Material Scaffolds in Numbers and Time

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*The present article develops a framework for interpreting Upper Palaeolithic artefacts from an analysis of material complexity, numeration systems and timekeeping using cultural categorizations, insights on the emergence of number terms in language, and the astronomy practices of 33 contemporary hunter-gatherer societies. Our key findings suggest that astronomy originates in the ability to estimate and infer contextual relations among natural phenomena and transitions from these natural associations to material representations and cognitive technologies that mediate conceptual apprehensions of time as a substance that can be quantified. Given that artefacts may act as scaffolds for explicit concepts of numbers, and numbers scaffold explicit concepts of time, prehistoric artefacts such as the Blombos Cave beads (*c. *75,000 bp), Abri Blanchard and Cellier artefacts (*c. *28,000 bp), and plaque from Grotte du Taï (*c. *14,000 bp) may represent similar scaffolding and conceptual development in numbers and time. It is proposed that the prehistoric societies making these artefacts possessed, in addition to material complexity, the abilities to express quantities in language and to use material externalization and cognitive technologies. Furthermore, the Abri Blanchard artefact is proposed to represent externalized working memory, a very modern interaction between mind and material culture.*

Some 28,000 years ago, an unknown member of an Upper Palaeolithic society engraved a small piece of reindeer bone, discovered in 1911 at an Aurignacian site near Sergeac, France, to represent the phases and movements of the moon (Jègues-Wolkiewiez 2005; Marshack 1972). The representational and quantificational features of the artefact suggest something about its maker's *material culture*, the mental and behavioural capabilities underlying the artefacts made and used by a society, as well as its *material complexity*, a characterization of cultural complexity that emphasizes its technological aspect (Chick 1997). Using comparative data from modern societies to form an interpretive framework, the present study suggests that the Abri Blanchard bone, the Blombos Cave (South Africa) beads (*c.* 75,000 bp), Abri Cellier (France) artefact (*c.* 28,000 bp), and Grotte du Taï (France) plaque (*c.* 14,000 bp) may signify the use of *cognitive technologies*, concepts like numbers and time that transform the cognitive and physical environments through mechanisms of imposed structure. These artefacts also suggest that their makers used material objects to externalize both memory (i.e. the passive storage of cognitive content) and working memory (i.e. the active manipulation of cognitive content).

An interpretative framework from comparative ethnology assumes that aspects of material culture and language represent differential environmental adaptations, which in turn reveal aspects of the human cognitive capacity. In the present study, modern ethnographic observations from Yale's Electronic Human Relations Area Files (eHRAF) World Cultures data base were used to examine the relationships between material complexity, number terms in language and timekeeping through cultural astronomy. Greater material complexity was consistent with two cognitive adaptations: the development and use of cognitive technologies and material externalization techniques. There were two overarching results in the present study. The first was that material culture appeared to *scaffold* number concepts, knowledge construction that facilitates developing the rudimentary recogni-

Cambridge Archaeological Journal 23:1, 19–39 © 2013 McDonald Institute for Archaeological Research
doi:10.1017/S0959774313000024 Received 5 Apr 2012; Revised 8 Aug 2012; Accepted 9 Oct 2012

https://doi.org/10.1017/S0959774313000024 Published online by Cambridge University Press

tion of quantity known as *numerosity* into complex numeration systems and enabling the use of numbers as a cognitive technology. The second was that the availability of numbers as a cognitive technology appeared to provide greater complexity and structure in timekeeping as the quantificational apprehension of time.

The interpretative framework was then applied to the Blombos Cave beads, the Abri Blanchard and Abri Cellier artefacts, and the Taï plaque to characterize the societies that made them in terms of their material complexity, number systems, and use of cognitive technologies and material externalization techniques. The artefacts are consistent with modern examples of representation, quantification, material externalization, and the use of numbers and time as cognitive technologies. As a result, it is proposed that the artefacts represent *material externalization*, physical objects that enable previously intangible concepts such as numbers and time to be made tangible, explicit and formalized, as well as *externalized memory*, physical devices used to retain and recall information and experience to enable their transmission between individuals and generations. It is proposed that the Abri Blanchard artefact also represents *externalized working memory*, a physical device that enables the active manipulation of information to increase its organization and apprehension and to support the attainment of a goal. Externalized working memory in particular comprises a relatively complex use of material culture to organize, manipulate and understand cognitive content; this implies that its makers possessed fully modern cognition.

Numbers and material culture

The use of numbers as a cognitive technology begins with *numerosity*, the ability to recognize small quantities (a capability referred to as *subitization* or *parallel individuation*) and differential quantity (a capability referred to as *magnitude appreciation* or the *analogue number system*) (Feigenson *et al.* 2004; Hyde & Spelke 2011; Piazza 2010). Many species, from those closely related to humans (i.e. non-human primates) to those fairly distant in phylogenetic terms (e.g. birds), share with humans the ability to recognize quantity (e.g. Ardila 2010; Cantlon & Brannon 2006; Cantlon *et al.* 2008; Dehaene *et al.* 1998; Haun *et al.* 2010). Ontogenetically, human numerosity has been demonstrated in infants only months old, when the influence of language and culture are minimal (e.g. Ansari *et al.* 2005; Cantlon *et al.* 2006; Carey 2009; Feigenson *et al.* 2004; VanMarle & Wynn 2010). Cross-species sharedness and ontogenetic earliness suggest that numerosity is innate; the fact that it is found in both pre- and non-linguistic organisms suggests that quantity recognition is also largely independent of language. As an innate trait, numerosity has plausible adaptive value. The ability to recognize quantity in resources or threats enables a species to exploit the one and avoid the other (e.g. Agrillo *et al.* 2007; Hunt *et al.* 2008; McComb *et al.* 1994).

Numerosity in *Homo sapiens*, however, is qualitatively different from that of other species because humans can express their innate, non-verbal sense of quantity in the material form of notches, beads and tokens (Malafouris 2010). This uniquely human ability may originate in the neuroanatomical integration of numerosity with cognitive abilities for directed vision and precise finger and object manipulation (Orban *et al.* 2006). Neuroanatomic integration may enable humans to express their embodied sensorimotor associations of quantity in external material phenomena — stones, bones, sticks, strings and clay — created and modified to represent quantity (Malafouris 2010). Thus, the confluence of abilities for precise finger and object manipulation, visual acuity and numerosity may endow *Homo sapiens* with the abilities to create objects that represent number concepts and to associate those objects with the concepts they instantiate (Coolidge & Overmann 2012). However, it is likely that other cognitive abilities contribute to the human ability to express numbers materially, including ordinality and sequence, abstraction and categorical representation (respectively, the cognitive abilities to organize and understand the relative position of objects and events; derive general, higher-level concepts; and associate elements through feature correspondences; see Carey 2009; Murai 2006; Pariyadath *et al.* 2005; Quinn 2011; Quinn *et al.* 2006; Wynn 1991).

In the human brain, the upper surface of the parietal lobe, a region known as the intraparietal sulcus (IPS), has been implicated in numerosity (Ansari 2008; Cantlon *et al.* 2006; Diester & Nieder 2008; Fias *et al.* 2007; Hubbard *et al.* 2009; Miller *et al.* 2003; Orban *et al.* 2006). The anterior part of human IPS appears to lack a homologue in the brains of old world monkeys (species of macaques), suggesting that those portions of the IPS and the cognitive functions they subserve are derived characteristics in humans (Orban *et al.* 2006). Imaging studies have demonstrated IPS activation during reaching, pointing and grasping movements; saccades (fast eye movements) and attention; object matching and grasping; object size and orientation discrimination; and 'by the tactile manipulation of objects, by the observation of others' hand movements, and even by the passive viewing of graspable objects, namely tools' (Culham & Kanwisher 2001, 158).

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Inchoate concepts of quantity, once externalized in material form, become tangible; in becoming tangible, they also become more explicit, more manipulable and more readily shared between individuals and generations (Malafouris 2010; 2012). This is not to suggest that number concepts are explicit mental constructs prior to their expression in material form. Rather, it may be the act of material expression that enables the recognition of the concepts thus instantiated; key to this recognition is noticing and apprehending the similarity between a concept and its material expression (Davidson & Noble 1989). The recognition of similarity in turn helps solidify the mental concept, an interaction between mind and material that is dynamic, a state of 'continuous reciprocal causation' (Clark 1997, 171) that yields, in the case of human numerosity, greater capability and complexity in the ability to quantify. Greater capability and complexity in quantification leads to the development of *numeration systems*, formalized systems of quantification increased in explicitness (e.g. discrete quantities; number concepts such as ordinality and cardinality), linguistic labels (e.g. 'ten', 'million'), and lexical rules for creating new linguistic labels (e.g. 'twenty-one' from 'two', 'ten' and 'one'). In addition, material devices such as a string of beads or notches on a tally stick make intangible quantity concepts recognizable, storable, recallable, and able to be shared, thereby representing both material externalization and externalized memory.

As they develop complexity and capability, numbers become a cognitive technology, or knowledge that transforms the physical and cognitive environments through imposed organizational structures; these highlight some features of the environment relative to others, enable discrete and finer differentiations to be made, and assemble and parse information in ways that support understanding, action, and control (de Cruz 2008; 2012). In this regard, numbers are similar to other cognitive technologies such as mapmaking and timekeeping (de Cruz 2012; Frank *et al.* 2008; Sterelny 2010). Arguably, cognitive technologies do not transform the cognitive environment directly; instead, they operate through mechanisms of material culture. Just as maps formalize the spatial understanding of terrain and geography to facilitate navigation and clocks and calendars facilitate the organization of time to improve the ability to plan (de Cruz 2012), the operation of material mediation can be seen in the way beads and tally sticks enable counting and measurement to yield accuracy (i.e. the ability to reproduce a quantity's actual value), precision (the ability to reproduce a quantity's value under different conditions) and capability (the ability to instantiate large or complex numbers) in quantification. The *Homo* lineage has a long history of adapting to its environment by externalizing concepts in material form, creating cognitive technologies that mediate the perception, understanding, and engagement of the environment (Gowlett 1984).

The prehistory of number concepts

Quantification may have begun with the recognition of correspondences between fingers or objects and quantities (Rouillon 2006). Quantification through correspondence can be non-verbal: for example, the bead–prayer correspondence in a rosary requires neither language nor concepts for numbers. D'Errico (1998) notes the challenge inherent in demonstrating that prehistoric beads were used in a rosary-like fashion, but ethnographically, the use of beads for both personal ornamentation and counting often coincide. That the string of beads was a likely material scaffold for realizing explicit number concepts from antecedents of numerosity is suggested by their unique utility (i.e. their capacity for instantiating a number line, ordinality, etc.), ubiquity (beads are found at nearly 30 MSA sites that span, at a conservative estimate, 40,000 years and 4000 miles: see Wynn *et al.* 2012 for a review), and social value (their tendency to be counted because of the effort needed to produce them). In the sample of societies considered in the present analysis, beads used as personal ornamentation were found in societies with simpler and complex material culture, as well as with early- and later-stage numeration systems. However, only materially complex cultures used beads for quantification. Such devices appear to precede the emergence of explicit number concepts (consistent with the idea that they can act as scaffolds) but do not guarantee that emergence (consistent with the idea that individuals and societies can react differently to similar conditions).

Fingers likely preceded material devices like beads, and finger-counting may extend to 27,000 years ago if Rouillon (2006) is correct that the pattern of finger lengths in the negative handprints at Grotte Cosquer represents finger-signs for integers. The role of fingers in expressing quantity concepts, either directly or in material form, is supported by their cognitive prepotence (likely a function of the shared neural substrate for numerosity and precise motor control of the fingers) and cross-cultural ubiquity (a prevalence that suggests a neural basis: see Andres *et al.* 2008; Orban *et al.* 2006; Rips *et al.* 2008; Tang *et al.* 2006). Finger and hand movements play an important role in the mastery of counting and simple arithmetic. Motor-evoked potentials for the muscles of the right

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hand increase during small numbers judgments (i.e. numbers consistent with subitization: see Sato *et al.* 2007), hand movements unrelated to counting can disrupt the ability to count (Imbo *et al.* 2011), and hand movements related to counting can facilitate learning to count and performing simple arithmetic (Domahs *et al.* 2010; Klein *et al.* 2011). The close association of number processing, finger movements, and directed vision has also been demonstrated in fMRI studies of children performing number and visual tasks (Krinzinger *et al.* 2011).

Using the fingers to count is a trait shared across cultures; furthermore, in the present study, finger-counting persisted despite increases in the complexity of material culture and numeration systems. This persistence reflects the usefulness of fingers for both learning to count (e.g. Crollen *et al.* 2011) and performance of simple arithmetic, and it is possibly a result of the neural interrelation between numerosity and precise manipulation of the fingers. Culture can also influence the specific expression of numbers by the fingers: neural connections develop under the influence of practice, a culturally-mediated mechanism that gives rise to phenomena such as the differential cross-hand reaction times noted in Chinese and German finger-counting (Domahs *et al.* 2010). In the German culture, people count to five on a single hand, demonstrating an increased reaction time when counting to six involves the other hand; in comparison, Chinese people count to nine on a single hand, and cross-hand reaction time increases when counting to 10 requires the other hand (Domahs *et al.* 2010).

As quantification devices, however, fingers are limited: material devices such as stringed beads, knotted strings and tally sticks enable quantities to be counted and calculated with an accuracy, precision, capacity and persistence that fingers (no matter how neurally interrelated or cognitively prepotent) simply cannot provide, even when supplemented by toes and other body parts. At some point, a material device such as a string of beads may be recognized as counting, instantiating a number line, or indicating higher quantities. Material artefacts capable of instantiating number concepts and repurposing the cognitive system for numbers may have been available for at least 30,000 and possibly as many as 100,000 years. Examples include the Blombos Cave beads (*c.* 75,000 bp; Fig. 1; see d'Errico *et al.* 2005), which may have enabled correspondence quantification or, more provocatively, have acted as a material scaffold for the indication of higher quantities (Overmann *et al*. 2011; Wynn *et al.* 2012). The Abri Cellier bones (*c.* 28,000 bp; Fig. 2) and Grotte du Taï plaque (*c.* 14,000 bp; Fig. 3) are notched in a manner that appears both deliberate and unrelated to butchery; the notches may represent tally notations, the Abri Cellier artefact indicating a lesser quantity, the Grotte du Taï plaque a greater one (Marshack 1991).

As in finger-counting, the use of material devices can restructure the brain. Neural connections are formed under the influence of deliberate practice as proficiency is acquired (de Cruz 2008; 2012). Similar to evidence that practice in reading increases both white-matter density and interhemispheric connectivity and that practice in spatial navigation increases gray matter, practice in arithmetic appears to change the relative contribution of different brain regions (Carreiras *et al.* 2009; de Cruz 2012; Maguire *et al.* 2006; Tang *et al.* 2006; Zamarian *et al.* 2009). Cultural learning (a phenotypic change) also results in behavioural change, and behaviour can interact with the environment in ways that enhance or degrade fitness. Since natural selection favours adaptive phenotypes and their genetic bases, over time, this might yield a dedicated neural substrate for what was originally a cultural acquisition (see Wynn *et al.* 2012 for a review of gene–culture co-evolutionary models).

However, rather than modifying the underlying cognitive ability, cultural acquisitions can simply map onto neural circuitry with compatible functionality and sufficient plasticity to support them (i.e. *neuronal recycling*: see Dehaene & Cohen 2007). For example, in reading, the brain maps visual inputs onto the lateral occipito-temporal junction, a location that is constant across individuals, cultures, languages, and orthographic systems (Wynn *et al.* 2012). The neuronal origins remain evident in the functional constraints that govern the co-opting cultural acquisition (Dehaene & Cohen 2007), seen in reading as limitations in the complexity of orthographic characters that can be parsed (Wynn *et al.* 2012) and in numerosity as Weber's law of just-noticeable differences and limitations of attentional resources that together form the *subitization constraint*, the component of numerosity enabling the rapid, unambiguous recognition of quantities only up to three or four (Burr *et al.* 2010; Piazza 2010; Pica *et al.* 2004). Material scaffolding (e.g. moving beads along a string) may help to escape the subitization constraint, which appears to predominate in the initial expression of number concepts (but see Piazza 2010), as evidenced by the way in which number terms emerge in language.

As they emerge, number terms appear to transition through two universal stages that reflect the level of enrichment and capability in the underlying numeration system. The early stage of number-term emergence produces only limited and inexact quantities (i.e. 'one', 'two' and 'many'), consistent with

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subitization (Menninger 1992). Material scaffolding — counting a string of beads, for example — may facilitate the conceptual 'leap' that first transcends the subitization constraint and then makes higher quantities accessible (Malafouris 2012; Menninger 1992; Overmann *et al.* 2011; Wynn *et al.* 2012). Hurford (2007, 91–2) suggests the scaffolding is also linguistic: 'Without using language, we still can't go [higher than the subitizing range of about four]', though arguably linguistic scaffolding is more applicable to quantities that greatly exceed the subitizing range. In comparison, the later stage of number-term emergence produces numbers in the hundreds, thousands or more with accuracy and precision, expanding the need for linguistic labels and lexical rules to create new number terms (Menninger 1992) and reflecting the use of material externalization and externalized memory (e.g. counting beads on strings or notations on tally sticks). At some point, material scaffolds for large numbers become infeasible (e.g. manually counting to hundreds of thousands), suggesting that large numbers become apprehended as linguistically (rather than materially) scaffolded concepts, though material devices may still be used to record and manipulate them. From the way in which number terms emerge from material and linguistic scaffolds, the present study predicted that later-stage numbers would be found in conjunction with material complexity and that early-stage numbers would be found with material simplicity. In general, this is what was found. In addition, there were no cases of material simplicity with later-stage numbers, and there were lags between material complexity and numeration complexity; this was interpreted as material complexity preceding and at least partially informing numeration complexity.

Material culture and the development and enrichment of numeration systems

In order to investigate the relationship between material complexity and the development of numeration systems, Hayden and Villeneuve's (2011) characterizations of cultural complexity were used. These authors classified 82 societies from Africa, Asia, Europe, North and South America, and Australia as 'simpler' or 'complex' based on characteristics of population density, mobility, property ownership, food storage, socioeconomic stratification, trade, surpluses and associated social activities, and indications of emerging social stratification and religion (Hayden & Villeneuve 2011, 334–5)[1]. Notably, though Hayden and Villeneuve (2011) listed numeration systems as a classification criterion, this was not a significant factor in classifying material culture as simple or complex (Hayden pers. comm.); accordingly, the present analysis excluded the numeration systems criterion as a determinant of material complexity on grounds of circularity.

Of the 82 societies considered by Hayden and Villeneuve (2011), there were 33 for whom sufficient data were available in Yale's eHRAF data base to characterize their numeration system complexity (Table 1 lists the societies considered in the present analysis and their geographic distribution; Table 2 contains the four categories created by the conjunction of material complexity and number-term emergence and the distribution of societies within the categories). For each of these 33 societies, the eHRAF data base contained between one and seven ethnographies (with an average of two per society) containing observations on which to base a categorization of the numeration system as early or later stage using Menninger's (1992) two-stage framework.

Simple material culture and early-stage number terms (Group 1)

Material simplicity (Hayden & Villeneuve 2011) was consistent with the early stage of number-term emergence. The societies in this group (hereafter referred to as Group 1; see Table 2) were likely to use the term 'many' to indicate quantities near or slightly higher than the subitization constraint, or to count in pairs (a correspondence method of quantification). The Mbuti, for example, used the term 'many' to indicate quantities higher than four or five and counted in pairs (Turnbull 1965; 1983). The Andamanese at times depicted quantities with only two categories, either as 'small' or 'big' (Cipriani & Tayler 1966), and they lacked terms for numbers higher than six (Man 1932). The Aranda counted 'many' after reaching 'four' (Spencer & Gillen 1927). Observers also noted a general lack of skill, interest, or both in characterizing and communicating larger quantities, as well as an absence of vocabulary with which to indicate higher quantities (i.e. these languages lacked terms analogous to 'tens', 'hundreds', or 'thousands' in English).

Several observers of Group 1 also noted a lack of material possessions for which number concepts would have been needed. For example, Gusinde (1931, 1580) observed of the Ona (also known as the Selk'nam), 'Proceeding from their extremely limited property in material cultural goods, one expects from the outset only a limited development of counting and the number system'. Gusinde and Schütze (1937, 1383) said of the Yahgan, 'Their material possessions are amazingly meager. Hence they can do without numbers even more easily than without a complicated scale of value'. The material culture and numeration system of the Amazonian Pirahã, a society renowned

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Table 1. *Geographic distribution of societies included in the study*

Region	Sub-region	Group	Society
Africa	East	1	Mbuti
	South-central	1	San
Asia	East	2	Ainu
	Northern	2	Chukchi
		3	Koryaks, Yakut
	Southeast	1	Andamans, Semang
Australia	Central	1	Aranda
	Northern (Islands)	2	Tiwi
Europe	Northeastern	2	Saami
North America	California	3	Chimaríko, Klamath, Maidu, Pomo, Shasta, Wintu, Yokuts, Yuki, Yurok
	Central	2	Ojibwa
		3	Assiniboine, Chipewyan
	Eastern	2	Innu
	Northern	2	Alutiiq, Inuit
		3	Aleut
	Northwest Coast	3	Quinault, Tlingit
	Northwest Interior	3	Sahaptin
South America	Southern	2	Tehuelche
	Tierra del Fuego	1	Ona, Yahgan

Note. Group 1 reflects societies categorized as materially simple with early-stage numeration systems, Group 2 materially complex with early-stage numeration systems, and Group 3 materially complex with later-stage numeration systems (see Table 2). Interestingly, in the seven sub-regions with two or more societies (northern and southeast Asia, California, northern and central North America, the Northwest Coast of North America, and Tierra del Fuego), classifications either fell into one group (e.g. the nine societies in California all fell into Group 3) or into two groups that differed only by one factor (i.e. material complexity or numeration system complexity but not both). This geographic consistency was interpreted as reflecting factors of common ancestry, social interaction, and shared environmental challenges, and the cultural affinity in turn implied that the categorization of material and numeration complexity, performed independently of geographic proximity considerations, was reliable. The cultural affinity also suggested that the data were not independent, a circumstance in cross-cultural studies known as Galton's problem, a factor that will be controlled in follow-on studies (Hendrix 1997; Schaefer 1974).

Table 2. *Intersections of material complexity and numeration systems.*

Simple hunter-gatherer societies	
Early-number stage (Group 1)	***Later-number stage***
Andamans, Aranda, Mbuti, Ona, San, Semang, Yahgan	(None identified in the present sample)
Complex hunter-gatherer societies	
Early-number stage (Group 2)	***Later-number stage (Group 3)***
Ainu, Alutiiq, Chukchi, Innu, Inuit, Ojibwa, Saami, Tehuelche, Tiwi	Aleut, Assiniboine, Chimaríko, Chipewyan, Klamath, Koryaks, Maidu, Pomo, Quinault, Sahaptin, Shasta, Tlingit, Wintu, Yakut, Yokuts, Yuki, Yurok

Note. Classification of 33 modern hunter–gatherer societies in terms of material complexity (Hayden & Villeneuve 2011) and number term emergence in language (after Menninger 1992). The sample was evenly split between material simplicity (n = 16) and material complexity (n = 17),yet the difference in the prevalence rate of the early or later stages of number term development was significant, $\chi^2(1, N = 33) = 9.44$, $p = 0.002$, two-tailed, Cohen's $w = 0.53$, a large effect; when the small sample size was corrected, $\chi^2(1, N = 33) = 7.00$, $p = 0.008$, two-tailed, Cohen's $w = 0.46$, a medium-to-large effect. There were no instances of a materially simple society with the later stage of numbers, and for materially complex societies the prevalence of later stage numbers was twice that of early stage numbers. The classification of the Andamans, Aranda, Ona, Mbuti, and Yahgan in Group 1, the Inuit, Tehuelche, and Tiwi in Group 2, and Tlingit, Yakut, and Yokuts in Group 3 agree with Divale's (1999) classifications, which were based on the highest number counted and the degree of food storage. Divale's analysis would also have placed the Koryak and Klamath in Group 2, though Group 3 appears more appropriate. Divale underestimated the Koryak's highest number counted, showing them counting no higher than 101; this is contradicted by Jochelson's (1905–8) observation of the Koryak counting to 1000. Divale may have similarly underestimated the Klamath's ability to count to high numbers; Spier (1930) noted their use of lexical rules to form number terms, suggesting an ability to count higher than the 101 noted by Divale.

for material simplicity and a lack of numbers (perhaps paradigmatically so: see Everett 2005; 2008), might fit this category as well. The association of minimal material culture and early-stage numeration systems highlights the potential importance of material scaffolding for the development of explicit number concepts, an insight that might be summed up as follows: with little material culture, few number concepts.

Complex material culture and later-stage number terms (Group 3)

In comparison, many of the societies designated by Hayden and Villeneuve (2011) as materially complex were in the later stage of number-term emergence (hereafter Group 3; see Table 2). Group 3 societies used material devices such as tally sticks or beads for counting; they were also likely to have a more formal system of numbers with one or two bases (five and twenty were common) and to form higher numbers through the combined application of material devices and linguistic lexicalization rules. Counting into the hundreds and in some cases to infinite quantities was observed. The Tlingit, for example, had a quinary (base five) system, formed higher numbers with lexicalization rules, and counted ordinally into the hundreds (Emmons & De Laguna 1991). The

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Chimaríko, Sahaptin, Shasta and Yuki possessed a method of counting based on the number five, the Klamath a numeration system including both quinary and decimal concepts, and the Wintu a numeration system based on base 10 (Gatschet 1890; Spier 1930). The Chukchi (or Chukchee) developed a numeration system with two bases, quinary and vigesimal (base 20) (Antropova & Kuznetsova 1964; Bogoraz-Tan 1904–9). Group 3 societies also used material devices for quantification: for example, the Pomo used stringed beads and tally sticks of various sizes, with a small stick equivalent to 80 beads and five tallies 'equivalent to one of the large sticks or four hundred beads' (Barrett 1952, 507). Quantification proficiency was not universal, however, as the counting ability of the Chukchi was described as minimal or, in some individuals, absent (Jochelson 1905–8), an unevenness of knowledge perhaps indicative of an emerging cultural development.

Complex material culture and early-stage number terms (Group 2)

Some of the materially complex cultures had early-stage numeration systems (hereafter Group 2; see Table 2). The lag suggested that material complexity precedes the transition of numeration systems from the early to the later stage and perhaps positions the first as a necessary precondition for the second. Further, there were no instances of societies with material simplicity and later-stage numeration systems, a finding consistent with the idea that greater complexity in material culture and social organization work to enrich numeration systems. Material culture, for example, provides the stringed beads that can instantiate higher quantities, as well as the social valuation inherent in reasons for counting the beads. Social requirements can also necessitate quantification: both the Ainu and Korak were described being cheated in trade through a disadvantage in quantification skills, implying both an awareness of the disadvantage and a possible inspiration to overcome it (Jochelson 1905–8; Takakura & Harrison 1960). In the process, individuals with number concepts understand the world in new ways, developing cognitively under the influences of exposure to the knowledge of explicit numbers and the practice of quantification.

Material possessions and counting

Not all aspects of material culture may be equally effective in scaffolding the development of numeration systems. Instead, some material possessions seem more likely to engender quantification because of their significance in socially important processes (e.g. their utility in ensuring the availability of resources supporting the group's survival, as argued by Divale (1999), as well as their value in trade or ritual or their cost in terms of the labour needed to create them). Beads, for example, are material possessions whose production entails a specific and somewhat specialized investment of labour, with the result that they acquire social value that makes them more likely to be counted. This was exemplified by the Pomo, who counted beads when giving them as gifts, paying them as wages or using them for such purposes as ritual sacrifices, sealing treaties or settling blood feuds (Barrett 1952). Thus, it may be material possessions with a specific social value, rather than material possessions in general, that inspire the need to quantify them to higher numbers, with greater accuracy and precision, and in ways that are more explicit and formal, thereby enriching systems of numeration. In this sense, greater enrichment in numeration systems also implies the development of systems of social value.

Simply, when it comes to counting, all material possessions are not equal: those that are counted have some kind of social importance, value or usefulness, as demonstrated by the range of domains in which numbers are employed:

- survival and economy (the Saami [Group 2] count reindeer: see Anderson 1978; Bernatzik & Ogilvie 1938)
- wealth and prestige (the Pomo [Group 3] count beads: see Barrett 1952)
- trade (e.g. the Saami: see Itkonen *et al.* 1948)
- gambling (e.g. the Mbuti [Group 1], Tlingit and Yokuts [both Group 3]: see Emmons & De Laguna 1991; Gayton 1948; Turnbull 1965)
- basket-making (the Yokuts: see Buckley 1982; Latta 1949)
- rituals (the Aleut, Pomo and Yurok [all Group 3]: see Aginsky 1939; Alexander 1949; Pilling 1978), and
- time (e.g. the San [Group 1], Saami [Group 2] and Pomo [Group 3]: see Anderson 1978; Barrett 1952; Loeb 1926; Silberbauer 1981).

The idea that material complexity and social value act together to enrich numeration systems is similar to (but broader than) the hypothesis offered by Divale (1999), who suggested that climatic instability caused the need to store food, necessitating the counting of seeds and other foodstuffs and leading to the development of numeration systems (arguably, given the wide variety of employments to which numbers are applied, there was more fueling the hominin environmental adaptation than extreme weather and the desire not to starve, though these incentives undoubtedly headed the list).

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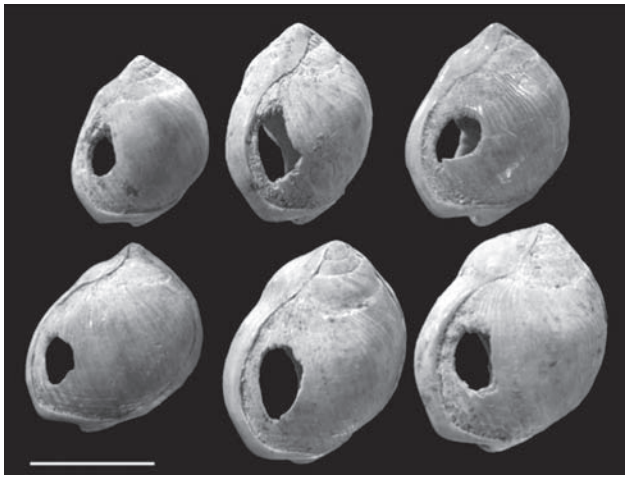


Figure 1. *Six of the Blombos Cave beads (*c. *75,000 bp). Once strung, they may have formed an early quantification device (similar to the modern rosary), permitting one-to-one correspondences and instantiating numeric concepts such as the number line and ordinality. More provocatively, they may have helped to scaffold higher numbers (i.e. to the number of beads on the string). (Courtesy of Christopher Henshilwood and Francesco d'Errico.)*



Figure 2. *The Abri Cellier artefact (*c. *28,000 bp); the notches might have represented quantity notations. (Courtesy of Logan Museum of Anthropology, Beloit College (LMA 100180 and 100181).)*

In general, the numeration systems of Groups 2 and 3 were more explicit and better developed than those of Group 1. This pattern, however, was not unequivocal, for several reasons. First, the emergence of number terms in any language may not be a simple two-stage transition but one that consists of multiple stages, sub-stages and significant variation, complicating the categorization of any particular numeration system as early- or later-stage. Second, the number of societies supporting material and number complexity categorizations was small (i.e. only 33 societies) and the ethnographic observations unlikely to have been comprehensive. Finally, some of the ethnographies predated the theoretical and methodological advances realized by anthropology as a discipline over the last century, with a concomitant lack of training and experience on the part of nineteenth-century ethnographers. However, against these factors must be set the fact that continued historical contact alters the cultural practices of previously isolated peoples, including their numeration systems, increasing the value of initial- and early-contact ethnographies.

The Blombos beads, Abri Cellier artefact and Taï plaque in context

When the Blombos Cave beads (*c.* 75,000 bp; Fig. 1), Abri Cellier bones (*c.* 28,000 bp; Fig. 2) and Taï plaque (*c.* 14,000 bp; Fig. 3) were considered in terms of the framework of material and numeration complexity developed in this analysis, the objects bore notable similarities to the strings of beads and tally notations used for quantification purposes by modern hunter-gatherer societies, something that has been previously pointed out, especially for the Cellier and Taï artefacts (e.g. Marshack 1985; 1991; Mithen 1996). This is a provocative interpretation of the Blombos Cave beads (Overmann *et al.* 2011) because their antiquity implies that modern cognition may reach a greater time depth than is commonly held, though the suggestion is consistent with the interpretation of Middle Stone Age cultural and cognitive complexity by McBrearty & Brooks (2000). It is less provocative for the Cellier and Taï artefacts because the cognitive capabilities of Upper Palaeolithic societies are frequently considered modern in essential respects.

The notches on the Abri Cellier bone appear deliberate, not inadvertent as the haphazard byproduct of butchery would appear (Marshack 1991). This suggests that their intent was the externalization of cognitive content (de Cruz 2004), perhaps for quantification purposes similar to those expressed by the notations on modern tally sticks and similar devices. The idea that the Cellier artefact represents quantification is unsurprising, given that its archaeological context contains cave art (Conneller 2011), exotic raw materials used to produce blades (Woods 2011), beads

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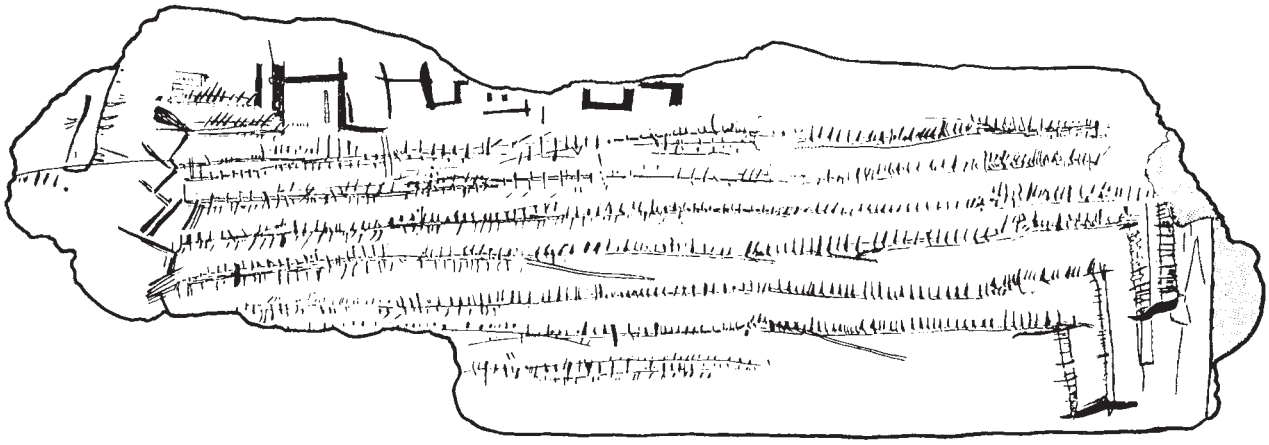


Figure 3. *The Taï plaque (*c. *14,000 bp); the incised marks may have represented quantity to a relatively high number. (From Marshack 1991, 31, fig. 5.)*

and ornaments made of teeth, shells and ivory, and regional differences suggestive of cultural variation (Vanhaeren & d'Errico 2006), all of which imply significant cultural complexity. That complexity would certainly be consistent with the complexity implied by the Abri Blanchard device (*c.* 28,000 bp: see Jègues-Wolkiewiez 2005) and Cosquer Cave number-sign handprints (*c.* 27,000 bp: see Rouillon 2006), evoking the distribution of complexity seen in the current sample (i.e. material and numeration complexity was similar for groups with geographic proximity, a finding interpreted as reflecting factors of common ancestry, social interaction and shared environmental challenges: see Table 1).

The organization of marks into groups, such as those seen on the Grotte du Taï artefact, reinforces the impression of an intent to represent numbers (de Cruz 2004; Marshack 1972; 1985; 1991). D'Errico and colleagues (d'Errico 1991; d'Errico *et al.* 2003) have noted that some of the Taï marks appear compressed, a disposition across the surface of the artefact that suggests their totality was unplanned, indicating temporal separation in their accumulation that would be consistent with quantification (d'Errico 1998). If the marks do not specifically represent a calendrical notation, as Marshack (1991) has suggested, their grouping is nonetheless consistent with the way in which number concepts have been shown to develop, which is in an overall progression from ordering to grouping and grouped groupings (Coolidge & Overmann 2012; Menninger 1992). Moreover, the use of material devices for quantification by modern societies occurs in Groups 2 and 3 (i.e. in conjunction with material complexity), suggesting that the Upper Palaeolithic societies who produced the Taï and Cellier artefacts were also materially complex and that, if they had only early terms for numbers, they might well have been on their way to developing greater complexity in numbers, given the availability of material devices with which to scaffold them.

Numbers, material culture and time

Time is a system of relations among events or occurrences (Dowden 2011), a cultural notion constructed through practices that estimate or quantify 'time' in, for example, daily or annual amounts. Time is conceptualized in terms of *motion* (i.e. who moves, the perceiver or time), *direction* (linearly or circularly), *pace* (fast or slow), *frame of reference* (whether event sequencing or temporal ordering is ego-centric or absolute), and *duration* (quantified through experiential associations or numbers). There is an extensive literature on the first four characteristics, particularly in metaphor and development (e.g. Boroditsky 2000; Casasanto & Boroditsky 2008; Gentner 2001; Kamii & Russell 2010; Torralbo *et al.* 2006); the final characteristic, duration, was the focus of the present study.

The societies in the sample estimate or quantify time through practices of cultural astronomy (i.e. by monitoring or counting appearances, positions or movements of the sun, moon and stars). These practices were observed in societies with both simple and complex material culture and with both early- and later-stage number terms. The consistency of cultural astronomy with the spectrum of material and numeration complexity suggests that the subjective awareness of time (see de Smedt & de Cruz 2011, for a review of the cognitive bases of the sense of time) may precede both material culture and the development of numbers, and that timekeeping may originate in innate cognitive abilities for estimating and infer-

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ring contextual relations among natural phenomena. With increased material and numeration complexity, however, timekeeping transitions from these relational estimations to techniques of material externalization and the use of cognitive technologies. In particular, the use of numbers as a cognitive technology enables the abstract concept 'time' to be made more explicit and to be conceptualized in terms of material and quantificational representations (i.e. counting the appearances of the moon with knotted strings). In the process, numbers provide a scaffolding effect for time similar to the scaffolding effect that mind–material interaction supplies for numbers.

Timekeeping can be characterized as the recognition of correspondences between two things, such as the height of the stars above the horizon and the present time of night or year. The two things in the relationship of correspondence are 'time', an abstract concept, and some physical representation of time, a materially realized and thus more concrete concept. Timekeeping can also be characterized as quantification: for example, in counting moons and partial moons (i.e. lunar cycles and phases) in order to describe years and partial years, through material techniques like notched sticks or knotted strings that represent discrete quantities of time. The material realizer might occur naturally, as the height of the sun used to estimate the approximate time of day. The material realizer might also be a manufactured representation, such as knots in strings or an artefact such as that found at Abri Blanchard, whose incised shapes suggest lunar phases and whose overall pattern of marks trace the moon's azimuthal positions over a period of several months (Fig. 4; see Jègues-Wolkiewiez 2005).

Factors governing relational estimations of time

As modern hunter-gatherers are, prehistoric societies were probably intimately familiar with the sun, moon and stars. The ability to assess whether they named these phenomena, told stories to explain them, or used relational estimation techniques or quantification is indirect (since such things do not preserve) but might be inferred from a comparison of their material artefacts with similar devices used in modern societies. Using the sun, moon and stars for timekeeping, however, is complicated by factors that enhance or inhibit the apprehension and usability of their patterns (i.e. predictability, which is a function of recurrence and regularity; variability, which constrains pattern apprehension and usability; and accessibility, functions of terrain and weather that impact observation). These factors act to limit what is initially possible in timekeeping.

The sun's diurnal pattern is easy to use for an approximate time of day, and variations in day length (in conjunction with other seasonal change) can be used to establish the approximate time of year, recurrence that is highly predictable and accessible. The incremental subtlety of the sun's day-to-day variation, however, means that use of the pattern for keeping track of intermediate amounts of time (e.g. monthly or weekly) is difficult without material support. The stellar progression similarly enables diurnal and annual timekeeping, but the latter necessitates remembering the pattern of star recurrence from year to year (Kelley & Milone 2005). Rising stars can be used to estimate the month (and perhaps even the week), but only if the stellar pattern is remembered in detail and viewed from a similar horizon (i.e. the same stars rise earlier in the plains than in the mountains). The most recognizable patterns of the moon are its recurrence (the sidereal month of 27.0 days) and succession of phases (the synodic month of 29.5 days) (Jègues-Wolkiewiez 2005), both of which can be used to estimate months and partial months.

Since these factors limit the range of timekeeping possible without material support, a paucity of material devices or numbers restricts timekeeping to techniques that work within the range (i.e. relational estimations, which use things like the height of the sun in the sky to estimate an approximate time of day). Relational estimation entails apprehending the significance of relationships among natural phenomena and may relate to the core domain of causality posited by Carey (2009) as an innate representational resource for contextual and relational knowledge. Relational estimation may also involve specific perceptual input analysers, such as the cognitive ability for drawing inferences from shadows. Shadows can be used to estimate the time of day or year; furthermore, if closely measured from a constant position, shadows can also enable detection of the *solstices*, the longest and shortest days of the year. Shadow perception is neurally configured to 'assume' things like there being a single, stationary light source located 'above' the viewer's retinal coordinates (Kleffner & Ramachandran 1992; Mamassian & Goutcher 2001; Tarr *et al.* 1998) to enable extraction of contextual inferences about the object casting the shadow (i.e. its depth, shape, location, background, movement and trajectory: see Cavanagh & Leclerc 1989; Kender & Smith 1987; Kersten *et al.* 1997; Mamassian *et al.* 1998; Ramachandran 1988; Sun & Perona 1995), as well as the movement and direction of the light source (e.g. Knill *et al.* 1997; Mamassian 2004).

The perceptual assumptions associated with shadows and the ability to infer contextual relations

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from them are shared across species, including non-human primates and human infants (e.g. Imura *et al.* 2006a,b). The cognitive basis for inferring contextual relations from shadows seems logically extensible to other relational estimation techniques used for time (e.g. sunbeam movement, sun height, lunar phases or the appearance of spring, though their specific cognitive bases have not yet been established). Because shadow and other cause–effect inferences are innate, the present study predicted their use would prevail in conditions of little material culture and early-stage numbers and would diminish as material culture and numbers became available and relied upon to mediate cognitive understandings of the environment. In broad terms, this is what was found.

Material devices in the quantification of time

Once they are available, material devices enable the quantification of time to have greater accuracy (i.e. the ability to reproduce an actual quantity), precision (ability to reproduce a quantity under different conditions) and capability (ability to represent smaller or larger quantities) than is possible, for example, by estimating the month from the season. Seasonal variability entails that the estimated annual time lacks accuracy and precision (however undeniable its practicality). By comparison, estimating the month from the stars is independent of seasonal variation and constitutes an improvement in accuracy but not in precision (because it can be affected by changes in viewpoint or visibility). Material techniques (e.g. knotting strings to count lunar appearances) have the potential to yield accuracy, precision and capability (for example, counting higher quantities of moons), but entail some form of material externalization and perhaps constancy of observational position as well.

In the current sample, timekeeping transitioned from estimations of natural phenomena (e.g. the growth of *Cyttaria darwinii*, a fungus the Yaghan (Group 1) use as an indication of annual time: see Guisinde 1931) to the use of manufactured artefacts (e.g. the wooden board with small holes and movable pegs the Aleut (Group 3) use to designate days; this device was possibly adopted from the Russian culture: see Innokentiĭ 1840), consistent with the greater availability of material devices and the increased capability of numeration systems. This is the transition from an associational integration with the environment to a cognitively organized understanding of the environment, and it is analogous to the one in numbers in which the use of fingers and correspondences yields to the use of manufactured objects that scaffold the transition from rudimentary to explicit concepts of quantity. Just as initial numbers were not explicit concepts, 'time' need not be explicit initially either, with quantification and material externalization enabling 'time' to become concrete, manipulable and sharable.

When astronomical timekeeping was organized by material and numeration complexity (Table 3), three themes with implications for material scaffolding emerged. First, the use of any particular astronomical phenomenon or strategy for timekeeping was initially constrained in its accuracy, precision and capability, with the use of material externalization enabling transcendence of the constraints. Second, material externalization facilitated the apprehension and use of astronomical patterns for timekeeping, with timekeeping accuracy, precision and capability improving with greater material complexity as a function of increased social investment and organization. Third, as material and numeration complexity increased, the concept 'time' became more explicit as something that could be quantified, with material devices and numbers as a cognitive technology enabling its quantification. These themes were consistent with the idea that cultural astronomy enables timekeeping, first by recognizing and interpreting correspondences between natural phenomena and then by developing techniques for material externalization that enrich, as numeration systems appear to, under the weight of increasing material complexity, investment of social resources, and geographic stability (Hayden & Villeneuve 2011).

Cultural astronomy and complexity in material culture and numeration systems

There were 29 modern hunter-gatherer societies for whom there were sufficient data to characterize material complexity (from Hayden & Villeneuve 2011), numeration system (as suggested by Menninger 1992) and cultural astronomy (e.g. tracking solstices, counting lunar cycles, or estimating the height of stellar constellations) (Table 1 lists the societies considered in the analyses of both numbers and time and their geographic distribution; Table 3 lists the categories and percentages yielded by the conjunction of material complexity, number-term emergence, and cultural astronomy). For each of the 29 societies, the eHRAF data base contained between one and eleven ethnographic sources (with an average of four) providing observations on cultural astronomy. From the comparison (Table 3), it appeared that timekeeping was consistent with both material simplicity and complexity and with both early- and later-stage numeration systems, a finding that suggests the subjective awareness of time (de Smedt & de Cruz 2011) may precede both material culture and numeration

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Table 3. *Changes in timekeeping with increased material and numeration complexity for 29 modern hunter-gatherer societies.*

Timekeeping practice	Percentage (%) of cultures with timekeeping practice*			ϕ **	Trend
	Group 1	Group 2	Group 3		
Height estimation (sun, moon, stars) for time	86	56	38	0.20	Decreasing
Use of material devices to keep time	0	44	69	0.38	Increasing
Human age estimated or counted	0	11	31	0.29	
Time divided into epochs	0	11	23	0.24	
Use of solstices for annual time	0	56	54 ***	0.35	
Lunar cycles counted for timekeeping	14	56	77	0.29	
Awareness of solar–lunar cycle mismatch	0	11	23	0.24	
Fingers used for counting	71	67	62	0.04	Constant
Myths about the sun, moon, and stars	86	89	85	0.02	
Seasons used for annual time	86	89	85	0.02	
Moon–menses relation	57	56	54	0.02	

Notes.
* Societies were rated dichotomously (0, *No practice noted*, or 1, *Practice noted*). Ratings of '0' were awarded under either of two conditions: (1) there were HRAF data specifically commenting on a society not employing a particular practice; or (2) there were no HRAF data regarding a society's employment of a particular practice. This is similar to the logic used by Divale (1999) in using HRAF data to rate food-storage practices; he noted that condition (2) 'seemed reasonable because food storage is a low-inference variable, which would be fairly obvious to the ethnographer if it were present and important enough to be reported' (Divale 1999, 346). Group percentages were then calculated from the sum of '1' ratings divided by the total number of societies in that category. A percentage change (delta) greater than 10% was interpreted as indicating an increase or decrease.
** Phi (ϕ) correlations, which measure the strength of the relationship between dichotomous variables, were performed, and the resultant values are interpreted on the following scale: negligible relationship, $\phi < 0.10$; weak, $\phi = 0.10$ to $\phi < 0.20$; moderate, $\phi = 0.20$ to $\phi < 0.40$; relatively strong, $\phi = 0.40$ to $\phi < 0.60$; strong, $\phi = 0.60$ to $\phi < 0.80$; and very strong, $\phi = 0.80$ to $\phi < 1.00$; see Coolidge 2000; Glass & Hopkins 1996; Rea & Parker 2005).
*** An increase was noted with the transition from simple to complex material culture; no further increase was noted with the transition from early- to later-stage numeration systems.

systems. However, interpretation of the data remains speculative, given the small number of societies in the sample and the limited number of ethnographic observations per society, which suggests there were gaps in what was recorded about any particular society's astronomy practices. Additionally, descriptions (e.g. solstice monitoring) were occasionally ambiguous as to whether what was being represented was a cultural practice or an outsider's knowledge; when this was the case, the observations were excluded from consideration.

An overview of the findings

The use of relational estimation techniques decreased as material and numeration system complexity increased. Aspects of timekeeping that increased with increases in material and numeration complexity included the use of material devices to quantify time, as well as the counting of human age and moons, an awareness of the mismatch between the solar and lunar cycles, and the division of time into epochs. The use of solstices for annual time increased with material complexity (but did not increase further with the transition from early- to later-stage numbers). Three aspects of timekeeping or related beliefs remained constant despite increasing material and numeration complexity: the telling of myths about the sun, moon and stars; the correlation of lunar cycles with menstruation, pregnancy or women's power; and the use of seasonal phenomena to estimate annual time. Interestingly, as material and numeration complexity increased and time was increasingly understood through quantification, fingers were still used to count. Moreover, fingers were used to count time (i.e. the Yuki, Klamath and the Maidu (all Group 3): see Foster 1944; Gatschet 1890; Kroeber 1972). For example, the Chukchi were noted as using their fingers and toes to count (Antropova & Kuznetsova 1964; Bogoraz-Tan 1904–9) and the Klamath not only counted lunar cycles with their fingers, they also named the lunar months after their fingers (Spier 1930).

The use of relational estimation techniques decreased, while the use of material devices increased

As complexity in material culture and numeration systems increased, the use of relational estimation techniques to keep time decreased, and the use of material devices increased (Table 3). While no society in Group 1 was observed using a material device to quantify or measure time, the Aranda, Ona and Yahgan (Group 1) estimated daily time from the height of the sun, stars, or moon, and the Aranda and Yahgan

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were observed estimating daily time from the movement of sunbeams (Basedow 1925; Gusinde 1931; Gusinde & Schütze 1937). Judgments of time were also made through correspondence quantification; both the Aranda and San (Group 1) calculated numbers of days from numbers of sleeps (Basedow 1925; Silberbauer 1981); the Semang (Group 1) so closely associated the sun with daytime that their words for 'sun' and 'day' shared linguistic form (Endicott 1979). Use of the stellar progression for annual time involved narrative myths. For example, the Alutiiq (Group 2) began their year in August, timed by the appearance of the Pleiades (Clark 1974), and explained the stars, moon and sun as rewards given to a raven-child, revered because he gave their light to his people (Lantis 1938).

As complexity in material culture and numeration systems increased, the use of material externalization for timekeeping increased. Using the stars for annual time involved pictorial representation, a form of externalized memory, which transitioned from no instances in Group 1, to one instance in Group 2 (the Tiwi represented stars as dots in body paint for ritual purposes: see Mountford 1958), to one instance in Group 3 (a Koryaks man created a detailed map of star patterns: see Jochelson 1905–8). The Ojibwa (Group 2) recorded time using notches on a stick, with large notches representing a new moon and smaller notches representing the days between new moons (Densmore 1929; the Ojibwa used a similar method of notation to record the passage of a copper medallion from one generation to the next: see Benton-Banai 1979). The Quinault (Group 3) tied knots in cords to count lunar phases, menstrual cycles, and the amount of time between a marriage and the birth of a couple's first child (Olson 1936). Increasing material complexity implies that a society is making a larger investment of social time and expertise and that it is possibly transitioning toward geographic constancy or sedentarism, which supports long-term observation of astronomical phenomena. Expertise was suggested by the old age of the men who watched sunrises or tracked solstices for the Aleut and Quinault (both Group 3: see Hrdlicka 1945; Olson 1936), and greater sedentarism was suggested by the construction of sweathouses used by the Yurok (Group 2) for observations of the sky (Buckley 1982).

Estimating or counting human age increased, and so did dividing time into epochs

As material and numeration complexity increased, so too did the likelihood of counting human age. The Andamanese (Group 1) had 'no means of counting, and no words to express gradations of time or size ... They take no interest in the passing of years, and have no idea of their own age' (Cipriani & Tayler 1966, 151). In comparison, Groups 2 and 3 were more likely to estimate age in relation to known events (the Koryaks, Pomo and Tlingit (Group 3): see Barrett 1952; De Laguna 1972; Jochelson 1905–8) or count age by winters (the Ojibwa (Group 2) and Assiniboine (Group 3): see Denig & Hewitt 1930; Grant 1890). In at least one case, there was a social (post-contact) reason for establishing someone's age: eligibility to collect a government pension (the Tlingit (Group 3): see De Laguna 1972). The division of time into epochs also positively correlated with increased material and numeration complexity. For example, the Ona (Group 1) identified the past only as 'many ago' (Guisinde 1931, 1580), while the Chipewyan, Tlingit and Yokuts (Group 3) identified two epochs, the long ago and the present. There were also hints of an emerging tripartite division for the Chipewayan and Tlingit: a remote and mythic time, the present, and an intermediate epoch loosely encompassing the last few hundred years (De Laguna 1972; Gayton 1946; Sharp 1994). This suggests that numbers enable the structuring time in a way that permits a society not merely to count days but also to conceive of time in an overarching sense as something large that can be parsed as mythology or history. By comparison, societies lacking numbers might be limited to a few days before and after 'today', and without much structure for time beyond 'today' might also lack myths describing a time 'before' the present. Such a description might apply to the Pirahã, who have been described as living in the present 'now' and as lacking both numbers and origin myths (Everett 2005; 2008).

Using solstices, counting moons, and being aware of the solar–lunar mismatch increased

As complexity increased, so did using the solstices for annual timekeeping and counting moons. The likelihood of being aware of the mismatch between the annual solar cycle and the number of lunar cycles per year also increased, a possible consequence of combined solstice use and lunar counting. The solstices enable greater accuracy in annual timekeeping (McKim & Putnam 1993), with the winter solstice holding a particular survival interest (a harbinger of returning spring), especially to peoples in the northern hemisphere. Interest in the winter solstice as an indicator of returning spring was rather poignantly expressed by the Aleut (Group 3), who named February and March for 'the last stored food' and 'foregoing hunger month', respectively, with the name for March indicating that as the food ran out, relatively inedible things like thongs and skins might be consumed (Jochelson 1933, 85–6). Counting moons by material

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devices such as knotting strings increased (e.g. the Quinault (Group 3): see Olson 1936). However, 12 or 13 lunar months approximate, but do not coincide exactly with, the annual cycles of the sun and stars. Knowledge of the solar–lunar cycle mismatch ranged from no idea that there was one (the San (Group 1): see Kaufmann 1910), to awareness of the discrepancy with no perceived need to correct it (the Chukchi (Group 2): see Sverdrup 1938), to awareness of the discrepancy with an attempt to fill it in by inserting an extra moon somewhere (the Yakuts (Group 3): see Sauer 1802).

Solstices are detected by closely measuring (as opposed to estimating) shadow length or by precisely noting the furthest point on the horizon in which the sun rises or sets (Schlosser *et al*. 1991). Both of these techniques entail relatively long-term observations (i.e. days to years) with implications for both cultural complexity and geographic constancy. In terms of cultural complexity, making solar observations on a long-term basis to increase timekeeping accuracy and precision implies a society that is investing greater time and effort in solar observations and which is likely dedicating individuals to the practice of astronomy with organizational strategies such as the division of labour, task specialization, leisure time and resource sharing (Hayden & Villeneuve 2011). Geographically, a society inhabiting a locale continuously uses resource strategies distinct from those used by migratory or nomadic peoples, who can simply relocate once resource depletion occurs (Harris 1927).

Some things resisted change with increased complexity

Several aspects of culture did not change with increased material and numeration complexity. These included traditions of myths about the sun, moon and stars; the correlation of lunar cycles with rituals or taboos related to menstruation, pregnancy or women's power; and the use of natural phenomena for annual timekeeping. Societies in all three groups performed these practices in roughly equal proportion, implying there are aspects of culture — perhaps those related to social cohesion and pragmatic survival functions — that remain relatively independent of material complexity and the reorganizing effect of cognitive technologies. Storytelling, rituals and taboos create a powerful framework for social identity, which in turn fosters cohesion and individual identity among members of the group and acts to increase the cooperation needed to ensure the group's survival (Ochs & Capps 2001). For the Tehuelche (Group 2), a mythical hero gave fire to human beings, forming their social identity from being the group thus favoured (Adem 2009). For the Innu (Group 2), the Morning Star (Venus), the first dog in a sled team and the Canadian prime minister were all called by a term meaning 'leader' or 'first man', an identity of similar social function (Henriksen 1972). By mediating the understanding of the social and natural environments, storytelling, rituals and taboos are cognitive technologies (de Cruz 2008; 2012), and though there was some incorporation of quantification — for example, gestation was recognized as lasting about nine moons, rituals needed some specified number of days to accomplish their purpose — their central aspect appeared to resist the change imposed by increased complexity and the cognitive technologies of number and time.

Pragmatically, a society would not likely depend in absolute terms on materially mediated timekeeping for its resource exploitation. As explained by Hayden and Villeneuve (2011), a modern farmer does not depend on a calendar to know when to plant her crops because the past and present weather and climate are far more likely to be accurate guides, a principle extensible to hunting and gathering regardless of the presence or lack of material complexity. Seasonal variation is simply more informative, as demonstrated by the Yuki (Group 3), who named their months with words indicative of weather conditions or plant growth (Foster 1944). This, however, is inexact timekeeping: for the Yuki, the 'indicated month … [was] not to be taken literally — it [was] simply the informant's guess of the approximate time of year' (Foster 1944, 202).

The present study focused on *duration* as the characteristic of time most amenable to quantification through the use of numbers as a cognitive technology. A future analysis might examine the relationship between increasing complexity in culture, numbers and conceptions of motion, direction, pace and frame-of-reference in time. It is possible to speculate that the relative motion of, for example, the sun across the sky as it is used to estimate the current time or approximate a future time of day might give rise to experiential associations of motion, direction, pace and structure, just as it gives rise to experiential associations of duration (e.g. numbers of sleeps), and these might transition to materially mediated concepts or cognitive technologies as experiential duration in time yields to quantification. Since there was insufficient fidelity in the eHRAF data to demonstrate whether this was the case, the question will require further research.

The Abri Blanchard artefact in context

A reason offered against Marshack's (1972) interpretation of the Abri Blanchard artefact (*c.* 28,000 bp; Fig. 4) as a lunar calendar has been that analysis of the marks indicated they were made by different tools,

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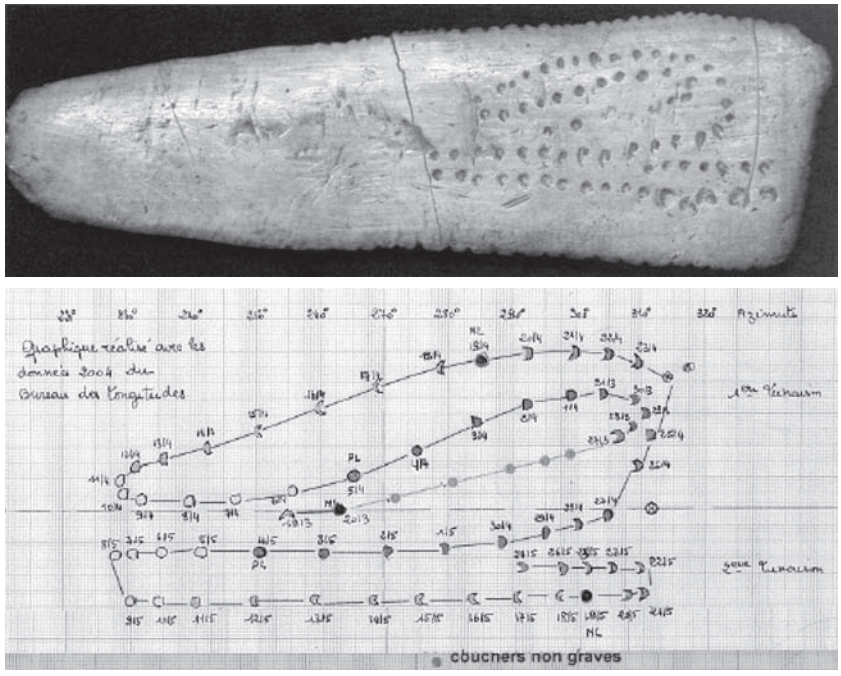


Figure 4. *Top: The Abri Blanchard artefact* (c. *28,000 bp) represents lunar phases and analemma, the serpentine figure created by the moon's successive azimuths and zeniths (respectively, the moon's positions of rising and setting on the horizon and nightly maximum height in the sky; see Jègues-Wolkiewiez 2005; Marshack 1972). Bottom (from Jègues-Wolkiewiez 2005): Once finished, the representations would have enabled the artefact's possessor to make one-to-one correspondences between the artefactual and lunar positions. The representations would have helped whoever made the artefact to understand the lunar sequence and cycle of appearances and movements, acting as externalized working memory in helping to organize and manipulate cognitive content. Significantly, the artefact appears to be a finished product, implying there were earlier rough drafts that helped create it.*

suggesting either temporal separation in their addition or cumbersome change to the cutting tool used to create them (d'Errico 1991). Against the former, the effective disposition of the pattern of marks across the available surface space of the artefact (d'Errico 1991) and the use of other marks enabling the pattern to be balanced during its production (Jègues-Wolkiewiez 2005) suggest planning in the execution of the artefact that weakens the idea the marks were accumulated in distinct events. Different tools used in a single production event can imply that the artefact was 'conceived as a whole' (de Smedt & de Cruz 2011, 69) or that the pattern was recreated to produce a 'fair copy', a neater version that increases the organization, refinement and apprehension of the represented information (i.e. a key distinction between externalized memory and externalized *working* memory).

Since the work by Jègues-Wolkiewiez (2005) offers compelling support for interpreting the artefact as a lunar calendar, it can be compared to the lunar timekeeping practices of modern hunter-gatherer societies. In the present sample, the societies who used the moon for timekeeping did so by naming, describing, depicting or tracking lunar *phases* (i.e. the Ojibwa (Group 2): see Grant 1890) or by counting lunar *appearances* (the Quinault (Group 3): see Olson 1936). Notably, none of the societies in the sample were described as tracking or making use of the pattern of lunar *movement*, which is what the Blanchard artefact depicts. Reluctance to use the lunar movement for timekeeping may be a function of variability, which constrains the apprehension and usability of the movement pattern; simply put, that movement is complex (i.e. the pattern takes 19 years to repeat: see Jègues-Wolkiewiez 2005), and understanding the pattern so that it is useful (perhaps for the esoteric purposes noted by Hayden & Villeneuve 2011) may require both stability of observational location and material externalization strategies to a greater degree than those used by the societies in the present analysis.

The complexity of the lunar movement also suggests there may be a significance to its representation that is absent in representing star patterns: the variability inherent in the lunar movement perhaps necessitates the cognitive organization achieved by material externalization. Simply, depicting stellar patterns in order to remember them for future years represents externalized memory (i.e. a physical device used to retain and recall information and experience to enable their transmission across time), while depicting lunar movements in order to understand and use them may also represent externalized *working* memory (i.e. a physical device that enables the active manipulation of information to increase its organization and apprehension and to support the attainment of a goal).

The interpretive framework from modern cultural astronomy suggests that the makers of the Abri Blanchard artefact represented the lunar movement beyond what is needed to use the moon for monthly or annual timekeeping, particularly when the pattern

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so exactingly recorded would not recur for another 19 years (Jègues-Wolkiewiez 2005). The complexity inherent in the pattern of lunar movements suggests that material externalization was a strategy for organizing and reducing that complexity in order to apprehend the pattern, in addition to recording and recalling it across significant spans of time. Beyond organizing and reducing complexity, a key aspect of the Abri Blanchard notations is their effective use of surface space, suggesting familiarity with the number of items and their approximate disposition (in comparison, some of the notations of the Taï plaque appear compressed, suggesting a notation process that unexpectedly continued beyond the intended accumulation: see d'Errico 1991; d'Errico *et al.* 2003). The effective use of surface space suggests that the Abri Blanchard artefact is no rough draft but a fairly finished product that in turn implies a tradition of gathering and organizing information materially over spans of time much longer than the months of observation inherent in the object.

Although geographic constancy is implied by the months of observation needed to develop the artefact, development of the underlying astronomical tradition need not be so directly tied to locale and would be consistent with models postulating the origin of the so-called symbolic revolution outside of Europe (e.g. d'Errico *et al.* 2003; McBrearty & Brooks 2000). The complexity of the artefact also suggests the development of material culture and quantification to the extent that the outright absence of any language seems unlikely; questions of material complexity, quantification vocabulary and numeration systems for a society capable of producing such an artefact are more appropriately ones of 'how much' rather than 'if'. As suggested by the changes related to material and numeration complexity (Table 3), it seems likely the society producing the Abri Blanchard artefact had decreased its use of relational estimations for timekeeping in favour of using material externalization and cognitive technologies. The material culture and social organization needed to support dedicated astronomers making detailed, long-term observations and material artefacts suggest an Aurignacian society that was geographically constant, had division of labour and expertise, and which may have possessed a later-stage numeration system with one or more base numbers and the ability to indicate higher quantities with material devices and lexicalization rules. Finally, the lunar timekeeping implied by the Abri Blanchard artefact suggests that the society creating it had transitioned from naming, mythic narration and pictorial depictions of astronomical phenomena to material externalization (i.e. especially externalized working memory, an interaction between mind and material culture that is quite modern) and the use of cognitive technologies (i.e. numbers and time).

The cross-cultural data on which this analysis was based were insufficiently granular to be able to draw conclusions of the specific timeline, environmental challenges, or social conditions in which any particular society experienced an 'aha' moment that created numbers from material scaffolds or applied numbers to structuring time. By extension, this analysis cannot determine either when or why this occurred in prehistoric societies, though presumably there was a point at which *Homo sapiens*' unique neural substrates for numerosity, detailed vision and fine motor control of fingers and objects developed sufficiently to enable the recognition of manipulated objects as instantiated number concepts. However, what these results suggest is that number systems do not develop without material complexity, that timekeeping beliefs and behaviours incorporate quantification when numbers are available, and that certain kinds of devices can assist and are perhaps indexical of the practice of quantification. While extending this analysis to prehistoric groups assumes a cognitive and cultural uniformitarianism with decreased utility the farther back in time one goes, the process of developing and using numbers necessarily started somewhere (or it would not currently exist) and can be observed in action in modern societies (albeit at a fairly insensitive level of analysis). It is also reasonable to assume that the prehistoric antecedents of the modern process would bear marked resemblance to what they not merely preceded but gave rise to.

Summary

In *Origins of the Modern Mind*, Donald (1991) theorized that evidence of significant cognitive change in the transition from mythic to theoretic culture would be found in new cognitive output classes. These would include the shift of intentional representation from auditory to visual modes of expression, the increased use of material technology to mediate the understanding of the environment and the emergence of analytic and symbolic thought structures. Intentional visual representation would be demonstrated by *visuographic invention*, first in self-adornment methods such as the use of body painting, then as two- or three-dimensional depictions of actual objects (Donald 1991). Technological mediation would be exemplified by measurement techniques, formal quantification strategies and the externalization of memory in material forms (Donald 1991). Finally, the emergence of analytic thought would be demonstrated by using external media not merely for passively recording

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information but also to represent and organize thought expressed in symbolic notation — not just externalized memory but externalized working memory, which frees up cognition for other purposes (Donald 1991; Malafouris 2012). Donald's description broadly characterizes the differences that emerged in the present analysis with increased complexity in material culture, numeration systems and timekeeping, and it arguably applies to the cultures creating the Blombos beads, Abri Blanchard and Cellier artefacts, and Grotte du Taï plaque as well.

In *Homo sapiens*, numerosity and its close relationship with the ability to manipulate fingers and objects with dexterity may provide an innate cognitive basis for the expression of number concepts as material culture. Material culture, the associated social value of material possessions, and the investment of resources, in turn, appear to scaffold the development of greater explicitness, capability and complexity in the ability to quantify, and the use of numbers as a cognitive technology appears to structure time as a quantified construct. Increased complexity in material culture and numeration systems was consistent with an increased use of material devices, solstices and quantification for timekeeping; a decreased reliance on estimating contextual relations from natural phenomena; and constancy in social–pragmatic realms. This pattern suggested that societies were investing in greater division of labour and expertise and transitioning toward greater geographic constancy and sedentarism. Finally, the compatibility of astronomical timekeeping with both simple and complex material culture and both early- and later-stage numeration systems suggested that timekeeping originates in abilities for detecting and understanding contextual relations among natural phenomena and transitions to strategies of material mediation and cognitive technologies as enabled by greater complexity in material culture and social organization. The framework developed from comparative cultures used to interpret the Blombos beads, Abri Blanchard and Cellier artefacts, and Grotte du Taï plaque suggested that the societies who manufactured the artefacts had complex material culture, later-stage numeration systems and quantitatively structured concepts of time.

Acknowledgements

I am grateful to Dr Tom Wynn, Dr Frederick L. Coolidge, and Dr Rex Welshon for closely reading several drafts of the manuscript and offering many helpful suggestions and criticisms. I would also like to thank Dr Helen de Cruz and an anonymous referee for their review and constructive comments.

Note

1. The term 'material complexity' is used herein to highlight the technological aspect of cultural complexity, though social valuation of material possessions and investment of resources are also important; see also Chick (1997) and Owens & Hayden (1997) for discussions of measures, issues, and validity in cultural complexity, including the interrelationship between mental, behavioural and material (or artefactual) aspects of culture.

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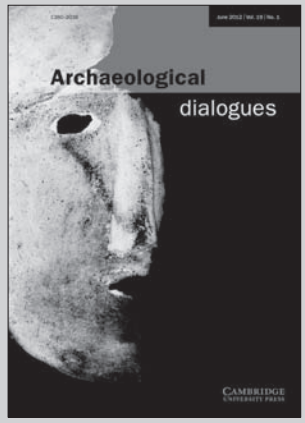
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