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Biological first principles for design competence

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Abstract

This paper interprets the concept of biologically inspired design as understanding design based on the biological evidence. Borrowing its concept of design competence from Chomsky's definition of linguistic competence, the paper reviews biological evidence from fields including evolution, genetics, and animal behavior from the perspective of design research to propose that design competence is the product of an evolutionary history during which five key developments in cognitive evolution came together: conception unbounded by sensory perception, symbolic manipulation at a level of metarepresentation, theory of mind, curiosity, and mental time travel. These cognitive capabilities were derived from the biological evidence based upon the criteria that they are presumed to be unique to humans (*Homo sapiens*), they may be lost because of neurodegenerative diseases or they may fail to develop because of neurodevelopmental disorders, and they are not immediately present upon birth and develop as a child's brain matures. Based on these five capabilities, the paper concludes by discussing how computation may provide a useful way to understand the origins and evolution of design competence.

Keywords: Biological Evidence; Biologically Inspired Design; Computation; Design Competence

1. INTRODUCTION

Birds, gorillas, and chimpanzees build nests; bees and wasps build hives; beavers build dams; and ants build anthills.

Humans build houses, flats, palaces, houseboats, shacks, huts, and igloos; elephants break off acacia tree branches and use them to scratch their backs; and humans break off elephant tusks (although, thankfully only illegally so nowadays) to make ivory and mother of pearl encrusted implements to scratch their backs.

Although there are many ways to characterize these behaviors, this paper describes the genuinely unique human version as design. For the purposes of this paper, I propose a working definition of design as the capacity to envision a nonexistent material world to a level of complexity that is not obvious based on the local material environment and then to reify that nonexistent world in material or symbolic semiotic form. In other words, this definition of design requires that we can do more than rely on the functional affordance of an object as it exists, say, to strip a branch of its leaves to use the stick as a skewer. We would design a new function for an object through a series of transformations that are not immediately observable nor is the final form necessarily obvious from the initial stages of transformation. We would tie those leafless branches together to make a thatched, waterproof cover, which requires an ability to perceive a form that is not determined *a priori* by the materials, and an ability to deal with numerous variables, including the length and thickness of branches, their flexibility or rigidity, and, if aesthetics were a concern, their coloring and the texture of the bark.

To our knowledge, no other animal seems to possess this capacity, at least not in the way that we understand design.

However, the biological substrate that shapes a capability we now name design may have existed in other species. Observations of animal innovations (e.g., Bernstein, 1962; Tutin et al., 1995; Reader & Laland, 2003; Rushbrook et al., 2008) point to the existence of a set of cognitive mechanisms that underlie animal innovations and the human capability to design. These observations suggest that an evolution toward cognitive mechanisms for design may have involved intermediary steps. It is for these reasons that we turn to biological evidence to understand how the human brain was built to have design as a function.

The human faculty of design as we know it today was not always present in the evolutionary ancestors of modern humans, *Homo sapiens*. Although a predominant theory of human evolution, the social brain hypothesis (Dunbar, 1998), suggests that socialization was likely to have been a primary driver for the evolution of modern human behaviors including design, this article takes as its starting point the premise that the imperative to design the world to suit our survival

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was the principal driver. The pressure to survive and to ensure the survival of our "selfish" genes provided the context for the selection of the genes necessary to build a brain with the cognitive mechanisms necessary for what we will call *design competence*, and that is the focus of this article. In borrowing the terminology Chomsky (1987) used to theorize a universal grammar to explain how it is that children can acquire language with such ease and relatively little stimuli, I argue that design competence is derived from a set of genetically influenced capacities necessary to build a brain "ready" to design. Elements of design competence exist in some species, especially the great apes, but they do not exist in any other species as a package and to the same degree of skill as in humans.

Design competence would have been a key driver of difference between modern humans, *H. sapiens*, and our ancestors. The engine for evolution, after all, is difference, because evolution, as Darwin observed, is descent with modification. One type of difference results from imperfect copies or "errors" in the intergenerational transmission of genetic code. The other type of difference stems from an inherited difference in chances for reproduction, which is known as natural selection. As species both compete and cooperate to survive, they aim to capitalize on their inherited differences. Designing the world to suit our survival would have been one way to maximize difference by actively modifying our environment, because we can change the environment to suit our survival rather than merely adapt to the changing environment, and thereby influence the selection of genetic traits through a human form of *niche construction* (Laland et al., 2001).

When humans build houses to protect us from inclement weather, vehicles to transport us and our goods across great distances with minimum effort (thereby leaving energy for recreation), and artisanal functional objects that not only perform effectively but also bring us great joy in their use and perception (Norman, 2005), we are performing a human version of *niche construction*, the behavior of animals actively modifying their environment. Through niche construction, animals influence the selection of genetic traits (Laland et al., 2000, 2001, 2006). By actively changing their environment, the offspring of animals are therefore subjected to different selection pressures than they would have been had the animals not actively changed their environment. Biologists distinguish between two forms of niche construction behavior (Laland et al., 2000; Day et al., 2003). The first is the active relocation of species themselves, such as when birds migrate during the winter. The second form is of most interest to us. In perturbation niche construction, animals actively modify their environment. A canonical example is the beaver dam. A characteristic of beavers is their ability to build dams (Gurnell, 1998). Beavers build dams because they require that their burrows or shelters have access points that are under water. The dams modify the landscape to stabilize water levels when necessary. It is intriguing that there is neither one type of dam nor are dams built of a single type of material. Gurnell (1998) provides an extensive description of the kinds of structures built by the European beaver *Castor fiber* and their hydromorphological effect on rivers. Although it is not possible for us to ascertain whether beavers plan (or design) dams in their minds before building them, the complexity of the ecological context and the beavers' ability to adapt the design of dams to the context would at least suggest a simple form of situated behavior (Suchman, 1987), although a beaver dam is probably best described as an extended phenotype (Dawkins, 1999).

The evolutionary pressure for humans to have and to pass on design competence is thus no more unusual than the set of pressures exerted upon other species. In other words, the idea of niche construction does not regard behaviors such as nest building as animals adapting to the environment but rather adapting the environment to their needs to increase the likelihood of the selection of a set of genetically endowed traits. The capability to design would have expanded the scope of our niches such that we could survive in almost any ecological condition found on earth.

In essence, design is an exemplar of modern behaviors in humans. Archaeologists characterize the emergence of modern behaviors in humans by evidence including the diversity of artifacts, social rituals, and the intensity of the exploitation of natural resources as to require some sort of technology, such as fishing or farming. During this transition, humans were starting to make tools with handles (hafted tools), tools with new materials, and objects that had ritual or symbolic importance. Although there is a great amount of debate within archaeology whether modern behaviors emerged (Mcbrearty & Brooks, 2000) or whether there was a "human revolution" (Klein, 2000), these modern behaviors would have required a "package" of cognitive competencies including abstract conceptualization, planning, an interest in innovation, and a representational mind (Mcbrearty & Brooks, 2000).

My aim in this article is to elaborate on this package to specify a set of proximate cognitive mechanisms for design competence. We will focus on proximate factors, that is, necessary factors for design competence, and exclude other factors such as long-term memory and visual spatial reasoning that are part of the general texture of human cognition. This set will then serve as the basis for computational models that could be used to enact design. The approach we will take is to start from what is currently known about design cognition and then look for the archaeological and biological evidence, including genetics, cognitive neuroscience, and ethology (study of animal behavior), that characterize and describe the origins of the behavior. In other words, I take a triangulation approach, looking for similar constructs of cognitive design behavior in the design and biological literature, with evidence from at least two disciplines of biology. In doing so, the following three criteria are applied to the evidence available in the scientific literature:

1. Is the cognitive mechanism found only in humans (*H. sapiens*) or only to a unique degree of skill in humans?
2. Is the cognitive mechanism subject to loss due to neurodegenerative disease or subject to a failure to appear due to a genetic neurodevelopmental disorder?

3. Is the cognitive mechanism not immediately evident in children and must develop as the child's brain develops?

The first criterion is a phylogenetic one: we need to identify behaviors that are unique to humans (*H. sapiens*) in degree of skill or gradual existence. These behaviors should have emerged as our species branched off from others, and there should be archaeological evidence to support an argument for the evolution of the cognitive mechanism. The second and third criteria aid in making arguments to the necessity of a cognitive mechanism, such that if it is lost or fails to develop, and its absence leads to a loss of designlike behavior, then we could conclude that the cognitive mechanism is necessary for design competence. In addition, we apply the restriction that the cognitive mechanism would develop in the child even in the absence of directly benefitting from skills and knowledge acquired from social groups. Then, we know it is heritable. Certainly, children do directly benefit from such knowledge when there is a disorder in cognitive development, such as autistic children who are taught how to play. However, if the cognitive mechanism develops as part of the early ontogeny of cognitive development but can fail to develop, then we have further evidence of its necessity. If we were not able to identify any further behaviors that satisfy these three criteria, then we would make the argument that the set of cognitive mechanisms, or the package for design competence, is necessary and sufficient.

Based on the evidence that I will present, we can identify the following five components in this cognitive package for design competence:

1. the capacity to have mental images unbounded from immediate sensory perception,
2. the capacity to reason symbolically up to the level of metarepresentation,
3. the capacity to think of others as having similar intentions and beliefs (i.e., theory of mind),
4. the capacity for an innate interest in novelty *and* utility, and
5. the capacity to formulate future actions based on past experience and to act upon them in a group context.

The goal of this article is to sketch out some of the evidence for these capacities. More than 40 years of cognitive design research has pointed to descriptions of cognitive processes characterizing design performance (fluency in design practice) that we distinguish from design competence, just as Chomsky distinguished between linguistic competence and linguistic performance. Yet, the field has yet to form a theory of what cognitive mechanisms should matter or underlie our ability to have design competence. "Biologically inspired design" is proposed as a way to see cognitive mechanisms in design by showing how different approaches from disciplines in biology may point to a unitary description of design competence. A framework theory may prompt novel questions, new computational formalisms, and motivate design researchers to integrate their findings with those of neuroscientists, ethologists, and others, and vice versa. I hope that the emerging convergent results form a deeper understanding of design and of how design competence might have behavioral contributions to other complex behaviors in humans in general.

2. THE COGNITIVE PACKAGE FOR DESIGN COMPETENCE

2.1. Capacity for mental images unbounded from sensation

The capacity to envision a world unconnected to ambient reality and to represent and to reify our imagination, that is, to make what is mental real, would have been a significant precursor to activities that we now call design. Psychologists use the term "mental imagery" to refer to a state of consciousness in which the mind can reassemble sensory perceptions to form a "memory" of a perceptual experience. Although mental imagery is strongly associated with designing (Purcell & Gero, 1998), cognitive design research has shown that it is possible for skilled practitioners to design solely using mental imagery alone without the assistance of external representations. Bilda and Gero (2007) studied six expert architects when they design in blindfolded (BF) and sketching (SK) conditions. Under the BF condition, the rate of cognitive activity dropped relative to the SK condition because of higher demands of cognitive processing under the condition of use of imagery alone. Nonetheless, all of the architects in the BF condition were able to able to complete the conceptual design in their minds without a need to off-load their working memory in sketches, and the quality of the designs between the BF and SK conditions were equivalent. In summary, we can form mental images of external objects that are not present and thereby create new objects.

All humans in all societies experience mental imagery that are unbounded from immediate sensory perception (Bourguignon, 1979). Prolonged sensory deprivation is known to cause our brain to conjure mental visions. Whether we call these dreams or hallucinations, these mental visions seem "real" to us, which may have important evolutionary consequences. To characterize the origins of mental imagery, we will look to three pieces of evidence: anthropological, archaeological, and neurological. The anthropological and archaeological evidence on abstract mental conception unrelated to ambient reality point to the emergence of this cognitive ability during human evolution.

Experiencing altered states of consciousness is a psychobiological capacity that all humans share. Its existence is an example of a psychological universal. Erika Bourguignon (1979) studies altered states of consciousness and its relation to the social functioning of human societies. The most familiar of these altered states of consciousness are possessions and trances, the latter generally associated with shaman who travel to a spirit world and then return and remember their contact with the spirits. In a review of 437 ethnographic studies, she found that 90% report on one or more institutionalized, culturally patterned forms of altered states of consciousness. Whether these altered states are remembered or forgotten, as in the case of dreams, it is clear that these visions and reality-directed behavior interact in a variety of different ways. The origin of the cognitive ability for having mental visions is the subject for the archaeological evidence.

Christopher Henshilwood, a Professor at the Centre for Development Studies at the University of Bergen in Norway, heads the African Heritage Research Institute in Cape Town. Along with the Iziko South African Museum in Cape Town and his research team, Henshilwood found abstract representations in two pieces of ochre, which were 2–3 in. long (Henshilwood et al., 2002). The objects date to at least 70,000 (±5,000) years ago and were recovered from the Middle Stone Age layers at Blombos Cave, a site on the southern Cape shore of the Indian Ocean 180 miles east of Cape Town, South Africa. In the figure, there were no iconic depictions of flora and fauna typically found in rock engravings and of the variety of cave drawings that normally come to mind when we think of cave art. Instead, the designs on the two pieces of ochre show a consistent crosshatched pattern consisting of two sets of six and eight lines partly intercepted by a longer line or another similar pattern divided through the middle by a third parallel line. Henshilwood et al. (2002) conjectured that "they may have been constructed with symbolic intent, the meaning of which is now unknown." To archaeologists, the finding of this symbolic expression is an unambiguous marker of symbolically mediated behavior. To architects, the patterns may look like a plan for a fence. To textile designers, the pattern may be for fabric. Whatever interpretation is assigned to this cave art, that the pattern has not been shown to resemble any other archaeological artifact found suggests that it was purely abstract and was likely the result of humans' emerging ability to have visions unbounded from perceptual reality. The previous earliest finding of symbolic art was the art of the Chauvet-Pont-d'Arc cave in France. That art, dating to about 32,000 years ago, included both abstract art, which has shown to be constructed from finger and palm prints, and representational art of animals found in the local area.

Although Henshilwood further suggests that the symbolic expression is tantamount to evidence on the emergence of syntactical language, there is no reason to believe yet that symbolic reasoning on the order required for language necessarily appeared at this time. Without the existence of durable records of language, it is quite difficult to pinpoint when humans developed a capacity for symbolic reasoning.

However, it is plausible to argue that the expression of the abstract conceptualization is evidence of an important precursor: the capacity to envision a world unbounded by ambient reality. Although there is sufficient evidence that all modern humans experience altered states of consciousness, it is not altogether clear whether modern humans' ancestors always had this capacity or whether this capacity gradually evolved. There is at least one theory that attempts to explain what factors would have led humans to produce the Blombos Cave art.

The theory comes from the work of David Lewis-Williams (2002). Lewis-Williams also cited this example of the world's oldest "art" and the intriguing characteristic about the art being purely abstract. We previously discussed that archaeologists debate whether this important find suggests fully modern minds, language, and symbolism at an unexpectedly early date. Lewis-Williams offered an alternative explanation. He argued that sensory deprivation in the caves, and possibly other factors, altered the states of consciousness of Upper Paleolithic *H. sapiens*. Given the sensory deprivation in the cave and the potential for entry into a hallucinatory realm as a consequence of the deprivation, perhaps the abstract cave art is actually a projection of mental imagery onto the surface of the cave. Lewis-Williams believes that what Upper Paleolithic *H. sapiens* hallucinated was to them reality; this capacity to envision, and then to reify symbolically, would have been advantageous to Upper Paleolithic *H. sapiens* over Neanderthals. He contends that representational art of the variety found in the Blombos Cave, along with other evidence of elaborate burial rituals, the use of red ochre over 285,000 years ago (Mcbrearty & Brooks, 2000), and the use of marine pigment in symbolic behavior about 164,000 (±12,000) years ago (Marean et al., 2007), was used to mark off social groups. These social groups competed for resources for survival. Those who had the ability to form and keep social groups succeeded.

Perception that is not tied to sensation is enabled by the network architecture of the brain. According to Mesulam (1998), the network architecture of the human brain is such that the conception of reality is neither concretely nor directly linked to its sensation as it is with other species. The brain's neural architecture allows the activation of representations that are not part of ambient reality because sensory information undergoes extensive associative transformations with similar sets of sensory inputs and with our memory. As a consequence, a single experience of sensations can produce multiple conceptions. If we allow a simple definition of creative imagination (mental imagery) as forming multiple conceptions from a single set of perceptions, then we must conclude that the brain's architecture is already "plumbed" for creativity.

When humans "decided" to represent what we "saw" in the cave as art, that in and of itself is a remarkable event given that many other animals appear to "dream" but no animal has yet spontaneously "decided" to represent a dream symbolically. This brings us to the next capacity.

2.2. Capacity to reason symbolically up to a level of metarepresentation

The recorded evidence of the abstract conceptualization in the earliest cave art also points to the next cognitive mechanism: symbolic reasoning. According to Peirce's sign theory, an icon is a reference to ambient reality encoded as similarity between the icon and the object it references. An index is an indication toward ambient reality. A symbol is an agreed upon conventional relationship between two "things." That is, a symbolic association is one that exists between two symbols. To be capable of indexical reference is to be already capable of iconic reference, and to be capable of symbolic reference is to be already capable of indexical reference. Reasoning at the symbolic level of symbols rather than their iconic or indexical level is the result of the highest level of abstraction produced by any species (Deacon, 1997). When a person can symbolically represent that one thing stands for another, the person employs so-called secondary representations, because in addition to the (primary) representation of what the object truly is, the person represents the object as something else (Perner, 1991). As Perner (1991, p. 7) explains, "secondary representations are purposely detached or 'decoupled' from reality and are at the root of our ability to think of the past, the possible future, and even the nonexisting and to reason hypothetically." That is, in secondary representation, a person represents the world independent of perception. The disconnection between symbols and their iconic link to ambient reality or indexical reference to ambient reality means that the brain is no longer limited to reasoning at a level of primary representation of objects. We are reasoning at a level of secondary representation (Leslie, 1987). The consequence of this reasoning with secondary representations means that we can assign an arbitrary meaning to any symbol.

However, even this is insufficient for designing. Secondary representation is insufficient for the purposes of designing, because we could, for example, only see a rock as something to pound nuts with, or with some imagination, as a charm. When we design, we conceive of alternative representations and find new ways to improve representations of what we "hold" in our mind (Perner, 1991). Further, rather than having relatively fixed and predetermined mental imagery of an object, we recognize that our representations (designed artifacts) are models of concepts, and that the designed artifact is a projection of concepts held in the mind (Gowlett, 2009). This crucial part of human reasoning is made possible by metarepresentation (Perner, 1991; Suddendorf, 1999). Because the representation can be purely internal, we can manipulate the internal representation based on new information and we can manipulate the external representations by changing its behavior to suit the internal representation (Perner & Doherty, 2005). In design, Schön (1983, p. 78) describes this type of manipulation as having a "conversation with the materials of the situation" to frame and reframe the design problem to be solved.

Children do not immediately recognize that the same representation can have multiple interpretations; the ability for metarepresentation develops in children after about 4 years of age, at which time they start to understand the representational mind and to realize that representation is a mental activity (Lillard, 1993). They begin to conceive of alternate interpretations and engage in complex pretend play. All of this is practice for a brain that will be ready to design. There is some evidence of secondary representational skills in the great apes, which partially accounts for their ability to make and use tools, but this skill is generally lacking in other species (Suddendorf & Whiten, 2001), and no species has yet been found to have metarepresentation skills.

It has been recently discovered that symbolic reasoning is a cognitive mechanism that may have specific genetic origins. The loss of symbolic reasoning capability shows up in language disorders and some forms of autism spectrum disorders (ASDs) that are tied to mutations in specific genes. Perhaps the most significant finding linking genes to the human faculty of language is the discovery of the *FOXP2* gene. This gene encodes an evolutionarily conserved transcription factor expressed in fetal and adult brain. This transcription factor is a member of the forkhead/winged-helix (FOX) family of transcription factors. Transcription factors are regulatory proteins that control the copying of genes (Latchman, 1997). Members of the FOX family of transcription factors are regulators of embryogenesis. The product of this gene is thought to be required for proper development of speech and language regions of the brain during embryogenesis. Although a point mutation in this gene has been associated with developmental verbal dyspraxia, no association between mutations in this gene and speech disorders associated with autism has been found.

Mutations in the *FOXP2* gene were first identified in the KE family, the designation given to this family to protect their privacy. The KE family first came to the attention of the scientific community in 1990 with the publication of a report that characterized the affected members' speech and language disorder as a developmental verbal dyspraxia (Vargha-Khadem et al., 2005). The disorder was described as one that affected the expression and articulation of language more than its comprehension, and problems were noted with organizing and coordinating the high-speed movements that are necessary for the production of intelligible speech. Members of the KE family had no hearing problems or neurological deficits that affected limb movements, and there was no evidence of difficulty with feeding or swallowing during infancy.

Functional neuroimaging studies have been carried out on members of the KE family using two functional magnetic resonance imaging language protocols (Liégeois et al., 2003). The first protocol involved covert verb generation, thinking of a verb but not saying it. The other protocol involved overt verb generation and repetition, that is, thinking and saying the verb. The findings for both the covert and overt protocols showed that the affected KE family members had significantly less activation in the language area of the brain, Broca's region, as well as abnormally low activation in other speech-related regions of the brain. Although it is premature to state that the *FOXP2* gene is the only gene associated with language, its isolation suggests that symbolic behavior such as language, although perhaps not language exclusively, may have strong genetic determinism.

In addition, symbolic behavior can be lost because of other genetic neurodevelopmental disorders. An important consequence of symbolic behavior at a secondary level is to be able to "play" with symbols in an arbitrary manner, and this is a clear advantage in terms of design. However, individuals with some forms of autism have inhibited ability to use secondary representations in symbolic play (Baron-Cohen, 1987; Jarrold et al., 1993) and must be taught how to engage in symbolic play (Stahmer, 1995). Symbolic play occurs when individuals use objects (as symbols) as if the object were another object (e.g., a box as a castle), as if the object has attributes, that are normally associated with another object, that it does not have (e.g., a plastic ice cream cone "tastes delicious"), or refers to an object that is not present (e.g., acting out an airplane flying). Children with some forms of ASD exhibit an absence of spontaneous symbolic play regardless of their mental age that cannot be explained as mental retardation in general (Baron-Cohen, 1987). At least one gene, *SHANK3*, has been associated with ASD (Moessner et al., 2007). A further intriguing loss of symbolic behavior is presented in a disorder known as William's syndrome. Those with William's syndrome exhibit the loss of an ability to externally represent what they hold in their mind, or symbolic reification (Adolphs, 2003; Meyer-Lindenberg et al., 2006) despite often presenting an overxuberant linguistic ability. Although we do not yet know which genes are associated with the kinds of symbolic behaviors that humans enjoy, the evidence from genetic neurodevelopmental disorders of the brain clearly point to strong genetic factors in building a brain with the capacity for symbolic representation and reasoning.

However, as designers, we need for the meaning that we assign to a symbol, in the form of a material artifact, to be recognizable and understandable by the people who will use it. For this, we rely on our ability to have a model of the mind, that is, to reason about the actions of others as agents with objectives similar to our own.

2.3. Capacity for theory of the mind

We design not generally for ourselves, but for others. We guess, or hope, that the people who will use our designed artifacts have the same sensibilities as we do, especially that people will apply background knowledge to understand a design concept in the same way as we would (Bloom, 1996). At the least, they will likely have similar motor–cognitive abilities or we will know what deficits they may have so that we can design the artifact to accommodate. We embed our intentions how an object is to be interpreted (Houkes et al., 2002; Crilly et al., 2009). We try to use methods such as participatory design or user-centered design to maintain a focus on the user throughout the conception of the design artifact. There are many intentions that guide the design of the artifact. These intentions include the personal commitment and autonomy of the designer, societal interests, client demands, peer critique and acceptance, and schools of design, all of which guide the "hand" of the designers. In industry, these intentions are typically economically rationalized as "stakeholder views" and "market needs."

None of this would be possible if we could not embed our intentionality into a material object, the design work itself, and expect that the user could recognize those intentions. That is, we assume that the user of the designed artifact can know what *our* intention was for the object and that we know the intentions of the users.

As much today as it has ever been, we are concerned with what our objects say about us and what people "read" from these objects. In evolution, this matter has been discussed in relation to explaining the prolific number of hand axes found in the archaeological record and their increasing degrees of symmetry. The arguments that have been forwarded to explain the variety of hand axe design vary from the development (evolutionary) of cognitive ability and motor control to culture. Kohn and Mithen (1999) propose their own "sexy" hand axe theory as an explanation. When it comes to the biological act of reproduction, females, unfortunately, have been given the burden of work. Females expend much more energy and require a much higher calorie intake for reproduction than males. Female mammals have a limited supply of eggs that is determined at the time of birth. Male mammals have nearly unlimited supply of sperm that is limited only by how much food they are able to consume. For this reason, in terms of biology, females must be more prudent in their selection of which males to copulate with if their aim is to increase the likelihood of their offspring surviving to pass on the female's genetic material. Given this context, Kohn and Mithen (1999, p. 519) claim that "hand axes were products of sexual selection and as such were integral to the processes of mate choice within socially complex and competitive groups."

Kohn and Mithen (1999) claimed that highly symmetrical hand axes would be reliable indicators (for females) of the male's fitness along the dimensions of knowing where to find good-quality raw resources, deep planning ability (which we will cover in the next section), good health, and the ability to monitor and maintain good social relations while the male was engrossed in making a hand axe and thus unable to engage in other activities crucial for survival. The ability to make a finely symmetrical hand axe would have been a reliable indicator of cognitive, behavioral, and physiological traits providing the potential for high reproductive success. Hence, females would preferentially mate with those who could make such tools. Although male–male competition for females could exist in the absence of a theory of mind to understand the intentions of other males, for example, bower birds compete to construct nests to attract mating partners but they certainly do not have a theory of mind (Wojcieszek et al., 2007), it is more likely that males would know this if they had a theory of the mind. Therefore, they would have made objects to catch the attention of potential mating partners and impress them with the knowledge, skill, physical strength, and mental characteristics required for the design and manufacture of hand axes. Conversely, females would have "read" through that object that only a clever male could have envisioned and produced such an axe. All this communication would have taken place through the object. Although there is debate as to whether Kohn's theory of sexual selection for hand axes is true (Hodgson, 2009), a further complication to Kohn's theory is that an understanding of intentions would have led to cultural ratcheting (Tomasello, 1999) and a much faster rate of artifact progress than what is supported by the archaeological evidence.

Nonetheless, theory of mind is deployed so extensively in design that it is entwined in descriptions of designing. Designed objects are manifestations of knowledge (Gero, 1990) and ideas (Youn-Kyung et al., 2008) that the designer tries to communicate to the user (Buchanan, 1989). Architecture has a semiotic structure (O'Toole, 1994) through which architects communicate how they want us to relate to the architecture. We try to read not only the function of the object and how it achieves the function (Norman, 1998), which we might be able to surmise through its affordance (Gibson, 1979), but also the thought that the designer is "persuasively presenting and declaring" (Buchanan, 1989, p. 109). This makes it possible for us to transmit culture through objects, which some biologists call cultural niche construction (Laland et al., 2001) and others called "ratcheting" (Tomasello, 1999). All of these behaviors are related to the theory of mind, the ability to think of other beings as having similar beliefs and intentions to ours, but also including understanding that others may have false beliefs.

Cognitive science aside, design is about making objects that are self-explanatory. The user should be able to understand the artifact's use or the designer's intention regarding its use with the minimum amount of instruction. In short, the designer relies on our capacity to "read" the designers' intention through the object; that is, we can construct a model of the mind of the designer vis-à-vis the object. Conversely, the designer is able to design for others because the designer can know what others know and embed the intentions of the designer and the user into the artifact (Crilly et al., 2009). At the moment, only humans are known to have theory of mind. Chimpanzees have a limited form of a model of the mind, but not the form of "human-like belief–desire psychology" (Call & Tomasello, 2008).

2.4. Capacity for curiosity-driven motivated behavior

It is unequivocal that humans have a biologically exceptional, even excessive, capacity for creative outputs. The sheer volume and variety of designed artifacts produced would all but rule out the possibility that any designed artifact is biologically programmed into our brain. We make houses in all sizes and shapes that far exceed the number that would be expected for the house design (structure) to be suited for certain environmental conditions.

One possible reason for this may be that the brain is predisposed "to seek and create novelty and change" (Mesulam, 1998, p. 1044), that is, creativity. Even if we could explain brain processes associated with creativity as the integration of stimuli into multiple abstract, conceptual representations (Mesulam, 1998), this explanation does not account for *why* we would want to have multiple representations. There must be some additional mechanism at work. The evidence in neuroscience is that the modulation of sensory input, as it is converted into abstract, conceptual representations, is driven in part by emotion (Mesulam, 1998; Burgdorf & Panksepp, 2006). I propose that curiosity, an innate interest in that which is novel and useful, must be a primary resource in this emotional modulation. Neural programming for curiosity underlies motivated behavior toward numerous alternative representations from sensation.

Yet, the most "curious" part of curiosity is that we are curious at all and that our curiosity galvanizes "inventive" behaviors to make use of novel objects and situations to invent new objects and situations. This behavior has not (yet) been recorded in other species. Primate research shows that monkeys do exhibit curious behaviors, such as investigating novel objects (Mayeaux & Mason, 1998) and are more curious about animate objects than inanimate objects (Jaenicke & Ehrlich, 1982). Innovation in animals is understood in a slightly different way than commonly understood in design research. Innovation in animals is observed when they respond to environmental stressors or ecological challenges by inventing a new behavior or using existing behaviors in a novel context. This is known as behavioral flexibility (Reader & Laland, 2003). However, there is no evidence to suggest that curiosity toward an object motivates the invention of new behaviors associated with that object and directed toward an innovative activity, not to mention using the novel object to make another new object or objects.

In what is perhaps the most comprehensive study of curiosity in animals (Glickman & Sroges, 1966), zoo animals were given novel objects in their cages. The animals included 207 from the Lincoln Park Zoo in Chicago and 35 primates from the Bronx Zoo in New York. The novel objects were two blocks of wood, two steel chains, two wooden dowels, two pieces of rubber tubing, and a piece of crumpled paper. The primates were the most "curious" in terms of the number of responses to the novel objects, orienting themselves or contacting the objects more often and for a longer duration of time than the other animals. Yet, none of their interactions with the objects could be considered "inventive." Most curious interactions were rather similar to the sort of behaviors associated with the consumption and manipulation of food. The most "interactive" responses were by the baboons and the macaque monkeys who physically manipulated the object by rubbing or stretching it, possibly to investigate the material potentials of the objects. Presumably, these materials were not useful enough because none of the primates spontaneously used the materials to construct a nest. The study authors conclude that both habitat and brain development are predictors of curious behavior, suggesting that the type of stimulation available to an animal and the available brain processes are integral to curiosity driven behavior. In summary, in addition to habitat, "the main contributions of a complex brain will be to increase the variety of things that an animal does with an object, or to extract novelty from situations that would not be apparent to a less complicated organism" (Glickman & Sroges, 1966, p. 182).

This is a finding that is entirely consistent with the research on the sources of creativity in humans. For animals, it is their habitat; for humans, it is the cultural vitality of their community (Florida, 2002; Jackson et al., 2006). The incontrovertible evidence is that humans tend to be more creative in societies that have a preference for novelty, or what Richard Florida (2002) characterizes as tolerance, and where the cultural stimulation is high.

If we abstract away the basic "needs" for survival and economics as drivers for the proliferation of designed artifacts, curiosity remains the key resource *sine qua non* for innovative behaviors. The desire to invent something, perhaps something that the world has not witnessed before, an invention that is likely to be judged by society as "novel to the whole of human history" or what Margaret Boden (2004) termed H-creativity, encapsulates a motivation to invent. In *The Clockwork Muse*, Martindale (1990) presented an extensive investigation into the role that individual novelty-seeking behavior played in literature, music, visual arts, and architecture. He concluded that the search for novelty exerts a significant force on the development of styles. Martindale illustrated the influence of the search for novelty by individuals in a thought experiment where he introduced "the law of novelty." The law of novelty forbids the repetition of word or deed and punishes offenders by ostracizing them. Martindale argued that the law of novelty was merely a magnification of the reality in creative fields. Some of the consequences of the search for novelty are that individuals who do not innovate appropriately will be ignored in the long run and that the complexity of any one style will increase over time to support the increasing need for novelty, hence, "sexier" hand axes.

We need to think of curiosity in two ways: first, as the instigator of action, and second, as a computational mechanism. As a motivator, curiosity can activate actions in the brain to form associative transformations of sensory input and prior conceptual representations as new conceptions. As a computational mechanism, curiosity is a way for the brain to evaluate perceptions, for instance of its own actions or of the ambient reality encountered, to achieve particular goals. We will take each of these functions in turn.

The drive toward voluntary action is essential to behavior. The will to act, or volition, consists of a series of decisions regarding whether one should act, what action to perform, and when to perform the action. Curiosity, an innate interest in novelty, provides us with a reason or value to choose one action over another, that is, to generate the internal signals to perform the action.

The neurological evidence for brain signals associated with a drive for novel behavior has been found in rats (Lee et al., 1998). In one experiment, rats were placed in an opaque Plexiglas box and allowed to explore the box for a period of time undisturbed, presumably to allow them to learn their surroundings. The box was fitted with nosepoke holes so that the rat could smell the fresh popcorn (food) that would be introduced into the box. At the same time, nonfood items were also placed into the box. The scientists found that the specific firing behavior of certain neurons associated with novelty-related stimuli could not be reduced to the motor activity of nosepoking alone, and had to be attributed to the exploration of novelty-related stimuli, in this case, the consumption of novel food.

The second issue has to do with curiosity as a computational mechanism, a way for the brain to evaluate perceptions. What would have been the evolutionary value of curiosity? Curiosity may actually waste mental processing time. Once I have figured out how to make the "optimal" house that suits the local environment, why should I expend further mental energy to design another type of domicile? We return to the sexy hand axe theory to illustrate why curiosity is valuable in such a context. The hand axe, as we discussed in the theory of the mind section, is a particularly apt designed artifact to discuss curiosity as a computational mechanism because one could also make the similar case that once I have designed the perfect hand axe for specific needs, what possible motivation could there be to make other types of hand axes? This is exactly what Kohn and Mithen (1999, p. 524) commented. "Greater time and effort were invested in hand axe manufacture than appears necessary for the adequate accomplishment of utilitarian tasks such as animal butchery, because hand axes also functioned in the social domain as indicators of health and intelligence and as aesthetic displays." The design and manufacture of hand axes is not a trivial task. One could have imagined as well that many unusable and ultimately discarded prototypes would have also developed along the way to the ones that have been found in the archaeological evidence.

Even if their sexual selection theory of the sexy hand axe were wrong, for the male, having a heightened sense of curiosity on the potential design space of hand axes would nonetheless have been a valuable trait. The more curious the male was, the more the society the male lived in was driven by Martindale's law of novelty, the more the male would have been attuned to novelty. A curiosity driven motivation for a diversity of hand axes would have been an advantage to design and produce *even more* novel and useful hand axes. Further, if males had theory of mind to know that the other males were producing novel and useful hand axes as a way to woo females and not just as a "hobby," then would have additional selective advantage. Thus, sexual selection aside, curiosity and theory of mind could account for the capacities and the drivers to design and produce the diversity of high quality hand axes.

If design were merely recombining sensory inputs into multiple, abstract conceptual representations, this certainly could not account for the design of very complex artifacts that are not obvious given the material reality. Designing requires a much more sophisticated level of recombination of sensor inputs; it requires coordinated planning.

2.5. Capacity for deep planning through mental time travel (MTT)

Although the appearance of simplicity is an oft-lauded characteristic of designed artifacts, the reality is that the simplest of objects may have undergone the most complex set of manufacturing operations to obtain a particular curvature or material finish. It is this capacity for depth of planning that is unique to the type of inventiveness that is associated with design.

One of the most compelling theories why humans developed this degree of complex and deep planning is our progression toward bipedalism and upright walking. Walking upright on two legs requires more mental complexity in coordinating the multitude of muscles yet yielded benefits in terms of locomotor economy (Pontzer et al., 2009). The additional complexity associated with bipedalism may have required a larger brain size and a more "connected" brain; the emergence of bipedalism, Aiello (1996) argued, provided an evolutionary engine for the formation of language.

Although it might be a stretch that bipedalism alone was a galvanizer for language, the growth of complexity in the brain may have had a more important consequence, the emergence of what cognitive scientists describe as MTT. Based on the work by Tulving (1993) on episodic memory, Suddendorf and Corballis (1997) define MTT as a general faculty that enables humans to go back in time and to foresee, plan, and shape events that happen at a specific future time. Suddendorf and Corballis have further argued that behaviors providing the ability to plan for the future based on past experience would have a selective advantage. By being able to MTT to the end state of a set of operations, each with a known outcome, acting upon an object, we could imagine a desired transformation. We could plan and rehearse the sequence of operations to achieve the desired shape of a hand axe, for example. We could imagine different sequences of operations to imagine different outcomes, and then select from the most optimal transformations so that we could reduce the manual labor involved making multiple hand axes. Thus, this ability would have been a driver for the evolution of brain structures responsible for human MTT and would have provided a strong adaptive advantage over other species (Suddendorf & Corballis, 2007).

Whether animals can plan for a specific event in the future is still contested. Yet, there is at least one important recently reported instance of planning by a chimpanzee in a zoo in Sweden (Osvath, 2009). Santino, a 31-year-old male chimpanzee at Furuvik Zoo in Sweden, may be the first animal to exhibit an ability to plan for the future. He did not like large crowds and would throw rocks at them. Santino did not merely collect rocks at the time that he was throwing them. At night, when the zoo was closed, he would collect rocks as a supply. He would then use his stash of rocks during the day. He would not use the rocks for any other purpose than for throwing them at people, and he always located the stones near the shoreline facing the visitors. Although this was not a scientifically controlled study, but is instead a very long-term observation over a decade, the zookeepers argue that the evidence could not be dismissed as merely coincidental. In order for Santino to have forward planning, he would have had to envisage future events and plan a way to deal with them. In this case, his plan was to make a cache of rocks specifically to throw at visitors during zoo visiting hours. For instance, he would not collect rocks during winter when the zoo was closed. Roberts and Feeney (2009) argued that Santino may have only relied on semantic knowledge, that is, knowing that humans appear at the zoo, rather than episodic knowledge that humans appear at the zoo at a specific time. Thus, it is inconclusive whether Santino satisfies the semantic and episodic knowledge requirement for MTT (Suddendorf & Busby, 2003). At the moment, the consensus is that only humans possess the capacity for MTT, given the lack of evidence to the contrary. Tomasello and Call (1997) made such a statement about theory of mind, but evidence was eventually produced and they partially retracted the claim (Call & Tomasello, 2008).

3. COMPUTATIONAL MODELS OF DESIGN COMPETENCE

In the present context, the important consideration for computational design is to offer an explanatory theory of design competence. To do so, computational design systems should model or mimic these capabilities, apply these biological first principles to study the evolution of works of design, and to test the relative influence of biology (natural and sexual selection) and culture on the evolution of competency in designing. In the following section, I propose computational models of design competence and experiments that could shed light on each of these aspects.

Starting with the first consideration, let us take the capability to envision. What we would need is a computational model of conception from sensation such that the system can create alternative concepts of the sensory input in a nonrandom manner. This is a problem that has been addressed in various areas including the autonomous formation of shared grounded communication systems (Steels & Kaplan, 2002; Steels, 2003), linguistic structure (Kirby, 2001), and object recognition (Hinton, 2010). Such a question was posed in the context of design problem optimization. In the work by Sarkar et al. (2009, 2010) the authors theorized that the co-occurrences of symbols across different design experiences embed an implicit "meaning" about the design artifact that is not explicitly evident from the formal mathematical problem statements themselves. Using singular value decomposition, the authors showed that a scaling of the variables, parameters, and constraints as design concepts occurring in "context" of each other could be used to construct new abstract variables that were useful in identifying alternative constructions of optimization problems that were solvable. This type of consideration would allow us to answer questions such as the "cold start" for design. In other words, starting from the "first" designed object, how could we computationally explain the "emergence" of subsequent objects? How were alternative concepts "seen" in the "first" works of design or in the local materials available to early hominins? Were the instructions required to produce certain types of objects biologically hardwired into our ancestors' brains? Alternatively, did they copy (mimic) other species and conspecifics as their brain developed the ability to understand the intentions of others (theory of mind) and thereby understand what the objects they observed were used for?

The second issue is to apply these cognitive mechanisms as a "package" to study how they would have been useful in an evolutionary sense (Dunbar & Barrett, 2007), that is, how they provided a selective advantage. Let us take the notion of style (Jupp & Gero, 2006). The emergence of design styles would have been as useful as the emergence of different "languages" as a way to unify and demarcate social groups. Similar work on innate learning biases with cultural transmission has been used to explain the emergence of variation of language in populations (Nettle, 1999; Kirby et al., 2007). We could computationally simulate the emergence of design styles in artificial agents that possess different capabilities and to increasing degrees. Using these agents, we would need to identify which of the cognitive mechanisms would be necessary and sufficient to explain how humans could have generated different styles of works of design and how variations in the degree of ability in one of those areas would have had the most significant influence on the rate of production of novel styles.

The final consideration is to test assertions of stronger biological or cultural determinism in the development of design performance, that is, ever increasing levels of sophisticated "designerly" behaviors. For example, to what extent might population density have been a factor in the emergence of the cognitive package for design competence (Powell et al., 2009) rather than evolution alone? Questions such as this one could be tested computationally in an artificial setting. Suppose we have an artificial creative society comprising artificial agents that design new letter faces (i.e., fonts). Individual agents can construct geometric forms by combining simple shape elements such as lines and points (Hu & Hersch, 2001). It may be possible to model this process through the use of Bayesian model of cognition and computational curiosity. Let us propose the following model of artificial agents that generate and identify new letter faces. These agents would autonomously generate many letter face prototypes, but should only select novel prototypes from those generated so that new styles could "emerge." Let r denote the set of experiences of styles; $P(r)$ the distribution on the variation of experiences, where a narrow distribution implies a strong prior bias and vice versa; and a denotes the new, generated prototype. The variation in experience after seeing the prototype $P(r|a)$ and the belief that the prototype is consistent with the experience $P(r|a)$ can be calculated using Bayes' rule. Given the probability calculations, the agents can, for example, identify a particular prototype as novel based on these degrees of belief. The degree of belief can be modulated in turn by an agent's novelty-seeking behavior given its hedonistic preference and the society's average curiosity (Saunders, 2007). How does the preferred novelty of the agent society influence individual generation of new styles? Does inventiveness correlate with a society's average curiosity or is it more strongly dependent on the agent's hedonistic preference? Answering these types of questions can help to understand the coupling between innate cognitive mechanisms and cultural influences.

4. A COGNITIVE "PACKAGE" FOR DESIGN COMPETENCE

The struggle to survive and pass on genetic code to the next generation has been exerting pressure on animals to perform behaviors that, at face value, look alarmingly similar to design, except that we have had a tendency to describe these behaviors as instinctive. When we see a beaver build a dam, we describe the animal behavior as instinct. When we discovered that humans started to make tools during the Middle Stone Age, we did not describe this as instinct, but as the evolution of modern behaviors. McBrearty and Brooks (2000, p. 495) described blade production in the following way:

> Blade production, whether by direct or indirect percussion, requires the cognitive skills to perceive artifact forms not preordained by the raw material and to visualize the manufacturing process in three dimensions, in addition to the dexterity to carry out a complex series of operations and corrections as the process advances.

From this definition, it would appear that human design competence appeared at least during the Middle Stone Ages. By that time, humans had a capacity to imagine an object with a specific purpose in mind; that is, they were designing. We were shaping our environment in a deliberate way.

The aim of this article was to examine the biological evidence for the cognitive package for design competence. The resultant texture of understanding design has been to show that triangulation of evidence from multiple fields could become a template for the identification of biological first principles for cognitive mechanisms underlying design competence and the exploration of computational models of design based on these first principles.

Because computational models of design take as their start some definition of design, these models of design are only as satisfactory as those definitions. The hypothetical package outlined in this paper is based on biological evidence. It was based on the premise that humans evolved the biological cognitive hardware for a sufficiently large and complex brain due to an imperative to design. The future of *H. sapiens* became unbounded as a consequence of design competence.

Yet, we know alarmingly little about how the human became a species innately predisposed to seek a new world that does not yet exist. Artists and musicians have often been quoted as saying that they create new worlds through their work because they do not care very much for the world in which they live. This concept of envisioning another world and reifying that world such that this world can be shared and communicated to others is a truly unique characteristic of language, art, music, and design that has been underdeveloped and is in need of further investigation. Although each of these might have areas in the brains specifically devoted to them, the explanation that I favor is that the ensemble of language, music, art, and design are cascade effects of a brain system predisposed to design its world. Computational studies in the evolution of design competence may provide some unifying evidence why human behaviors including tool making, art, music, and language may have all been shaped by one fortuitous amalgamation.

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REFERENCES

Adolphs, R. (2003). Cognitive neuroscience of human social behaviour. *Nature Reviews Neuroscience 4(3)*, 165–178.

Aiello, L.C. (1996). Terrestriality, bipedalism and the origin of language. In *Evolution of Social Behaviour Patterns in Primates and Man* (Runciman, W.G., Maynard Smith, J., & Dunbar, R.I.M., Eds.), pp. 262–290. Oxford: Oxford University Press.

Baron-Cohen, S. (1987). Autism and symbolic play. *British Journal of Developmental Psychology 5(2)*, 139–148.

Bernstein, I.S. (1962). Response to nesting materials of wild born and captive born chimpanzees. *Animal Behaviour 10(1–2)*, 1–6.

Bilda, Z., & Gero, J.S. (2007). The impact of working memory limitations on the design process during conceptualization. *Design Studies 28(4)*, 343–367.

Bloom, P. (1996). Intention, history, and artifact concepts. *Cognition 60(1)*, 1–29.

Boden, M.A. (2004). *The Creative Mind: Myths and Mechanisms*, 2nd ed. London: Routledge.

Bourguignon, E. (1979). *Psychological Anthropology: An Introduction to Human Nature and Cultural Differences*. New York: Holt, Rinehart & Winston.

Buchanan, R. (1989). Declaration by design: rhetoric, argument, and demonstration in design practice. In *Design Discourse: History, Theory, Criticism* (Margolin, V., Ed.), pp. 91–109. Chicago: University of Chicago Press.

Burgdorf, J., & Panksepp, J. (2006). The neurobiology of positive emotions. *Neuroscience & Biobehavioral Reviews 30(2)*, 173–187.

Call, J., & Tomasello, M. (2008). Does the chimpanzee have a theory of mind? 30 years later. *Trends in Cognitive Sciences 12(5)*, 187–192.

Chomsky, N. (1987). *Language and Problems of Knowledge: The Managua Lectures*. Cambridge, MA: MIT Press.

Crilly, N., Moultrie, J., & Clarkson, P.J. (2009). Shaping things: intended consumer response and the other determinants of product form. *Design Studies 30(3)*, 224–254.

Dawkins, R. (1999). *The Extended Phenotype: The Long Reach of the Gene*. Oxford: Oxford University Press.

Day, R.L., Laland, K.N., & Odling-Smee, F.J. (2003). Rethinking adaptation: the niche-construction perspective. *Perspectives in Biology and Medicine 46(1)*, 80–95.

Deacon, T.W. (1997). *The Symbolic Species: the Co-evolution of Language and the Brain*. New York: W.W. Norton.

Dunbar, R.I.M. (1998). The social brain hypothesis. *Evolutionary Anthropology: Issues, News, and Reviews 6(5)*, 178–190.

Dunbar, R.I.M., & Barrett, L. (2007). Evolutionary psychology in the round. In *The Oxford Handbook of Evolutionary Psychology* (Dunbar, R.I.M., & Barrett, L., Eds.), pp. 3–9. Oxford: Oxford University Press.

Florida, R. (2002). *The Rise of the Creative Class: And How It's Transforming Work, Leisure, Community and Everyday Life*. New York: Basic Books.

Gero, J.S. (1990). Design prototypes: a knowledge representation schema for design. *AI Magazine 11(4)*, 26–36.

Gibson, J.J. (1979). *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.

Glickman, S.E., & Sroges, R.W. (1966). Curiosity in zoo animals. *Behaviour 26(1/2)*, 151–188.

Gowlett, J.A.J. (2009). Artefacts of apes, humans, and others: towards comparative assessment and analysis. *Journal of Human Evolution 57(4)*, 401–410.

Gurnell, A.M. (1998). The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography 22(2)*, 167–189.

Henshilwood, C.S., d'Errico, F., Yates, R., Jacobs, Z., Tribolo, C., Duller, G.A.T., Mercier, N., Sealy, J.C., Valladas, H., Watts, I., & Wintle, A.G. (2002). Emergence of modern human behavior: Middle Stone Age engravings from South Africa. *Science 295(5558)*, 1278–1280.

Hinton, G.E. (2010). Learning to represent visual input. *Philosophical Transactions of the Royal Society B: Biological Sciences 365(1537)*, 177–184.

Hodgson, D. (2009). Symmetry and humans: reply to Mithen's "sexy handaxe theory." *Antiquity 83(319)*, 194–195.

Houkes, W., Vermaas, P.E., Dorst, K., & de Vries, M.J. (2002). Design and use as plans: an action–theoretical account. *Design Studies 23(3)*, 303–320.

Hu, C., & Hersch, R.D. (2001). Parameterizable fonts based on shape components. *Computer Graphics and Applications 21(3)*, 70–85.

Jackson, M.R., Kabwasa-Green, F., & Herranz, J. (2006). *Cultural Vitality in Communities: Interpretation and Indicators*. Washington, DC: Urban Institute.

Jaenicke, C., & Ehrlich, A. (1982). Effects of animate vs. inanimate stimuli on curiosity behavior in greater galago and slow loris. *Primates 23(1)*, 95–104.

Jarrold, C., Boucher, J., & Smith, P. (1993). Symbolic play in autism: a review. *Journal of Autism and Developmental Disorders 23(2)*, 281–307.

Jupp, J.R., & Gero, J.S. (2006). A qualitative feature-based characterization of 2D architectural style. *Journal of the American Society for Information Science and Technology 57(11)*, 1537–1550.

Kirby, S. (2001). Spontaneous evolution of linguistic structure—an iterated learning model of the emergence of regularity and irregularity. *IEEE Transactions on Evolutionary Computation 5(2)*, 102–110.

Kirby, S., Dowman, M., & Griffiths, T. L. (2007). Innateness and culture in the evolution of language. *Proceedings of the National Academy of Sciences of the United States of America 104(12)*, 5241–5245.

Klein, R.G. (2000). Archeology and the evolution of human behavior. *Evolutionary Anthropology: Issues, News, and Reviews 9(1)*, 17–36.

Kohn, M., & Mithen, S. (1999). Handaxes: products of sexual selection? *Antiquity 73(281)*, 518–526.

Laland, K.N., Odling-Smee, J., & Feldman, M.W. (2000). Niche construction, biological evolution, and cultural change. *Behavioral and Brain Sciences 23(1)*, 131–146.

Laland, K.N., Odling-Smee, J., & Feldman, M.W. (2001). Cultural niche construction and human evolution. *Journal of Evolutionary Biology 14(1)*, 22–33.

Laland, K.N., Sterelny, K., & Harrison, R. (2006). Perspective: seven reasons (not) to neglect niche construction. *Evolution 60(9)*, 1751–1762.

Latchman, D.S. (1997). Transcription factors: an overview. *International Journal of Biochemistry & Cell Biology 29(12)*, 1305–1312.

Lee, R.-S., Koob, G.F., & Henriksen, S.J. (1998). Electrophysiological responses of nucleus accumbens neurons to novelty stimuli and exploratory behavior in the awake, unrestrained rat. *Brain Research 799(2)*, 317–322.

Leslie, A.M. (1987). Pretense and representation: the origins of "theory of mind." *Psychological Review 94(4)*, 412–426.

Lewis-Williams, D. (2002). *The Mind in the Cave: Consciousness and the Origins of Art*. London: Thames and Hudson, Ltd.

Liégeois, F., Baldeweg, T., Connelly, A., Gadian, D.G., Mishkin, M., & Vargha-Khadem, F. (2003). Language fMRI abnormalities associated with *FOXP2* gene mutation. *Nature Neuroscience 6*, 1230–1237.

Lillard, A.S. (1993). Pretend play skills and the child's theory of mind. *Child Development 64(2)*, 348–371.

Marean, C.W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A.I.R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P.J., Thompson, E., Watts, I., & Williams, H.M. (2007). Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature 449(7164)*, 905–908.

Martindale, C. (1990). *The Clockwork Muse: The Predictability of Artistic Change*. New York: Basic Books.

Mayeaux, D., & Mason, W. (1998). Development of responsiveness to novel objects in the titi monkey, *Callicebus moloch. Primates 39(4)*, 419–431.

Mcbrearty, S., & Brooks, A.S. (2000). The revolution that wasn't: a new interpretation of the origin of modern human behavior. *Journal of Human Evolution 39(5)*, 453–563.

Mesulam, M.M. (1998). From sensation to cognition. *Brain 121(6)*, 1013–1052.

Meyer-Lindenberg, A., Mervis, C.B., & Berman, K.F. (2006). Neural mechanisms in Williams syndrome: a unique window to genetic influences on cognition and behavior. *Nature 7*, 380–393.

Moessner, R., Marshall, C.R., Sutcliffe, J.S., Skaug, J., Pinto, D., Vincent, J., Zwaigenbaum, L., Fernandez, B., Roberts, W., Szatmari, P., & Scherer, S.W. (2007). Contribution of *SHANK3* mutations to autism spectrum disorder. *American Journal of Human Genetics 81(6)*, 1289–1297.

Nettle, D. (1999). *Linguistic Diversity*. Oxford: Oxford University Press.

Norman, D.A. (1998). *The Design of Everyday Things*. New York: Basic Books.

Norman, D.A. (2005). *Emotional Design: Why We Love (or Hate) Everyday Things*. New York: Basic Books.

Osvath, M. (2009). Spontaneous planning for future stone throwing by a male chimpanzee. *Current Biology 19(5)*, R190–R191.

O'Toole, M. (1994). *The Language of Displayed Art*. London: Leicester University Press.

Perner, J. (1991). *Understanding the Representational Mind*. Cambridge, MA: MIT Press.

Perner, J., & Doherty, M. (2005). Do infants understand that external goals are internally represented? *Behavioral and Brain Sciences 28(5)*, 710–711.

Pontzer, H., Raichlen, D.A., & Sockol, M.D. (2009). The metabolic cost of walking in humans, chimpanzees, and early hominins. *Journal of Human Evolution 56(1)*, 43–54.

Powell, A., Shennan, S., & Thomas, M.G. (2009). Late Pleistocene demography and the appearance of modern human behavior. *Science 324(5932)*, 1298–1301.

Purcell, A.T., & Gero, J.S. (1998). Drawings and the design process: a review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies 19(4)*, 389–430.

Reader, S.M., & Laland, K.N. (2003). Animal innovation: an introduction. In *Animal Innovation* (Reader, S.M., & Laland, K.N., Eds.), pp. 3–35. Oxford: Oxford University Press.

Roberts, W.A., & Feeney, M.C. (2009). The comparative study of mental time travel. *Trends in Cognitive Sciences 13(6)*, 271–277.

Rushbrook, B.J., Dingemanse, N.J., & Barber, I. (2008). Repeatability in nest construction by male three-spined sticklebacks. *Animal Behaviour 75(2)*, 547–553.

Sarkar, S., Dong, A., & Gero, J.S. (2009). Design optimization problem (re)-formulation using singular value decomposition. *Journal of Mechanical Design 131(8)*, 10.

Sarkar, S., Dong, A., & Gero, J.S. (2010). Learning symbolic formulations in design: syntax, semantics, knowledge reification. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 24(1)*, 63–85.

Saunders, R. (2007). Towards a computational model of creative societies using curious design agents. In *Engineering Societies in the Agents World VII* (O'Hare, G., Ricci, A., O'Grady, M., & Dikenelli, O., Eds.), Vol. 4457, pp. 340–353. Berlin: Springer–Verlag.

Schön, D.A. (1983). *The Reflective Practitioner: How Professionals Think in Action*. New York: Basic Books.

Stahmer, A. (1995). Teaching symbolic play skills to children with autism using pivotal response training. *Journal of Autism and Developmental Disorders 25(2)*, 123–141.

Steels, L. (2003). Evolving grounded communication for robots. *Trends in Cognitive Science*, *7(7)*, 308–312.

Steels, L., & Kaplan, F. (2002). AIBO's first words: the social learning of language and meaning. *Evolution of Communication 4(1)*, 3–32.

Suchman, L. (1987). *Plans and Situated Actions: The Problem of Human–Machine Communication*. Cambridge: Cambridge University Press.

Suddendorf, T. (1999). The rise of the metamind. In *The Descent of Mind: Psychological Perspectives on Hominid Evolution* (Corballis, M.C., & Lea, S.E.G., Eds.), pp. 218–260. Oxford: Oxford University Press.

Suddendorf, T., & Busby, J. (2003). Mental time travel in animals? *Trends in Cognitive Sciences 7(9)*, 391–396.

Suddendorf, T., & Corballis, M.C. (1997). Mental time travel and the evolution of the human mind. *Genetic, Social, and General Psychology Monographs 123(2)*, 133–167.

Suddendorf, T., & Corballis, M.C. (2007). The evolution of foresight: what is mental time travel, and is it unique to humans? *Behavioral and Brain Sciences 30(3)*, 299–313.

Suddendorf, T., & Whiten, A. (2001). Mental evolution and development: evidence for secondary representation in children, great apes and other animals. *Psychological Bulletin 127(5)*, 629–650.

Tomasello, M. (1999). *The Cultural Origins of Human Cognition*. Cambridge, MA: Harvard University Press.

Tomasello, M., & Call, J. (1997). *Primate Cognition*. Oxford: Oxford University Press.

Tulving, E. (1993). What is episodic memory? *Current Directions in Psychological Science 2(3)*, 67–70.

Tutin, C., Parnell, R., White, L., & Fernandez, M. (1995). Nest building by lowland gorillas in the Lopé Reserve, Gabon: environmental influences and implications for censusing. *International Journal of Primatology 16(2)*, 53–76.

Vargha-Khadem, F., Gadian, D.G., Copp, A., & Mishkin, M. (2005). *FOXP2* and the neuroanatomy of speech and language. *Nature Reviews Neuroscience 6(2)*, 131–138.

Wojcieszek, J.M., Nicholls, J.A., & Goldizen, A.W. (2007). Stealing behavior and the maintenance of a visual display in the satin bowerbird. *Behavioral Ecology 18(4)*, 689–695.

Youn-Kyung, L., Erik, S., & Josh, T. (2008). The anatomy of prototypes: prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions Computer–Human Interaction 15(2)*, 1–27.

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