Perspective

Phase transitions of brain evolution that produced human language and beyond

Rafael Vieira Bretas\textsuperscript{a,b,*}, Yumiko Yamazaki\textsuperscript{a}, Atsushi Iriki\textsuperscript{a,b}

\textsuperscript{a} Laboratory for Symbolic Cognitive Development, RIKEN Center for Biosystems Dynamics Research, Kobe, Japan
\textsuperscript{b} Azrieli Brain, Mind & Consciousness Program, Canadian Institute for Advanced Research, Canada

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\textbf{A B S T R A C T}

The brain capacity of human ancestors underwent two phase transitions, which were supported by preadaptations during the animal protolanguage period, resulting in the emergence of human language. The transitions were (1) the emergence of the primate cerebral cortex, with its unique characteristic of additional cortical areas together with size expansion, and (2) the replacement of natural selection as the main evolutionary mechanism by \textit{triadic niche construction}, an interactive expansion of ecological-, neural-, and cognitive-niches. These phase transitions accelerated the expansion of the hominid brain, exceeding the neural capacity threshold required for the emergence of language. Extrapolating these developments enabled the researchers to predict a third phase transition, which may be induced by the current explosion of artificial intelligence, accelerating human cognitive capacities to the next threshold required for a novel mode of language.

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\textbf{1. Introduction}

The semantic richness and syntactic complexity of human language far exceeds those of nonhuman animals (hereinafter simply “animals”), with the required cognitive support that most likely originated from the sheer size of the human neocortex (Dunbar, 1993). However, despite encephalization and linguistic differences between humans and animals, fundamental structures and latent capacities subserving communication in humans must also be present in precursory forms in animal brains. These could be in the form of biological preadaptations that, given the right conditions, would result in sudden, phase transition-like (“Évolution du volume cérébral des Hominidés,” n.d.) development, such as that which occurred during the Paleolithic hominid brain, coinciding with the onset of lithic technology (Fig. 1). Although the hominid brain dimensions may not be beyond the expected for a primate of such body weight (Azevedo et al., 2009; Herculano-Houzel et al., 2015), its expansion happened rapidly, tripling in size within
Mousterian Culture

Acheulean Culture

Oldowan Culture

Fig. 1. Transition of cranial capacity (ordinate) along the evolutionary process of various ancestral prehominids and hominids (abscissa) (adapted from “Evolution du volume cérébral des Hominides,” n.d.). Inset illustrations of a skull and brain depict representative hominids plotted on the graph. Brain expansion suddenly accelerated when Homo Habilis started manufacturing and using stone tools (oblique red arrow). Insets of stone tools (top left) depict the development level of stone tools in each culture. Oldowan culture: The earliest widespread stone tools were simple, usually made with one or a few flakes chipped off with another stone, used by Homo Habilis. Acheulean culture: Stone tools characterized by distinctive oval and pear-shaped “hand-axes,” manufactured and used by Homo Erectus. Simple syntax in vocal communication, a primitive form of human language, is thought to have been required for the transmission of this culture. Mousterian culture: Technically complex and significant archaeological industry of lithic tools developed from Homo Sapiens Neanderthalensis throughout early Homo Sapiens Sapiens. Complex and rich semantic contents and syntax, close to modern human language, were necessary for the transmission and inheritance of this culture.

2. Preadaptations in the brain mechanisms of animals’ protolanguage and the first phase transition

2.1. Gradual expansion of the nervous system

During animal evolution, the brain emerged as a rostral-most ampulla of the nervous system to process information regulating internal (through the autonomic nervous system) and external (through the somatic nervous system) bodily movements. In addition to evolution making animals’ bodies larger and more complex, the nervous system increased in size and complexity to connect input (sensory) and output (motor) organs for survival and adaptation to environmental conditions. As evolution proceeded, bilateral animals with a symmetric body and the resulting ability of moving along a main axis of their body plan, developed a vector of sensory-neuro-motor information flow following their movement direction. The front extremity, as the first part to encounter a stimuli, concentrated the feeding and sensory organs, forming the head. This resulted in the accumulation of nervous functions in this end of the body leading to cephalization, with one species after another appearing equipped with a neuraxis, higher centers, and eventually a telencephalon and cerebral cortex (Fig. 3B). Such enlarged brain parts, initially devoted solely to generating sensory-
induced motion, gradually developed the capacity for cognition and communication, with some species acquiring language-like capacity. Similarly in humans, this underlying sensorimotor processing machinery culminated in the formation of a symbolic system (Fig. 3A) intrinsically associated with human language (Cassirer, 1944).

However, unlike the lengthy processes commonly associated with anatomical changes in natural selection through evolution, the brain seems to be able to enlarge within a species over relatively few generations. For example, bats and shrews in rural environments were reported to undergo brain expansion across only several decades, probably in adaptation to environmental changes through anthropogenic development (Snell-Rood Emilie and Naomi, 2013). In humans, recent changes in diet, geographical dispersion, and population density have been inferred as the main cause for the recent rapid selection of multiple genes, some of which related to lactose digestion in adults, tolerance to temperature extremes, and disease resistance (Laland et al., 2010). As evolutionary pressures mounted, the hominin brain also enlarged rapidly (Grabowski, 2016; Torrey, 2019). Thus, the brain is not an exception to the biological principle that useful organs enlarge when supplied with increased demands and resources, such as the need for behavioral plasticity coupled with a richer diet (Riska and Atchley, 1985; Grabowski, 2016). As to how such genetic traits can be selected in only a few generations, extragenomic evolutionary mechanisms may account for the fast rate of change by exploiting latent features.

2.2. Gene-culture coevolution

The development of rich linguistic cultural diversity allowed post-Neolithic humans to adapt to swiftly changing ecological conditions (Roffet-Salque et al., 2018); new opportunities arose for genomic adaptation because augmented behavioral plasticity provided a buffer for natural selection processes (Crispo, 2007; Waddington, 1953). This process allowed the rapid colonization of novel niches and demographic expansion, namely gene-culture (language) coevolution. Precursors of such phenomena were recently discovered in killer whales (Foote et al., 2016), one of the few animal species that exhibit vocal learning and resulting complex vocal communication. In these whales, genetic structuring, including the segregation of potentially functional alleles, was associated with a socially inherited ecological niche in which regional genomic divergence was demonstrated to be associated with habitat, dietary preferences, and postzygotic reproductive isolation. Furthermore, adipose depots have also been observed to be negatively correlated with brain size in mammals, suggesting increased brains and their resulting behavioral gains as a compensatory strategy against starvation (Navarrete et al., 2011). In humans, two genes related to brain growth and development that have suffered recent positive selection (Evans et al., 2005; Mekel-Bobrov, 2005) have been associated with speakers of tone or non-tone languages. As geographical and historical factors can’t explain the differences between haplogroups, cognitive bias is deemed to be responsible for the selection of these genes, with cul-
Fig. 3. A: Cassirer’s philosophy of the human being (Cassirer, 1944); the worlds of humans and animals are divided by the horizontal dashed line in the center. Animals experience the world through a direct connection of sensory and response systems, surviving through the detection of their current environment and optimally responding to it. These systems link only the physical environment and information encoded intrinsically attached to it. Humans possess a symbolic system in addition to the animals’ sensory and response systems. A symbolic system can process abstracted symbolic cognition, which is disconnected from the subject and information in the real physical world, although it relies partly on it. B: Evolution of the animal nervous system; first emerging to regulate bodily movements within an environment by connecting input (sensory) and output (motor) functions, originally linked directly within the cell in protozoa. As evolution made animals’ bodies larger and more complex, the nervous system also increased in size and complexity to connect input (sensory organs accumulated at the front of the body, along moving direction) and output organs (motor organs located around the center of gravity of the body, for efficiency), now separated by a substantial distance. Along the continuous evolutionary process, neurons were grouped closer together for efficiency and information processing speed, forming the central nervous system and eventually the telencephalon and cerebral cortex. The nervous system, initially devoted solely to sensorimotor processing, developed an overlay machinery of higher centers able to manipulate symbolic information detached from the physical environment (top right diagram; note that this structure resembles Cassirer’s philosophy of the human being depicted in A). C: Phylogenetic tree of mammalian orders (ordinate indicates millions of years in the past, from top to bottom). Rodentia (2256 species), Chiroptera (1151 species), and Primates (504 species) are the three most radiated orders among extant taxa (Estrada et al., 2017). Rodents are phylogenetically the most proximal order to primates, diverging less than 100 million years ago. D: Diagrams illustrating different brain organizations between rodents (top) and primates (bottom). Colored areas in the brain indicate primary sensory (red: somatosensory, blue: visual, yellow: auditory) areas in representative extant primate and rodent species of different body (first number in brackets) and brain (second number in brackets) sizes. Note the difference in the proportion of these primary (colored) and association areas (in white) in differently sized brains between primates and rodents (Dooley and Krubitzer, 2013).

2.3. The unique design of primate brains: the first phase transition

Although diverse brain preadaptation mechanisms seem to be present in animal species that exhibit language-like vocal communication, why language emerged only in our evolutionary lineage remains unclear. Was there anything special about the primate brain? A distinct feature shared among the three most successful (i.e., radiated in the most species) extant mammalian orders (Fig. 3C) (Estrada et al., 2017) is that their ecologies largely depend on different sensory modalities; for example, haptics in rodents, audition in bats, and vision in primates. Hence, their brain layouts could favor different styles of interactions with their environment. Comparisons of the distinctly sized brains of primates with those of rodents (Dooley and Krubitzer, 2013; Ventura-Antunes et al., 2013), their closest mammalian order (Fig. 3C), have clearly shown this difference (Fig. 3D). Larger primate brains have considerably increasing heterogeneous cortical areas (Fox et al., 2005; Kaas, 1997; Petrides and Pandya, 1999), whereas larger rodent brains remain as rather straightforward expansions of analogous smaller brains (Dooley and Krubitzer, 2013). In the case of primates, maintaining sensory and motor precision, despite an increased body size without a proportional increase in spinal and peripheral fibers, could have been a significant factor in brain expansion and corticalization (Herculano-Houzel et al., 2016). Thus, once ecological conditions demanded it, primate brains were ready to incorporate supplementary brain areas, thereby adding novel functions.
one after another. Although the mechanisms of how this unique feature developed in the primate brain during evolutionary processes remain unknown, this represents the first major phase of transition-like predaptation in mammalian brains.

3. The second phase transition: Conversion in evolutionary mechanisms

As previously described, the brains of human ancestors were developed through predaptations with (1) a tendency for gradual expansion, (2) the potential for gene-culture (through vocal communication) coevolution, and (3) the unique characteristic of novel cortical areas being added along with volumetric enlargement. These brains encountered an opportunity for the next phase transition when ancestral hominids started using and making stone tools (Fig. 1). Despite the human brain not being an outlier among primates in regards to its cellular composition and size (Herculano-Houzel et al., 2015), the usage and manufacturing of tools could have induced fundamental differences such as corticalization of motor control (Herculano-Houzel et al., 2016), combined with an already moderately advanced cognitive and vocal communication capacity, led to the development of the human mode of language in our ancestors through the allocation of overlapping and recently expanded brain areas. This consequently provided the means for the transmission of knowledge and eventual formation of modern technological civilizations. We previously proposed the theory of triadic niche construction (Iriki and Taoka, 2012) as the mechanism responsible for such phenomena—an accelerated positive feedback loop for expansions among (1) neural (brain), (2) cognitive, and (3) environmental niches (Fig. 4). That is, human evolution is characterized by continuous processes of adding new modalities of cognition, including the manufacturing and usage of tools and linguistic faculties, supported by dramatic brain expansion and the accompanying addition of new functional areas. Such extended brain functions have driven rapid and drastic changes in the hominin ecological niche, which have in turn demanded further brain resources to adapt to them.

Thus, in this manner, the evolutionary mechanism has shifted from passive “natural selection” to an active triadic niche construction phase, which led and continues to lead humans’ cognitive-, communication-, and technology- capacities into a continuous innovation loop throughout its history. Human language emerged during this phase, which featured an additional layer over the existing animal (proto-language) layer (Fig. 4). Language then became a powerful instrument in this continuously accelerating triadic niche construction. Despite this, some critical factors remain unknown; for instance, how did this accelerated expansion exceed the “threshold capacity” for the emergence of a novel mode of communication (human language) derived from (and in addition to) the original mode (animal language)? What was this threshold and how was the emergence of discontinuous qualitative differences induced from continuous quantitative differences? New insights from animal language studies are expected to provide answers concerning distinctive properties in the emergence of human language.

4. Ongoing shifts in the human brain through AI and the putative third phase transition

Because the expansion of the human (as a primate) brain is intrinsically connected to its products, including civilization, economies, and industry, one could argue that its evolutionary mechanism is also subserved by and based on the principle of growth (Meadows et al., 1972). This perspective engenders a new consideration in the future of cognitive development: that limitations to civilization and industrial growth impose a barrier to brain evolution. While environmental resources could have easily been considered infinite at the beginning of this process, when the human population was still small enough, currently at the maturity of the Anthropocene (Crutzen, 2006), after significantly exploiting terrestrial resources, we have become conscious about the limit of growth (Meadows et al., 1972). However, humans cannot be released from the principle of growth because they are evolutionary bound to it as a primate species. One possible solution to this problem could be to apply the theory of triadic niche construction to create novel dimensions of mental space with abstract and metaphysical axes, such as value, quality, or identity. In the same way that a theory of mind enhanced behaviors such as deception, empathy and seduction (Torrey, 2019), this novel cognitive niche could be exploited with the support of human language-based mental functions (Cassirer, 1944).

Another efficient and feasible method of overcoming the limit of growth is expanding those abstract niches with the aid of AI.
The recent emergence of AI technology has created cognitive tools able to link with, subsidize, and even partially replace human brains. Although currently at the task level rather than serving a general purpose, AI presents as a unifier of different domains across cognition, technologization, and environments into a single interconnected architecture (Fig. 4), whereby the speed of triadic interactions is accelerated close to an infinite level. In this model, novel dimensions constituting abstract/symbolic niches can be constructed and exploited to theoretical extremes. Whether AI-assisted progress will be influenced by social and personal inequalities in access to technology remains to be seen, under the risk of accentuating the current digital divide (van Deursen and van Dijk, 2019).

Through directly extrapolating the lessons reviewed in the previous sections concerning the transition from animal communicatio to human language, it can naturally be assumed that humans are now in the midst of experiencing the next (third) phase transition. Eventually, the threshold capacity of our brain function will be exceeded, triggering the emergence of the next mode of language in the near future. Such a novel mode of “language” might be based in in silico algorithms or programming of sorts, to be built overlaying the bases of animal and human languages (Fig. 2). Although it is too early to observe any transgenetic effects of these electronic too tools, more efficient, immersive, and interconnected structured communication may allow to overcome the natural limits that were either imposed by or shaped the human brain (Danbur, 1998).

5. Concluding remarks

As summarized in Fig. 2, animal protolanguage emerged as an advanced communication/cognition ability when brain sizes exceeded the first threshold capacity through gradual expansion by natural selection. From there, brain structures/functions subserving language faculties underwent two phase transitions (first and second phase transitions) during the animal protolanguage period (lower shaded block) when gradual expansion continued. The first occurred when the primale brain, the mode of expansion of which allowed additional brain areas to emerge upon enlargement, experienced tool use by ancestral hominids (arrow on Fig. 1). The evolutionary mechanisms (at the time passive natural selection) developed a novel mode of active triadic niche construction—the interactively accelerated expansion of neural/cognitive, and environmental niches (second phase transition). This resulted in an explosion in brain growth, easily exceeding the brain capacity threshold required for human language to emerge (second threshold). These processes could be immediately extrapolated to predict the future of human language in the form of the expected third phase transition, perhaps through the development of AI. In this sense, human language can be viewed as an intermediary layer in a three-layered structure enabled through AI, with the protolanguage of animals below it and the next additional mode of language above, to be superimposed when the future AI-aided brain capacity exceeds the next putative threshold capacity (third threshold).

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References

Azevedo, F.A.C., Carvalho, L.R.B., Grinberg, L.T., Farfel, J.M., Ferretti, R.E.L., Leite, R.P., Filho, W.J., Lent, R., Herculano-Houzel, S., 2009. Equal numbers of neuronal and nonneuronal cells make the human brain an isometrically scaled-up primate brain. J. Comp. Neurol. 513, 532–541, http://dx.doi.org/10.1002/cne.21974.

Cassinelli, E., 1944. An Essay on Man: An Introduction to a Philosophy of Human Culture. Yale University Press.

Crispo, E., 2007. The Baldwin Effect and Genetic Assimilation: Revisiting Two Mechanisms of Evolutionary Change Mediated by Phenotypic Plasticity. Evolution 61, 2469–2479, http://dx.doi.org/10.1111/j.1558-5646.2007.00203.x.

Crutzin, P.J., 2006. The “anthropocene”. In: Ehlers, E., Krafft, T. (Eds.), Earth System Science in the Anthropocene. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 13–19, http://dx.doi.org/10.1007/978-3-540-69505-6.

Dediu, D., Ladd, D.R., 2007. Linguistic tone is related to the population frequency of the adaptive haplogroups of two brain size genes, ASPM and Microcephalin. Proc. Natl. Acad. Sci. 104, 10944–10949, http://dx.doi.org/10.1073/pnas.0610849104.

van Deursen, A.J., van Dijk, J.A., 2015. The first-division digital divide shifts from inequalities in physical access to inequalities in material access. New Media Soc. 21, 354–375, http://dx.doi.org/10.1177/146144481779082.

Dumay, J., Krubitzer, L., 2013. Cortical plasticity within and across lifetimes: how can development inform us about phenotypic transformations? Front. Hum. Neurosci. 7, http://dx.doi.org/10.3389/fnhum.2013.00620.

Danbur, R.M., 1993. Coevolution of neocortical size, group size and language in humans. Behav. Brain Sci. 16, 681, http://dx.doi.org/10.1017/S0140525X00032325.

Danbur, R., 1998. Grooming, Gossip, and the Evolution of Language, First Paperback Edition, ed. Harvard University Press, Cambridge, Mass, pp. 197–199, 203–207.

Estrada, A., Roos, P.A., Byland, A.B., Roos, C., Fernandez-Duque, E., Fiore, A.D., Nakaris, K.A., Nijman, V., Heymann, E.W., Lambert, J.E., Rovero, F., Barelli, C., Setchell, J.M., Gillespie, T.R., Mittermeier, R.A., Arreguitova, L.V., Guinea, M.de, Gouveia, S., Dobrovolski, R., Shane, S., Shane, N., Boyle, S.A., Fuenteas, A., MacKinnon, K.A., Amato, K.R., Meyer, A.K., van Rompaey, R.J., Kone, B., 2017. Impending extinction crisis of the world’s primates: why primates matter. Sci. Adv. 3, e1600946, http://dx.doi.org/10.1126/sciadv.1600946.

Evans, P.D., Gilbert, S.L., Mekel-Bobrov, N., Vallender, E.J., Andersen, J.R., Vaezi, M., Tishkoff, S.A., Hudson, R.R., Lahn, B.T., 2005. Microcephalin, a gene regulating brain size, continues to evolve adaptively in humans. Science 309, 1717–1720, http://dx.doi.org/10.1126/science.1113722.

Evolution du volume cérébral des Hominides, (2019) [http://www.linternaute-scientifique.net/science/biologie/dossiers/06/0608-memorie-8.html] [WWW Document] n.d. URL (Accessed 1.29.19).

Foote, A.D., Vijay, N., Ávila-Arcos, M.C., Baird, R.W., Darwin, J.W., Fumagalli, M., Gibb, R.A., and van Rompaey, R.J., 2015. Human, nonhuman, and nonneuronal cells: a perspective on the diversity of brain cells and functions. Proc. Natl. Acad. Sci. 102, 9673–9678, http://dx.doi.org/10.1073/pnas.1504136102.

Grabowski, M., 2016. Bigger brains led to bigger bodies?: the correlated evolution of human brain and body size. Curr. Anthrop. 57, 174–196, http://dx.doi.org/10.1525/curan.2016.57.3.174.

Herculano-Houzel, S., 2016. The Human Advantage: a New Understanding of How Our Brain Became Remarkable, 1 Edition, ed. The MIT Press, Cambridge, MA, pp. 89–93, 187.

Herculano-Houzel, S., Catania, K., Manger, P.R., Kaas, J.H., 2015. Mammalian brains are made of: a dataset of the numbers and densities of neuronal and nonneuronal cells in the brain of Primates, Sirentida, eulipotyphlans, and their relationship with body mass. Brain Behav. Evol. 86, 145–163, http://dx.doi.org/10.1159/000437413.

Herculano-Houzel, S., Kaas, J.H., de Oliveira-Souza, R., 2016. Corticalization of motor control in humans is a consequence of brain scaling in primate evolution; corticalization of human motor control. J. Comp. Neurol. 524, 448–453, http://dx.doi.org/10.1002/cne.23792.

Iriki, A., Takaoka, M., 2012. Triadic (ecological, neural, cognitive) niche construction: a scenario of human brain evolution extrapolating tool use and language from the control of reaching actions. Philos. Trans. R. Soc. B Biol. Sci. 367, 10–23, http://dx.doi.org/10.1098/rstb.2011.0190.

Kaas, J.H., 1997. Topographic maps are fundamental to sensory processing. Brain Res. Bull. 44, 107–112, http://dx.doi.org/10.1016/S0361-9230(97)00064-4.

Laland, K.N., Odling-Smee, J., Myles, S., 2010. How culture shaped the human genome: bringing genetics and the human sciences together. Nat. Rev. Genet. 11, 137–148, http://dx.doi.org/10.1038/nrg2734.

Meadows, D.H., Meadows, D.L., Behrens-III, J.R.W., 1972. The Limits to Growth Club of Rome, URL (Accessed 1.29.19) [http://www.clubofrome.org/report/the-limits-to-growth/].

Mekel-Bobrov, N., 2005. Ongoing adaptive evolution of ASPM, a brain size determinant in Homo sapiens. Science 309, 1720–1722, http://dx.doi.org/10.1126/science.1116815.

Navarrete, A., van Schaik, C.P., Isler, K., 2011. Energetics and the evolution of the human brain: size. Nature 480, 91–93, http://dx.doi.org/10.1038/nature10629.

Petrides, M., Pandya, D.N., 1999. Dorsolateral prefrontal cortex: comparative cytoarchitectonic analysis in the human and the macaque brain and corticocortical
connection patterns, Eur. J. Neurosci. 11, 1011–1036, http://dx.doi.org/10.1046/j.1460-9568.1999.00518.x.

Riska, B., Atchley, W.R., 1985. Genetics of growth predict patterns of brain-size evolution. Science 229, 668–671, http://dx.doi.org/10.1126/science.229.4714.668.

Roffet-Salque, M., Marciniak, A., Valdes, P.J., Pawlowska, K., Pyzel, J., Czerniak, L., Krüger, M., Roberts, C.N., Pitter, S., Evershed, R.P., 2018. Evidence for the impact of the 8.2-kpyBP climate event on Near Eastern early farmers. Proc. Natl. Acad. Sci 115, 8705–8709, http://dx.doi.org/10.1073/pnas.1803607115.

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Snell-Rood Emilie, C., Naomi, Wick, 2013. Anthropogenic environments exert variable selection on cranial capacity in mammals. Proc. R. Soc. B Biol. Sci. 280, 20131384, http://dx.doi.org/10.1098/rspb.2013.1384.

Torrey, E.F., 2019. Evolving Brains, Emerging Gods: Early Humans and the Origins of Religion, Reprint Edition, ed. Columbia University Press, pp. 35–36, 59-61.

Ventura-Antunes, L., Mota, B., Herculano-Houzel, S., 2013. Different scaling of white matter volume, cortical connectivity, and gyriﬁcation across rodent and primate brains. Front. Neuroanat. 7, http://dx.doi.org/10.3389/fnana.2013.00063.

Waddington, C.H., 1953. Genetic assimilation of an acquired character. Evolution 7, 118–126, http://dx.doi.org/10.1111/j.1558-5646.1953.tb0070.x.

**Glossary**

*Artificial Intelligence (AI):* Mimicry of human intelligence (or discrete parts of it) by manmade devices utilizing methods that can be mathematically represented.

*Encephalization:* Increase in brain size with the addition of new cortical areas and functions.

*Limit of growth:* The amount of natural resources that are able to sustain a population as calculated by an exponential index that takes into account the increase in consumption by time.

*Protolanguage:* Any means of auditory communication that predates human language.

*Triadic niche construction:* An evolutionary process whereby the activities of organisms modify three coevolutionary domains, ecological, neural, and cognitive, which in turn the organisms evolve to adapt.

*Symbolic system:* The human capacity of processing abstract information, independently of sensory or motor systems.