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Bootstrapping Ordinal Thinking

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Introduction

Paleoanthropology has long championed a biocultural perspective on human evolution in which biology and culture are seen to have evolved together to produce the modern human condition. Most paleoanthropological accounts of evolutionary mechanism, however, remain fairly straightforward Darwinian models elaborated with ecological and demographic insights. In such models, biology–culture co-evolution occurs via selection for cultural capacity. In the narrower domain of cognitive evolution, the interrelationship between culture and biology, especially via technology, has been a tantalizing but poorly explored area of research. Are there components of human cognition that evolved specifically in response to human culture? It certainly seems as if there should be; after all, extensive reliance on culture is one of the things that distinguishes us from our primate cousins. Yet the literature remains frustratingly vague. Dunbar and colleagues (Dunbar, Gamble, & Gowlett, 2014) have proposed theory of mind as a response to complex social life, with Cole (2014 and Chapter 8, this volume) proposing a role for handaxes in the evolution of second- and third-order levels of intentionality. Recently, Overmann has explored the material basis of numerosity (2013, 2015, and Chapter 5, this volume) and literacy (2016), but there are few other examples that integrate a *specific technology* with a *specific cognitive ability* and its *neural substrate*. In this chapter, we propose to do just this by describing how a narrowly circumscribed cognitive ability—conceiving of ordinal sequences—could have evolved relatively quickly via embodied and extended cognition and the developmental process of neuronal recycling.

The Extended Mind

Cognition does not happen just in the head; it employs and thus in some sense includes the physical resources of bodies and artifacts. This is the core realization of the perspective in cognitive science known variously as the embodied/situated/extended mind (Clark, 1997; Malafouris, 2013; Robbins & Aydede, 2009; also see Chapter 4). One obvious example is the calculator; anyone can perform complex calculations (including calculus) using a handheld device. In a very real sense, this device makes its users smarter (i.e., able to solve problems they could not otherwise solve). The calculator is a recent and obvious example, but there are others, many of which have considerable antiquity. One example of such a device is the calendar, which enables its users to plan activities far in advance and remember activities performed in the past. In addition to external devices, there are in-the-head knowledge systems that enable users to take advantage of these devices, perform operations mentally, structure their understanding of environmental stimuli, act and interpret the actions of others in meaningful ways, and so on. Arithmetic, for example, is a cultural algorithm (i.e., a learned set of rules), and it in turn is based on yet another cultural algorithm, the formal number concept. Neither of these algorithms is natural, in the sense of pre-existing in the world waiting to be discovered; instead, both must be constructed and learned by an individual in a cultural context. Similarly, a calendar is a cultural algorithm that presupposes time to be structured as a divisible substance with a sequence of units that can be extended into the past and the future. And if these knowledge systems were not impressive enough on their own, they in turn rely on specific neurocognitive resources. In the case of number concept, these neurocognitive resources are subitization and magnitude estimation (Chapter 5; Coolidge & Overmann, 2012). In the case of calendars, there are two cognitive bases: *autonoesis*, the subjective feel for present, future, and past (De Smedt & de Cruz, 2011; Tulving, 2002), and *ordinality*, the arranging of sequences along a uniform dimension.

So where is the modern mind in these examples? Is it in the devices? In the knowledge systems? In the neural networks of the brain? Or in all of them together? Untangling these elements in an evolutionary sense is the key issue for understanding the evolution of the human mind.

Arguably, even the neurocognitive components of these systems developed and evolved via the extended resources of knowledge systems and artifacts. Malafouris (2008, 2013; Malafouris & Renfrew, 2008), for example, has made an elegant argument for how material social markers such as beads could act as scaffolds for extending a concept of self into the past and future—autonoetic thinking, the first of the two cognitive bases for calendric time. Simply, the temporal extension of beads enables the user to extend his or her self from the present into the past and future: “These special epistemic qualities emanate primarily

from the ability of the beads, as material things attached to the body, to transform the phenomenological self-as-subject to a social self-as-object” (p. 408). To put it another way, wearing beads today identifies this self as me; wearing the beads tomorrow or yesterday identifies the future or past self as me.

How material culture might have worked to scaffold the second neurocognitive component of calendric time—ordinality—is the focus of the following analysis.

Ordinality

Ordinality is an essential component of modern calendars, alphabets, and number concepts. The term has two related meanings. The more general meaning is the construction of or attention to invariant sequences of some kind (e.g., days of the week, months of the year, numbers, alphabets, and so on). The narrower meaning limits ordinality to numbers that can be arranged in terms of increasing cardinal value (e.g., Ischebeck et al., 2008). The following discussion will use the first, more general meaning of invariant sequence.

Evidence from cognitive neuroscience in the form of imaging studies, experiments demonstrating double dissociation, and an unusual condition known as synaesthesia suggest that the ability to represent ordered relations may be a comparatively coherent cognitive ability distinct from other components of quantitative thinking (Rubinsten & Sury, 2011). The basic ability to rank items in terms of size (a minimal ordinal relationship) is present in infants as young as 11 months and has been demonstrated in monkeys and even chicks (Lyons & Beilock, 2011; Rubinsten & Sury, 2011). Neuroimaging studies have established the intraparietal sulcus (IPS) as the locus of ordinal representations in both children and adults (Ischebeck et al., 2008; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009), and the IPS is also the location activated in numerical quantity judgments (Orban & Caruana 2014). There is some evidence that numerical sequences and alphabetic sequences activate slightly different locations of the anterior IPS, but this distinction is far from established (Rubinsten & Sury, 2011). There is also a tentative indication that the right IPS is more heavily activated in nonsymbolic number processing and the left IPS in symbolic numerical processing, but again this remains preliminary (Kaufmann et al., 2009).

Neuroimaging evidence is provocative. Not only does it reveal the close neurological contiguity for the processing of numbers and sequences, but it also links them closely with spatial cognition. However, this contiguity does not require that they be linked in a functional or evolutionary sense. Indeed, neuropsychological evidence suggests that the processing of numbers and sequences are separate: individuals with brain lesions demonstrate a classic double dissociation of cardinal value and ordinal judgments. Delazer and Butterworth (1997) describe

a patient with an impaired ability to judge the cardinal value of numbers but who retained ordinal judging ability, and Turconi and Seron (2002) describe a patient with ordinal impairment who retained most quantitative abilities. As with neuroimaging studies, such neuropsychological evidence must be used with care, but these studies do suggest that ordinality and quantity judgments may have relatively separate neural bases.

The evidence for dissociation is further corroborated by a phenomenon known as *synaesthesia*, a neurological condition in which perceptual information from one domain leaks into percepts of another type—sounds evoking tastes, smells evoking colors, vision evoking smells. The most common forms of synaesthesia are *grapheme synaesthesia*, in which numbers or letters evoke colors (found in an estimated 4% of the population); *number-space synaesthesia*, in which numbers appear to occupy positions in space; and *day-month synaesthesia*, in which days of the week and/or months in the year evoke colors (see Cohen Kadosh, Gertner, & Terhune, 2012; Cohen Kadosh & Henik, 2007; Gertner, Henik, Reznik, & Cohen Kadosh, 2013; Novich, Cheng, & Eagleman, 2011; Simner, 2009, 2012).

The neurological basis of synaesthesia has not been clearly established, but many researchers believe that it results from an incomplete “pruning” of neural networks during cortical development, such that normally separate perceptual networks remain linked and able to “cross-talk” (Spector & Maurer, 2009). This cross-talk has been demonstrated in positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) imaging studies. When Tang, Ward, and Butterworth (2008) used fMRI to study individuals with number-form synaesthesia, they found that, for these individuals, ordinal tasks (which involve representing and recalling overlearned sequences) activated bilateral IPS regions that were slightly posterior to the regions activated by number value. In another fMRI investigation of synaesthetes, Pariyadath and colleagues (Pariyadath, Churchill, & Eagleman, 2008) found that the overlearned sequences activated regions of the right middle temporal gyrus, the right temporo-parietal junction, and the left inferior frontal gyrus.

The cross-talk between cognitive domains supplies a handy noninvasive tool with which to explore the nature of cognition (Cohen Kadosh & Henik, 2007). In essence, output from one neural network or neuronal group illuminates the working of a second, normally independent network, thereby revealing structure that is not otherwise apparent. Alphabets, numbers, days of the week, and months of the year all share one salient feature: they are all overlearned ordinal sequences (Eagleman, 2009). In synaesthetes, output from neuronal groups in the visual cortex “colors” overlearned sequences, revealing the existence of brain resources that facilitate sequential organizing. Note that it is not the values themselves that evoke color; rather, it is the ordinal positions. If there were no neural ordinal generator, there would be nothing for the neural cross-talk to color, and there would be no grapheme or day/month synaesthesia. Thus, one of the most common forms of synaesthesia strongly indicates that the human

brain is endowed with a neural mechanism for representing and recalling overlearned ordinal sequences.

Here is the odd thing about such overlearned sequences: they are not natural. Nothing in the natural human life-world or environment exists as an invariant sequence with elements that change uniformly according to some unidimensional value.¹ Days are constructs, months are constructs, numbers are constructs, and alphabets are constructs. This in turn suggests the tantalizing possibility that a specific neural network has evolved in service of a specific kind of cultural thinking.

Bootstrapping

Bootstrapping is a metaphor for a particular kind of cognitive development in which a more powerful cognitive system (CS2) is self-generated using a less powerful antecedent system (CS1). The classic example, discussed at length by Carey (2009), is children's construction of number concept. Children are born with innate abilities to judge small numbers (subitization) and compare larger quantities (magnitude estimation; Coolidge & Overmann, 2012). But they must learn numbers, and the manner in which they acquire this ability is quite revealing. They use the *words* for numbers as "placeholders" for the concept itself. Children first memorize the list of numerals, sometimes as high as twenty or more, without understanding the basic rule of cardinal value ($1 + 1 = 2$, $2 + 1 = 3$, . . . $n + 1 = x$). These placeholders enable them to notice and think about numerical relationships. They learn that small numbers follow the cardinal rule, and eventually they realize that all numbers are constructed using it. Here, it is the lexical labels that act as placeholders, but material objects can also play this role. In US grade schools, it is common for teachers to use colored blocks of proportional length to teach basic arithmetic. The blocks act as placeholders for numbers as children explore the combinatorial possibilities and invariances. From this they construct concepts of addition and subtraction.

Much the same process must have underpinned the initial development of such concepts in the human past. In this context, however, lexical labels could not have acted as placeholders because the labels did not exist; similarly, labels for days of the week could not have existed prior to a concept of "week." When there are no pre-existing lexical labels or concepts, there are actually two avenues by which ordinality might have evolved—through embodied cognition using anatomical parts or through material extension.

Fingers

Developing the ability to count begins with making one-to-one correspondences between a reference set of objects and a set of objects to be counted. Fingers

provide a particularly convenient reference set. Moreover, the ability to control precise movements of the fingers is neurofunctionally associated with the perceptual system for quantity; both are subserved by the IPS, making their interaction in counting cognitively prepotent. The close association of the perceptual system for quantity and finger movement has also been demonstrated in fMRI studies of children performing number tasks (Krinzinger et al., 2011).

Finger-counting is shared across cultures, regardless of the complexity of number systems (Crollen, Seron, & Noel, 2011; Overmann, 2013, 2014). Not all cultures use the same system, but all seem to function under similar neuromuscular constraints. Given the cross-cultural ubiquity of finger-counting, it appears likely that the use of the fingers for counting preceded the use of material devices like knotted strings, tokens, tally sticks, or stringed beads (for a more detailed discussion, see Chapter 5 and Overmann, 2013, 2015).

As quantification devices, fingers and the body are limited, functioning mainly to aid working memory in the moment. Their accuracy (ability to reproduce a quantity's actual value) is generally limited to values that can be counted using both hands, both feet, and arbitrary locations on the arms, legs, head, and torso. Their precision (ability to reproduce a quantity's value under different conditions) diminishes whenever something interrupts the counter's attention. Their capacity does not generally afford an ability to handle large or complex numbers, and they lack the ability to communicate across time or distance. Thus, as useful as such a system clearly is and has been, it is unlikely on its own to have been the scaffold for ordinality. Something else was needed.

Beads

Material devices provide a better avenue for bootstrapping an ordinal concept than do fingers. As discussed earlier, material objects can extend cognition, enabling the limited resources of one conceptual system (CS1) to construct a more powerful understanding (CS2). In the case of ordinality (CS2), the antecedent abilities (CS1) consist of core numerosity (subitization and magnitude estimation) and an ability to label. How could such limited resources lead to an ordinal concept? In the absence of an ordinal model, it would seem to be impossible (Fodor's paradox; see Carey, 2009): for example, how could one conceive of a calendar without an ordinal sequence as a model? A material scaffold provides a way around the impasse.

Ethnographic examples of such devices are fairly common. In the 19th century on the Southwestern Plains of the United States, the Comanche used tally sticks to transmit detailed route instructions to young men raiding into terrain unknown to them. Older, experienced men would sit the young men down around the fire the night before the raid and provide each with a stick. The

experienced men would describe each landmark the raiders would encounter on their journey. For each change in direction the young men would be instructed to make a notch on the tally stick. The novices would then recite by feel what landmark each notch on the tally marker indicated, and they were expected to repeat the directions back until it was perfectly memorized (Dodge, 1883). Here, the notches on a stick acted as an ordinal mnemonic that helped the user recall a sequence of moves that had to be made in the proper order. In the modern world, beads can similarly act as extensions of cognition. *Ranger beads*, for example, are used by mountaineers and specialized military units to keep track of distance traveled on foot. In a typical example, a bead user will determine the number of his or her paces that equal 100 meters. When traveling, users can then count paces and pull down a bead every time they hit their 100-meter mark. This application of tally markers extends the users' working memory while navigating and provides a very accurate means of determining distance traveled. Skilled users can be accurate to within a few meters after navigating many kilometers using this system.

A string of beads is potentially more powerful than notched sticks or knotted strings because it materially instantiates three phenomena (CS1): a one-dimensional series, individuation of items, and an invariant sequence. Each bead occupies an unchanging sequential position along the dimension of the string, although there are two different sequences determined by the direction of movement. If the various beads have different sizes, shapes, or colors, the structure becomes a feral ordinal composition, with each bead occupying a unique, invariant place (until the string is broken). These qualities are inherent to the structure of a string of beads and do not require that the maker possess an ordinal concept. But stringing and manipulating beads enables anyone to *notice* and even *think about* certain relationships, with beads acting as placeholders, much as modern children use numerical labels. One of the relationships is one-to-one correspondence; beads on a string can be matched with items in another array. From this, a simple quantifying device—*without numbers* (i.e., like the rosary, which matches beads to prayers)—could be developed. It is also possible to attach labels to different beads, at which point the invariant sequence becomes a material ordinal device that could be used to track and organize other sequential phenomena (e.g., days). The labels could then become an overlearned sequence detached from the device itself; that is, a true ordinal concept.

Evidence for Beads in the Middle Stone Age

Our choice of beads as a primary example stems from a confluence of evidence and interpretations that emerged during investigations into the evolution of working memory capacity. The South African Middle Stone Age (MSA)

boasts a number of sites that have presented the paleoanthropological community with the earliest evidence for a number of posited components of modern culture: bow-and-arrow at Sibudu (Lombard & Haidle, 2012), engravings at Diepkloof and Blombos Cave (d'Errico, Henshilwood, & Nilssen, 2001; Henshilwood, 2007), and, most famous of all, beads at Blombos Cave (d'Errico, Henshilwood, Vanhaeren, & van Niekerk, 2005; Marean, 2010; Vanhaeren, d'Errico, Niekerk, Henshilwood, & Erasmus, 2013). At Blombos, evidence clearly indicates that the beads were strung (Vanhaeren et al., 2013).

On the interpretive side, these beads, especially those from Blombos, have anchored arguments for symbolic culture, social marking, and language (d'Errico et al., 2003; d'Errico et al., 2005; Henshilwood, 2007; Henshilwood & Dubreuil, 2009; Henshilwood & Marean, 2003). Our own investigations into the evolution of modern working memory capacity (e.g., Wynn & Coolidge, 2010) emphasized other features of the archaeological record. However, more recently in our investigation into the evolution of numerosity (Coolidge & Overmann, 2012; Overmann, 2013, 2015; Overmann, Wynn, & Coolidge, 2011; Wynn, Coolidge, & Overmann, 2013; Chapter 5), we examined the possible uses of beads, including possible use as a counting device (Janulis, 2012). We determined that beads alone, even if strung, would not imply the presence of a true number concept because they would not require a cardinal rule ($1 + 1 = 2$, $2 + 1 = 3 \dots n + 1 = x$). However, strings of beads have a number of inherent features that make them provocative candidates for scaffolds of other cognitive abilities.

Bead use in the MSA was widespread, geographically and chronologically speaking, in Africa and the Near East (Bar-Yosef Mayer, Vandermeersch, & Bar-Yosef, 2009; Bouzouggar et al., 2007; d'Errico, Vanhaeren, & Wadley, 2008; d'Errico et al., 2009; Güleç, Kuhn, & Stiner, 2002; Henshilwood, d'Errico, Vanhaeren, van Niekerk, & Jacobs, 2004; Kuhn & Stiner, 2007; Lombard, 2012; Vanhaeren et al., 2006), so much so that the archaeological evidence warrants the claim that the manufacture and stringing of beads was regularly practiced for thousands of years. Moreover, beads were clearly a component of the artifact repertoire of the modern people who colonized Australia (Balme & Morse, 2006). Bead use in the MSA after 80 kya was common, if not ubiquitous—common enough for beads to be included among the everyday artifacts of human culture.

The Adaptive Value of Ordinality: Enhanced Planning and Structured Time

Why should ordinal thinking have acquired dedicated cognitive resources? Ordinality is a very useful organizational concept, especially for repeated or sequential phenomena. Instantiated through a simple string of beads or other material device, it could have solved a number of adaptive problems.

Some foraging strategies, for example, could have been made more efficient through the use of tally markers. Lyn Wadley and colleagues, for example, have argued that traps and snares were used during the time of the Howiesons Poort industry and perhaps the Still Bay industry in the South African MSA (Wadley, Hodgskiss, & Grant, 2009). One of us (KJ) has undertaken actualistic research in cooperation with primitive skills experts John McPherson to test the efficacy of such trapping systems. Results clearly suggest that acquisition of small mammals would have been greatly enhanced by a methodical harvesting strategy that incorporated an external mnemonic aid. In order to rely on food from traps, snares, or other “remote capture” systems, the devices must be employed in large numbers. Eight to ten traps is arguably the bare minimum when targeting small game such as rats or rabbits, with much higher numbers being required to reliably provide food on a day-to-day basis (McPherson & McPherson, 2003, p. 174). In order to make effective use of such traps, they must be moved frequently and checked daily in order to avoid overharvesting one area or spoiling meat that is not retrieved soon enough. Daily recall of the location of 10 or more traps in novel locations, and which by their nature are hidden from sight, would have stressed long-term and working memory capacity and been extremely challenging. Many modern trappers use cairns or markers left along paths of travel to indicate trap location. In effect, these act as a materially enabled one-to-one correspondence. If the trapper has a number concept, he or she can perhaps recall how many were set. Lacking a number concept of some kind, a tally marker would provide a very useful means of keeping track of numbers of remote capture systems. Thus, even in the absence of a number concept, material artifacts could have acted as a system of one-to-one correspondences and become a scaffold for more powerful ordinal concepts. Perhaps the most significant of these was a concept of time.

Our everyday concept of time is a cultural construct, invented as a means of solving problems related to the pastness and future-ness of human experience. In essence, our understanding of time is a concept of “folk physics,” invented when it became necessary for us to recollect an accurate passage of events in the past or to forecast an event or sequence in the future. In Western folk physics, for example, time is conceptualized as a linear succession of equivalent units that extends infinitely behind or ahead of us. Alternative systems (e.g., Mesoamerican) have equivalent sequences of units that repeat in cycles of some specified number or which are characterized by the vastness of their size. In either system—linear or cyclical—the structure of time relies on an ordinal sequence of units (actual space-time is quite a different phenomenon; see Einstein, 1916/2005).

Ordinality structures the conception of time, facilitating the ability to plan. Natural rhythms (circadian, seasonal) provide some structure to time, and many organisms have evolved mechanisms for exploiting such structure, but any activity that requires a different or more precise level of planning (scheduled

foraging, for example) would benefit from a calendar of some sort. And the minimum requirement for a calendar is an invariant ordinal sequence of time units, which could be provided by an appropriate sequential artifact and one-to-one correspondence (e.g., a string whose knots represent lunar appearances). In the spate of recent publications on the evolution of the modern mind, the ability to “plan ahead” has often been emphasized, although more often than not the accounts lack any clear discussion of just what this entails in a cognitive sense. The ability to construct and use ordinal sequences is a planning tool that had obvious benefits in structuring future action. Moreover, it has a clear neurological basis. It is therefore an excellent example of a cognitive trait that co-evolved with human material culture to produce an enhanced problem-solving ability.

Bootstrapping Ordinality

To reiterate an earlier point, neural resources devoted to representing overlearned ordinal sequences are a rather odd evolutionary product. At the scale at which humans operate, the natural world appears to provide no such sequences, and hence, nothing that could select for a human phenotype sensitive to them. But several such overlearned sequences can be found in cultural constructs. There is, then, the likelihood that the neural circuitry for overlearned ordinal sequences co-evolved with material culture and that it is a product of the extended mind.

Various mechanisms of gene–culture co-evolution have been proposed, including niche construction (Kendal, Tehrani, & Odling-Smee, 2011), the ratchet effect (Tomasello & Herrmann, 2010; Tomasello, Kruger, & Ratnet, 1993), genetic assimilation (Hall, 2003), and the Baldwin effect (Baldwin, 1896; Depew, 2003). Neuroscience itself has developed models of learning and neural phenotypic change known collectively as “neural reuse” models. In neural reuse, “circuits established for one purpose are commonly exapted (exploited, recycled, redeployed) during evolution or normal development, and put to different uses, often without losing their original function” (Anderson, 2010, p. 246). One well-known example of neuronal reuse comes from reading. When children learn to read, the brain maps the visual inputs onto circuitry in the lateral occipito-temporal junction, a region now known as the visual word form area (VWFA). In different individuals, the VWFA has the same location and organization regardless of the orthographic system in use (e.g., ideographic or alphabetic); individuals who learn to read Chinese use the same basic neural resources as those who learn to read French. The brain region in question lies within the left occipito-temporal sulcus, very close to other shape recognition areas for faces and objects. Research with macaques indicates that the comparable areas of the nonhuman primate brain are devoted to shape recognition,

with a posterior–anterior hierarchy of increasing sensitivity to complex shapes. Thus, the VWFA appears to have an evolutionary precursor in primate shape recognition neurons (Dehaene & Cohen, 2007).

Based primarily on this well-documented phenomenon, Dehaene and Cohen (2007) have proposed a specific mechanism for neural reuse, the *Neuronal Recycling Hypothesis*,² to explain the process of neural localization in learning. This hypothesis posits that cultural acquisitions such as reading “find their neuronal niche” (p. 384). That is, the brain leverages circuits that have similar functions and which are sufficiently plastic to orient to slightly different inputs (in the case of reading, these are circuits in the form recognition area of the occipito-temporal cortex). Learning then maps the new inputs onto the older neuronal groups. Interestingly, the organization of the precursor network had an effect on the kinds of orthographic systems humans developed. Many orthographic systems are based in minimal units of one, two, or three strokes that are combined into more complex units, a limitation apparently imposed by the specific function of the neural circuits exapted for reading (Cantlon & Brannon 2007; Coltheart 2014; Tan, Laird, Li, & Fox, 2005).

Neuronal recycling is also a factor in learning quantitative abilities. Numbers and arithmetic calculation are processed by areas in the IPS, although in this case the function of the primate precursor is also devoted to numerosity, so the functional shift is not as dramatic. The number example is particularly pertinent to our interest because ordinality, too, engages IPS resources, although slightly posterior to those used in numerosity. In addition, the close neural proximity of number processing and spatial processing has been well-established (Tang et al., 2008) and has led synaesthesia researchers to suggest that there is a common neural substrate, found in everyone, in which sequential processing has exapted neuronal resources that initially evolved for spatial cognition: “brain areas that evolved initially for one cognitive function (e.g., representation of space) reuse these earliest existing structures during evolutionary development to acquire culturally-driven capabilities (e.g., representation of numbers)” (Gertner et al., 2013, p. 1360). Gertner and colleagues focus on the mental number line, an imaginary horizontal line progressing from small to large numbers that is influenced by such things as culture (e.g., reading direction and finger-counting habits) and handedness (Fischer, 2008). Of course, in evolution, a true number line could not have emerged prior to a number concept, but non-numerical sequences could have, enabled by a bodily or artifactual scaffold. The close neural proximity of finger-counting corroborates this particular co-evolutionary complex—spatial cognition, fingers, and overlearned sequences.

Neuronal recycling provides a provocative description of how learning can alter neural phenotypes, and, if added to a co-evolutionary mechanism such as the Baldwin effect or Waddington’s genetic assimilation, a realistic co-evolutionary mechanism for cognitive abilities emerges (Depew, 2003; Hall,

2003; Weber & Depew, 2003). Waddington's genetic assimilation, for example, would predict that some individuals in every population would be, for reasons of their individual neural development and alleles already present in the gene pool, more adept at finger-counting or using material sequences. If such a phenotype also had a reproductive advantage, then in the course of comparatively few generations a genetically determined phenotype might emerge.

We envision a two stage co-evolutionary development of the ordinal ability itself. The first stage relied on embodied resources, primarily fingers. Using fingers in one-to-one correspondence, and perhaps to track small quantities, would have relied on the most appropriate "neuronal niche"—the abilities for numerosity, spatial cognition, and finger control that reside in the IPS. Their use for millennia, along with neuronal recycling, would have established the neurofunctional association between finger movement and quantification. This limited quantifying system is now virtually pan-human, suggesting an evolutionary antiquity at least as far back as the African MSA. But finger-counting is too limited to have led to a true ordinal concept. This evolved not via embodied resources, but via an artifactual scaffold or scaffolds. The most likely candidate known from the archaeological record of the African MSA is the string of beads. Initially, the phenotypes would have developed ontogenetically via neuronal recycling. But if they had a distinct fitness advantage, the part of the neural circuitry recycled for ordinality would have evolved via co-evolutionary mechanisms into circuitry devoted to constructing ordered sequences. For ordinality to have developed through the effects of material scaffolding, neuronal recycling, and co-evolution, a material scaffold such as cultural bead use would have had to be in place over many generations, and it would have to have had a selective advantage favoring the phenotype (and associated alleles) that was most adept at learning the appropriate cultural practice.

Conclusion

The preceding analysis has drawn on both cognitive neuroscience and embodied/extended cognition to address the evolutionary development of ordinal thinking. We believe the analysis warrants two conclusions, one specific and one general.

First, a gene-artifact co-evolutionary mechanism is the most likely explanation for the human neural circuitry devoted to ordinal sequence construction. Ordinal sequences are available in the human natural world only in the guise of fingers and toes, anatomical sequences that are too limited to select for a general ordinal sequencing ability. But artifacts, especially strings of beads, have the requisite characteristics to have played a co-evolutionary role. Through neuronal recycling and gene-culture co-evolution, neural resources

devoted to ordinal sequencing could have evolved rapidly. Beads are not the only possible artifacts; other possibilities include notched sticks and knotted strings. However, beads are the most likely candidate. Presumably, people would have made and used notched sticks only after an ordinal concept was in place. Beads appeared in the archaeological record of the African MSA soon after the evolution of modern brain anatomy with parietal lobe expansion (Bruner, 2003, 2004). And they appear to have been common. Regardless of their specific cultural use, stringing and manipulating beads for thousands of years provided ample opportunity for the problem-solving potential (e.g., planning via ordinal time keeping) to be realized, exploited, and become the basis of a co-evolutionary process. Eventually, ordinality was coordinated with numerosity to produce numbers, a cultural construct that revolutionized human planning and reasoning (Coolidge & Overmann, 2012; Overmann et al., 2011; Chapter 5). Thus, ordinality represents a specific example of a neurally based concept that co-evolved rapidly with material culture in support of human problem-solving.

This specific evolutionary scenario is open to falsification. Research into neuronal function could demonstrate that the ordinal sequencing ability of the human brain is not a dedicated circuit, in which case the evidence from double dissociation and synaesthesia would need to be accounted for in another way. Or, archaeological evidence could provide a better alternative than beads; notched bones in the MSA, for example.

The more general conclusion of this analysis is that gene–artifact co-evolution may have been responsible for many uniquely human cognitive abilities. Several possibilities proffered by other scholars might well fit this mechanism. Malafouris (2008), as we seen, has argued that beads may have acted as extensions of the social mind, thus scaffolding concepts of social identity. Calvin (1993) has argued that aimed throwing was the key factor in human brain evolution. Good evidence for ballistic weaponry is later than Calvin suggested (roughly contemporary with beads; see Shea & Sisk, 2010), but thrown spears could still have acted in a gene–tool co-evolutionary system to yield humankind’s remarkable ability to hit moving targets. Finally, Rossano (2007) has suggested that humans employ fire to achieve joint meditative states and that this ability has a clear neurological basis.

Concluding that genes and human culture co-evolved is neither novel nor particularly insightful. Here, we have proposed a specific example of gene–culture co-evolution, one that incorporates elements of embodied and extended cognition, neuronal recycling, and gene–culture co-evolution. We suspect that the ability to organize using ordinal sequences is not the only example and that humans, especially those who lived after the evolution of modern brains, relied on this mechanism to produce many unique abilities that have had a profound impact on recent human evolution.

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Notes

1. We have asked in a number of venues for examples of natural ordinal sequences, and the only possible example offered was the light spectrum, but here the problem is not the uni-dimensional change, but the individuation of elements.
2. Hannah Kovach, an undergraduate at the University of Colorado, Colorado Springs, drew our attention to the neuronal recycling hypothesis.

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