be a fortuitous consequence of early hominins beginning to forage predominantly near the ground in an open woodlot or savanna habitat.

A situation similar to the one described above can be found at present in meerkats and dwarf mongoose that forage in troops within open habitats –for which we have an extensive body of field research. Here one or more sated individuals move to positions in trees or bushes (or other high points with a panoramic view) and act as sentries by producing functionally referential alarm calls (indicating the type of predator and its threat level, determined mainly by a predator's distance from the troop) that alert foraging individuals (with highly restricted views) of predation threats (Clutton-Brock et al. 1999; Clutton-Brock 2009; Manser et al. 2014). They also produce a recurrent 'watchman song' vocalization that indicates a less specific, general level of perceived threat. The presence of the sentry phenotype (lookout) in these two mongoose species is associated with by far the highest diversity of instinctual and vocal communication signals in the form of functionally-referential alarm calls (Clutton-Brock et al. 1999; Manser et al. 2014; Clutton-Brock 2009).

Consider a sated A*ustralopithecus* individual positioned in a tree (hereafter a 'lookout') with ground-foraging individuals nearby (Supplemental Figure S1). Next consider a situation that will inevitably and recurrently occur in which a lookout sees a resource that it cannot access, e.g., an ungulate fawn hiding in the grass below, which because of intervening vegetation, is undetected by the ground foragers. Because the ground foragers will soon flush the fawn from it hiding location, and because the unsuspecting ground-foragers are unlikely to capture the fawn due to its superior agility and running speed, the fawn represents a resource that can be seen by the lookout but not accessed.

Caged chimpanzees are observed to make nonvocal sounds like 'raspberries' to attract the attention of a nearby human and then point to out-of-reach food items that cannot be accessed (reviewed in Lameria 2017; Perlman 2017). This behavior is not universal and occurs primarily in animals which have had many interactions with humans and formed an expectation that humans will provide helping, prosocial behaviors (Lameria 2017). The substantial fossil evidence for self-domestication in A*ustralopithecus* (that first evolved earlier in *Ardipithecus; Mongle et al. 2019*) indicates that food sharing would be expected in these hominins –as it is currently observed in self-domesticated bonobos (Hare et al. 2012) and marmosets (Ghazanfar et al. 2020) that have a lesser degree of the domestication-syndrome phenotypes. As a consequence, an expectation of helpful prosocial behaviors plausibly also would be present in these early hominins –generating selection for the pointing and nonvocal sounds like raspberries that occur between captive chimpanzees and humans in the present-day. Because the pointing and volitional sound components (nonvocal) are learned phenotypes, they can accumulate via cultural evolution at far faster rate than would be expected if they required genetic evolution. Note also that the look-at-me vocalization would need to be volitional because a wide array of different resources would need to trigger the call (e.g., an ostrich nest, a nutritious patch of mushrooms or berries, a subterranean bees' nest with honey, or a rare tuber plant), all of which could be obscured from ground foragers –but not arboreal lookouts– by intervening vegetation (Supplemental Figure S1).

The pointing part of this two-part volitional-sound/pointing phenotype would plausibly begin more simply with gazing at the overlooked resource (Zuberbühler 2008) and then later be replaced by learned pointing because from a distance it less ambiguously indicates the location of the target of the gaze. So without the need for new adaptations except the preadaptation of food-sharing due to self-domestication, lookout A*ustralopithecus* hominins that observed resources that they perceived to be overlooked by ground-foragers would be expected to learn to attract attention to themselves with a volitional, nonvocal 'look-at-me' sounds (like raspberries) and then gaze at the overlooked resource –and eventually learn to point to the resource. The extant capacity for all great apes to pass-on learned traits culturally (Rendell and Whiten 2001) indicates that A*ustralopithecus* hominins would be able to pass-on across generations the pointing/nonvocal-look-at-me-sound phenotype once it was initially learned. Nonvocal sounds like raspberries have a substantially limited volume and are therefore restricted to close-distance communication. The benefit of extending the range of the look-at-me sound-signal would generate selection for a volitional vocal sound because it has much higher potential volume.

To summarize to this point, the lookout phenotype that would fortuitously have occurred in early hominins when they moved into an open habitat would have generated selection for a volitional look-at-me sound-signal (like a nonvocal raspberry) in combination with gazing at the target of interest. The ambiguity of the target of a gaze when viewed from a distance would select for the gaze to be augmented by pointing. Studies of extant great apes indicate that early hominins would have been able to learn to make volitional nonvocal look-at-me sound-signals followed by gazing and pointing, so the look-at-me/pointing phenotype could develop via learning and cultural evolution –and therefor require no new genetic evolution. Once the non-vocal volitional look-at-me sound-signal developed (like a raspberry) it would necessarily be limited to short distance communication and therefore generate selection for a vocal volitional look-at-me sound-signal that was capable of longer-distance communication. This transition, non-vocal look-at-me signal ➔ vocal look-at-me signal, however, would require new evolution to make it possible: the evolution of volitional vocalization, which as described in the main-text, is a trait that substantial empirical evidence indicates would have a high a capacity to readily respond to selection (high evolvability), and hence one that could evolve at a nontrivial rate once selectively favored.

To illustrate how vocal look-at-me signals could expand to learned words, contrast two types of resource sightings by a lookout hominin when ground-based foragers were present. The first type of sighting is, as described above, a hiding ungulate fawn in tall grass. The second type of sighting is a male ostrich incubating its nest of eggs in tall grass (Supplemental Figure S1). To capture the fawn, the ground-foragers would optimally surround the pointed-to location in order to insure that there was no escape route for the fawn –which has a much higher running speed and agility compared to the hominins. To capture the eggs from the ostrich nest, the ground-foragers would optimally approach as a group from one side in order to use their numbers to intimidate the highly dangerous ostrich while also providing a clear pathway for it to flee once an escape response was triggered. If the lookout only vocalized a generic look-at-me call and then pointed to the resource, the ground-foragers would not know the identity of the resource that was being pointed out, and this ambiguity (which could lead to a very costly error in the ground-foragers' response in the case of the ostrich eggs) would select for a resource-specific vocalization to remove the uncertainty, i.e., it selects for a word to replace, or be appended to, the look-at-me vocalization. Similar reasoning would apply to replacing a generic look-at-me sound with volitional words when the target of pointing is a threat like a predator, when different responses are optimal for different predators (leading to a learned word analog for a functionally-referential alarm call).

The lookout phenotype would also plausibly lead to learned word-like vocal names for individuals, as have evolved in parrots (Berg et al. 2012) and dolphins (King et al. 2013). For example, consider a lookout who sees a resource, like a large nutritious mushroom concealed from a ground-forager by intervening vegetation –and therefore likely to be overlooked (Supplemental Figure S1). A generic vocal look-at-me/point procedure would unnecessarily disrupt the foraging of additional ground-foragers because the information only applies to the single ground-forager near the resource. It would be selectively favorable for the look-at-me vocalization to be replaced by calling out a learned name for the appropriate individual, thereby increasing the net gain to the troop.

The evolution of protolanguage via simple words from lookouts directed to ground-foragers would be expected to increase the effectiveness of foraging and predator defense, as has occurred in social mongoose species in the context of instinctual functionally-referential alarm calls and watchman's songs (Clutton-Brock et al. 1999). Because the words are learned, such an evolutionary event would be expected to select for increased learning and memory ability (to learn and remember what specific words mean, when and how to use them, and how to respond to them when heard) and hence plausibly select for an increase in brain size. But such simple and limited repertoire of words by themselves would be expected to generate only a transient pulse of brain size increase –one sufficient to accommodate use of the limited vocabulary needed for naming features like resources, individuals, and threats/threat-levels. As described in the following paragraph, the expected pulse on brain size increase is observed in the early evolution of the *Australopithecus* lineages.

Australopithecus lineages that evolved subsequent to *Ardipithecus ramidus* developed substantial variation in body size that was consistently smaller than the size of both *A. ramidus* and chimpanzees (Figure 2; data from Püschel et al.. 2021). But despite this body size variation, all *Australopithecus* lineages retained highly similar brain sizes that were consistently larger than that of both *A. ramidus* and chimpanzees (Figure 2; data from Püschel et al.. 2021). Put another way, despite high variation in body size, all *Australopithecus* lineages were smaller than present day chimpanzees, but they all had brains nearly as large at that of present day gorillas –despite the high metabolic cost of brain tissue (Aiello and Wheeler 1995). This brain size pattern differs markedly from bonobos: a species that also evolved low-aggression/self-domestication but have brains that are ~10% smaller than those of chimpanzees (Rilling et al. 2011). Some difference between the selective regimes experienced by the *Australopithecus* and bonobo lineages that favored a larger brain in the hominins must have lead to a difference in the direction of the trajectories of their brain size evolution. Use of words in the *Australopithecus* lineages plausibly explains this difference.

Supplemental Text S2. Perimeter defense without volitional vocal words.

In nature there are unambiguous examples of a perimeter defense against predators that function without the use of vocal volitional words. This observation would seem to refute the deduction that a mobile perimeter defense by early *Homo* hominins required such words. However, closer examination of such animal perimeter defenses show that this is not the case.

For example, muskoxen form a stationary closed-ring (perimeter) defense against wolf attacks. Adult animals line-up side-by-side facing outward and more vulnerable juveniles are enclosed within the ring (e.g., see Lent 1988). When attacked from a forward-facing position, the muskoxen's superior strength and large horns can readily repel the much smaller wolves. Nonetheless, wolves sometimes circumvent the muskoxen's perimeter defense by repeatedly harassing individual muskoxen and eventually causing it to panic and break formation –which can lead to panic of neighboring muskoxen and eventually to a more widespread panic and stampeding of the whole herd. During the stampede, the wolves repeatedly use their fangs to lacerate the poorly protected hind quarters of muskoxen and eventually cause an animal to become immobile (and vulnerable to further injury and death) due to blood loss and damage to leg muscles and connective tissue. In this example, the muskoxen have a functional (but precarious) stationary perimeter defense without volitional vocal words. This perimeter defense, however, is prone to occasional catastrophic breakdown due to harassment-induced panic among the muskoxen, and it lacks the mobility that hominins would need.

African elephants also have a closed-ring defense behavior that is similar to that of muskoxen (referred to as 'bunching' and including a matriarch and her extended family) with the smaller and vulnerable juvenile individuals enclosed by the ring (Poole and Granli 2011). The defense ring becomes disorganized when the elephants move away from a threat but an adult female positions herself a few meters behind the departing group and will charge at trailing predators that get too close: a procedure that would not have been functional for small hominins against much larger predators, especially when they attack in groups.

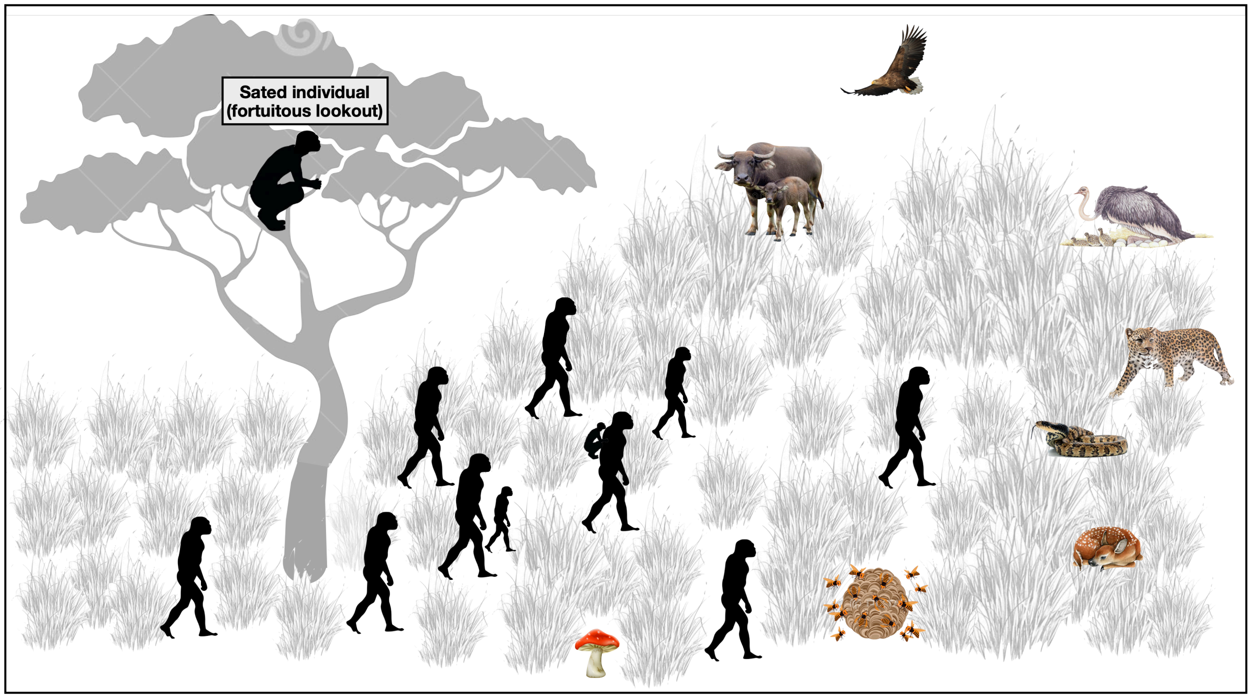
When defending against predators like lions, African buffalo form dense clusters that are far less organized than the closed-ring defenses of muskoxen and African elephants but nonetheless protect vulnerable juveniles by sheltering them within centrally located regions (Sinclair 1977). Lions entering the cluster are attacked and sometimes killed. These clusters are stationary and do not have an organized process for movement. The large size and strength disparity between adult African buffalos and their predators enables them to tolerate occasional penetration of predators into the interior of the cluster and injuries from short-duration attacks from any direction: a situated that would be fatal for small hominins against much larger predators.

All of the examples of perimeter defenses described above rely on the defender being larger, more powerful, and having anatomical weapons like horns, tusks and/or a strong grasping trunk that provides overwhelming protection from a frontal assault by the smaller predators, and also an ability to withstand occasional wounding during defense. In sharp contrast, hominins were smaller, weaker and lacked sufficient anatomical weapons against the predators in the LgCar-guild. Also, occasional wounding during defense against these large predators would be expected to commonly be fatal. Suitable fabricated weapons like thorn branches (structural-UPs) could plausibly generate the same level of frontally-directed protection as the large bodies and anatomical weapons of muskoxen, African elephants and African buffalo –so a stationary defense without words would also seem to be plausible for hominins without a requirement for vocal volitional words (and assuming that panicked individuals did not compromise the defense too frequently). But hominins would have needed to seek safe nighttime shelter due to their poor night vision. They would also need a mobile perimeter defense to displace extant predators from a kill site when they obtained prey via kleptoparasitism, and to move safely across the landscape in the context of hunting or moving to new sites for kleptoparasitism. It is the mobile component of the mobile perimeter defense system that is the primary factor generating the requirement for vocal volitional words to achieve sufficient teammate coordination.

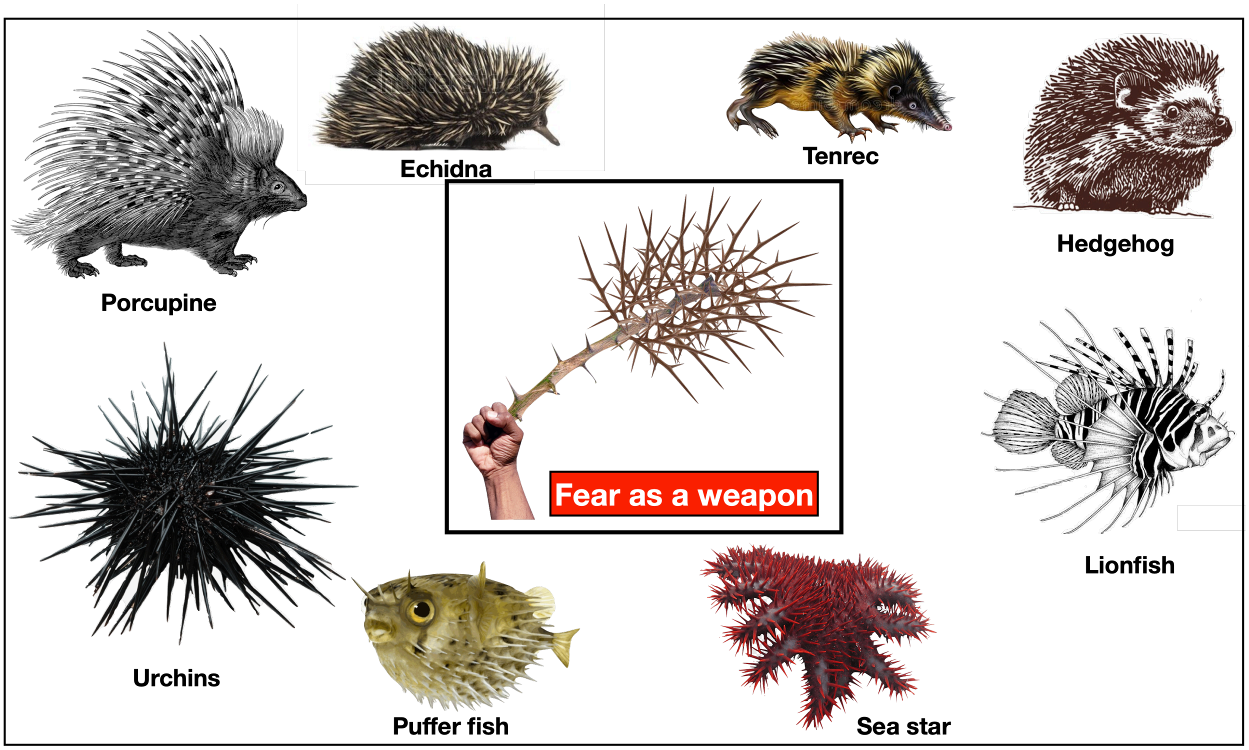
I next use a series of examples illustrating the need for vocal volitional words to coordinate a mobile perimeter defense. First, when hominins in the rear of a moving perimeter defense are forced to abruptly stop due to one of many possible reasons (e.g., to repel a challenging predator, help a fallen teammate, or recover from: stumbling, stepping on a thorn, a cramped leg, or a twisted ankle) and do not signal this problem to the hominins in the front of the perimeter defense via a volitional vocal word(s), a gap in the defense would develop and thereby compromise the perimeter defense. The vocal signal must be volitional because many different sensory inputs must be integrated to generate the appropriate 'stop moving forward' vocal signal: so a simple and innate stimulus-response sound signal (like an alarm call in response to a predator) would be insufficient. Second, when hominins in the front of a moving perimeter defense observe any of many different features that could trip or hinder the advance of the backward-facing rearguard of a forward-moving perimeter defense, and do not signal this problem via a volitional vocal word(s), a gap in the defense would develop when the hominins in the rear tripped, stubbled or in some other way were delayed: thereby compromise the perimeter defense. Third, if the movement of the group was determined by a lead individual (e.g., an older and/or more experienced individual), then the the leader would have to integrate complex and fast-changing information, formulate a decision about what to do next (e.g., stop, go forward, reverse, retreat) and communicate this decision to teammates that are not in visual contact via volitional vocal words. Fourth, when in a seemingly safe context (e.g., after a prolonged lull in predator attacks and/or detections during retreat from a kill site) one teammate detects a stalking large predator and does not alert, via a vocal volitional word(s), other teammates with views in other directions, the other teammates will be prone to being caught off-guard, panic when surprise-attacked, recoil away from the attacker, and generate a gap in the perimeter defense: thereby compromising the moving perimeter defense. Fifth, even at times when the mobile perimeter defense is stationary (e.g., when surrounding an animal being butchered) some teammates (e.g., those that are younger, less experienced, and or more susceptible to panic) within a perimeter defense will be prone to developing panic and recoil backward (or in some other way become ineffectual) when repeatedly harassed by peripheral predators (as occurs in muskoxen). When such nearing-panic teammates were detected by neighboring teammates they would need to use vocal volitional words to recruit help from out-of-sight regions of the defense that were less compromised: and thereby make the defense less prone to failure.

These examples illustrate why volitional vocal words were essential to coordinate the actions of a functional mobile perimeter defense by hominins: without them the defense is too uncoordinated and prone to failure. They also illustrate how an increased diversity of vocal volitional words would be expected to increase the level of teammate coordination and thereby increase the efficacy of the mobile perimeter defense and enable it to expand over time to new and more challenging applications.

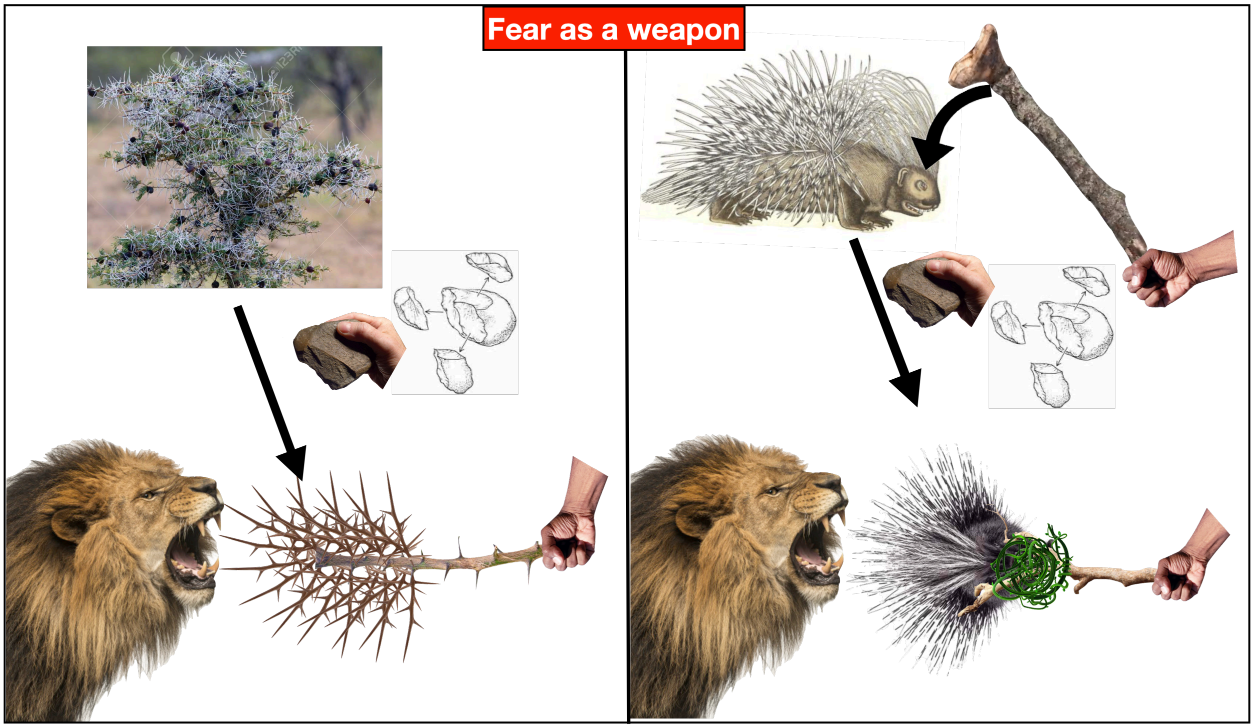
Other high-intelligence species like chimpanzees (Boesch 2002) and dolphins (Gazda et al 2005) have evolved a capacity for learning-based cooperative hunting, despite not using volitional words to coordinate this complex group behavior. The cooperative hunting by chimpanzees and dolphins is complex because it includes the integration of individuals that carry out different and complementary hunting roles. What distinguished the mobile perimeter defense of early hominins was the need to coordinate group-wide behaviors based on complex information that: i) is only available to part of the group, and ii) needs to be analyzed and interpreted to generate a vocal signal that induces an appropriate response by the entire group –including out-of-sight teammates. The vocal signal must be volitional because the mental processing required to generate the appropriate signal is too complex to be achieved via simple and innate stimulus-response signaling, e.g., like an alarm call.



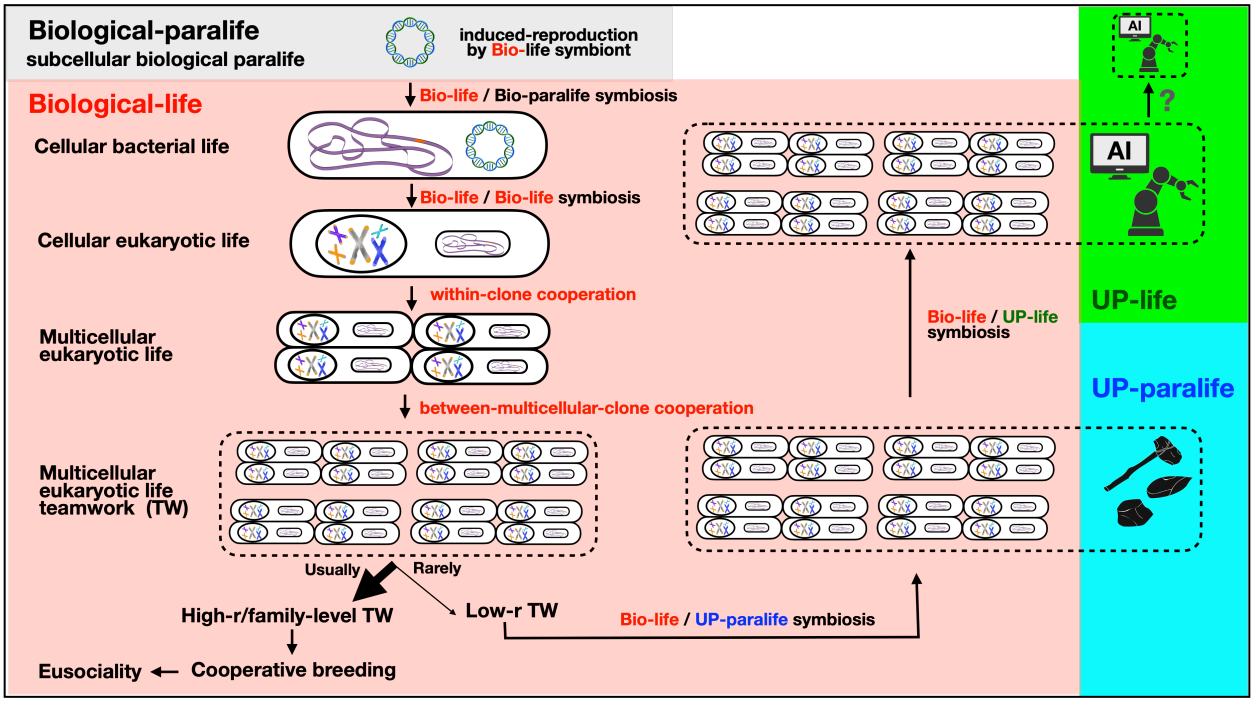
Supplemental Figure S1. Hominin lineages that lived in a savanna or open woodland environment, like those in the early stages of the genus *Australopithecus,* were selected to evolve volitional phonation and learn to use volitional spoken words. The hominin is assumed to have previously evolved sufficient self-domestication to promote food-sharing. Also, most food resources are assumed to be located on or near the ground. Sated individuals are further assumed to move to nearby and elevated arboreal locations because of the safety of these sites. Once located in an elevated tree location, a sated individual has a fortuitous 'lookout' phenotype that has an enhanced ability to see items on the ground that are not visible to ground-foraging individuals due to intervening upright vegetation. Many different features (colored items in the figure) that only can be seen by the lookout individuals produce selection for volitional vocalizations to i) call attention to the lookout, and ii) communicate what the lookout has seen via gaze, pointing, and simple volitional words, as described more fully in the main text and Supplementary Text S1.



Supplemental Figure S2. Many different animal taxa that are small, slow-moving, and/or poorly defended from predators by anatomical weapons have independently evolved spines as a 'weapon-of-fear'.



Supplemental Figure S3. Oldowan flaked-stone tools could be used to fabricate two different types of 'weapons-of fear': **Left:** thorn branches from acacia and other species (Kortlandt 1980; Guthrie 2007) and **Right:** the skins of porcupines (with spines attached) that had been clubbed to death and then attached to the ends of wooden branches.



Supplemental Figure S4. The relationship between UP-paralife and some of the major complexity transitions that occurred during the evolution of biological life (Szathmary and Maynard-Smith 1995). Biological paralife is shown in the region with grey background (left-top of figure) and must induce its reproduction in a biological life-form. The increasing levels of complexity in biological life are shown in the region with pink background. Once high-intelligence animals learned to fabricate UPs with sufficient UP-evolvablity, UP-paralife emerged (blue background) and its symbiosis with its biological fabricator gave rise to a new and advanced level biological complexity (Bio-life/UP-paralife symbiosis). UP-paralife and its biological symbiont can then coevolve via cultural evolution and genetic evolution, respectively. This coevolution has the potential to lead to the evolution of non-biological UP-life (aka mechanical life, green background), that can potentially self-perpetuate in the absence of biological life (as described in the companion paper Rice 2022).

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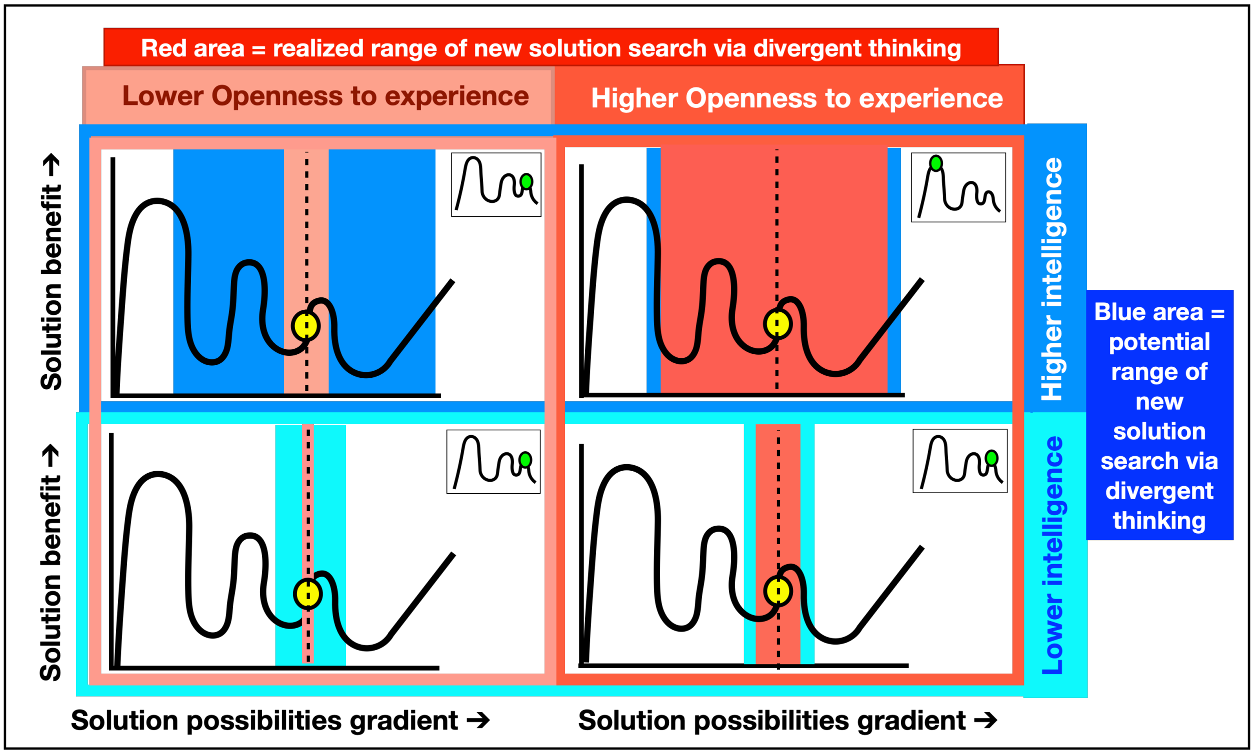

Supplemental Figure S5. A creative-solutions landscape model that integrates the joint influences of intelligence, openness-to-experience, and convergent and divergent thinking on creative problem solving. The model incorporates three well established empirical relationships by assuming that: i) higher intelligence increases convergent thinking ability (Zhang et al. 2020) and the potential for divergent thinking (meta-analysis by Karwowski et al. 2016 and see also Weiss et al. 2020), ii) higher openness-to-experience increases the potential for divergent thinking (meta-analysis by McCrae 1987) and thereby facilitates novel solutions to problems through increases in intellectual curiosity, an aesthetic appreciation and emotional attraction to novel perspectives irrespective of their utility, vivid and beyond-norms imagination, and the use of adventurous trial-and-error (DeYoung et al. 2005; Nekljudova 2019), iii) there is a strong interaction between the influences of intelligence and openness to experience on divergent thinking such that when either factor is low it strongly reduces the influence of higher values from the other factor (Shi et al. 2016; Harris et al. 2019; Zhu et al. 2019). The height of the black curves represents the perceived benefit (Y-axis values) of different solutions (X-axis values) to a problem and is estimated via convergent thinking. The possible solutions are arranged along the X-axis as a gradient, such that increased distance between X-axis points represents more divergent solutions. Higher intelligence is assumed to substantially expand the potentially searchable region on the X-axis due to its strong positive association with divergent thinking ability (blue area in each graph centered at a specified starting solution [yellow circle]). The realized searchable region on the X-axis (a central subset of the potentially searchable region) is determined by the level of openness to experience (central red area within the blue area in each graph). Higher openness to experience increases the proportionate size of this central subset of the potentially searchable region because it increases the propensity to use divergent thinking to explore more divergent solutions. The yellow dot represents an established solution to an extant problem or the solution initially generated by intuition when confronted with a new problem. When thinking about a better solution to a problem, the thought process first evaluates (using convergent thinking to estimate benefits) all solutions within the realized evaluation range (red region) and identifies the solution with the highest perceived benefit. Starting at this perceived highest benefit solution, the second step of the thought process uses convergent thinking to find the highest local solution-benefit peak by recurrently generating the benefit of neighboring solutions and then moving uphill on the black curve in the direction away from the nearest local solution-benefit valley. The final solution is depicted by the green point on the small inset curve located in the top right corner of each quadrant. Highly creative solutions via divergent thinking are generated by a combination of higher intelligence and higher openness to experience that enable the solution search to be broader and able to cross wider landscape valleys and thereby find better solutions despite their novelty.