Biology is only part of the story ...

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The origins and development of human cognition constitute one of the most interesting questions to which archaeology can contribute today. In this paper, we do so by presenting an overview of the evolution of artefact technology from the maker's point of view, and linking that development to some hypotheses on the evolution of human cognitive capacity. Our main hypothesis is that these data indicate that, in the first part of the trajectory, biological limits to cognitive capacity were a major constraint that limited technology, whereas, in the second part, this biological constraint seems to have been lifted and others have come in its place. But these are modifiable by means of conceptual frameworks that facilitate concept innovation and therefore enable learning, thereby permitting acceleration in the pace of change in technology. In the last part of the paper, we elaborate on some of the consequences of that acceleration.

Keywords: cognition; artefact technology; innovation; evolution; cognitive constraints

1. INTRODUCTION

In this paper, we are interested in extrapolating from what we know about the development of prehistoric technologies to the evolution of human cognition. Our interest is driven by the following (unsolved) questions concerning the history of human technology:

- (i) Given that primates, for millions of years, have made and used simple tools, but have not developed any complex technologies, what is different about human beings that enabled them to develop the latter?
- (ii) Are the enabling factors biological, are they social/cultural or are they a bit of both?
- (iii) When was that capacity acquired? Was that the result of a sudden change, an incremental one or a more complex process that combined both?
- (iv) Why did it take so long to 'invent' and accelerate innovation?
- (v) Why did the rate of innovation increase so rapidly, once that point was reached?

2. PART ONE: FROM PRIMATES TO MODERN HUMANS

Numerous authors (e.g. Stout *et al.* 2000 and references therein) have argued that changes in the technology of artefact production and in artefact form, variety and diversity relate to cognitive changes, but what constitutes those cognitive changes has remained unclear due to our as yet imprecise understanding of how the brain functions. Some suggestions have been

made, which are as follows: Ambrose (2001, p. 1751), for example, argues that the composite tools which appear *ca* 300 kyr BP may relate to language development since 'explaining how to make one is the equivalent of a recipe or short story' (see also electronic supplementary material, section1).

Others (Coolidge & Wynn 2005) have pointed to the role of working memory (Baddeley & Hitch 1974; Baddeley 1986) for understanding the development of complex artefacts.¹ Working memory integrates (episodic, conscious) short-term memory with (declarative and procedural, preconscious and non-conscious) long-term memory through a central executive (intentionality) that involves 'the ability to maintain memory representations in a highly-active (conscious) state ... [that] consist of plans of action, short- or long-term goals, or task-relevant stimuli' (cf. Engle *et al.* 1999a; Kane & Engle 2000, 2002; Coolidge & Wynn 2005, p. 8).

Neurologically, it is located in the prefrontal and parietal cortices and in areas of the sensory cortex (Miller 2000; Fuster 2001, 2002; Pasternak & Greenlee 2005). The prefrontal cortex is relatively much larger in humans than in non-human primates (Semendeferi *et al.* 2001) and changes in skull morphology towards a high forehead and non-prognathic face enables the expansion of the prefrontal cortex (Lieberman *et al.* 2002). Hence, the expansion of the relevant brain areas leading to increased working memory is consistent with evolutionary changes in hominid morphology. Moreover, Fuster (2001) argues that the prefrontal cortex is the area of the brain that links memory of the past to perception of the present and anticipation of the future, and that it is therefore the area where 'choice' resides.

Coolidge & Wynn (2005) have addressed recent expansion in the capacity of working memory for modern *Homo sapiens* by suggesting that genetic mutation expanded less-developed working memory into

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Figure 1. Trend line projected from the regression of time delay response (Diamond & Doar 1989) regressed on infant age. Data rescaled for each dataset to make the trend line pass through the mean of that dataset. Working memory scaled to STWM = 7 at 144 months. 'Fuzzy' vertical bars compare the age of nut cracking among chimpanzees with the age for relative clause acquisition and theory of mind conceptualization in humans. ●, Imitation (Alp 1994); +, time delay (Diamond & Doar 1989); *, number recall (Siegel & Ryan 1989); x, total language score (Johnson *et al.* 1989); *, relative clauses (Corrêa 1995); ■, count label, span (Carlson *et al.* 2002); o, 6 month retest (Alp 1989); ▲, world recall (Siegel & Ryan 1989); ●, spatial recall (Kemps *et al.* 2000); ♦, relative clauses (Kidd & Bavin 2002); ▽, spatial working memory (Luciana & Nelson 1998); —, linear (time delay; Diamond & Doar 1989).

'enhanced working memory (EWM)'—comparable to the working memory of modern-day humans—certainly by 13 kyr BP, most probably by 30 kyr BP and possibly as far back as 80 kyr BP. Coolidge & Wynn consider four kinds of evidence for EWM: (i) contingency planning, (ii) innovative plans of action, (iii) temporally remote action, and (iv) the use of cultural algorithms (p. 16). But they address only the genetic event for the appearance of EWM rather than the evolutionary sequence from an ancestral hominid with working memory comparable to that of chimpanzees to the vastly larger working memory of modern *H. sapiens*. We therefore compare the overall pattern of change in working memory, measured through the increase in the short-term working memory (STWM), with the pattern of change in the design of artefacts over the same time horizon.

(a) Working memory in chimpanzees (*Pan paniscus*)

We estimate the STWM in chimpanzees in two ways: directly based on performance of tasks and indirectly by examining individual development trajectories for working memory in modern *H. sapiens* from birth to puberty.

(i) Direct evidence

The data on nut cracking by chimpanzees are particularly informative. Nut cracking requires manipulation of three objects: an anvil; the nut; and a

hammerstone (see also electronic supplementary material, section 2). Although chimpanzees observe each other cracking nuts, about one-quarter of them never learn to carry out the sequence involving the three objects, suggesting an STWM of size 2. Other data on token combinations, object manipulation, gesture combinations, as well as a study of number recall by a chimpanzee (taught to link number symbols with quantities) all suggest that their STWM is of the order of 2 ± 1 (see the review in Read 2006). This contrasts with an STWM of 7 ± 2 associated with modern humans.

(ii) Indirect evidence

Figure 1 shows the growth trajectory for working memory in modern *H. sapiens* based on a meta-analysis of several datasets and with STWM used for the units of the vertical axis (see also electronic supplementary material, section 3). The figure shows that, assuming that working memory develops at essentially the same rate in *Pan* as in *Homo*, the data on *Homo* imply that STWM = 2 is achieved at approximately 3–4 years of age, precisely the age period for which nut-cracking behaviour begins to appear (when it appears!) in *Pan*. Thus, the indirect evidence on STWM for *Pan* is consistent with assigning STWM = 2 to *Pan*.

The difference in the time needed for the development of working memory accounts for the difference in

STWM between *Pan* and *Homo*. In *Pan*, STWM increases only to approximately 2 at the age of puberty (approx. 3–4 years of age for *Pan* females; males reach puberty approx. 2–3 years later), whereas, for *Homo*, STWM increases to 7 at approximately 12 years of age. This difference between adult *Pan* and *Homo* individuals allows for conceptualizations by *Homo* which do not occur in *Pan*. ‘Theory of mind’,² for example, does not develop in *Homo* individuals until approximately 4–5 years of age when STWM = 3, and the same is true of relative clause acquisition. Theory of mind has been controversial as to whether it is (Hare *et al.* 2000, 2001; Premack & Premack 2000) or is not (Povinelli & Eddy 1996; Heyes 1998) present in *Pan*. STWM = 2 ± 1 would imply that it is not found in *Pan*.

Both theory of mind and relative clause acquisition require that a third concept must be active in working memory while the relationship between (at least) two concepts is being considered. To project an action onto another individual associated with one’s own behaviour, for example, requires that one cognizes oneself doing the behaviour as well as another person as a possible actor for that behaviour. This would not be possible with STWM = 2. A similar comment applies to relative clause acquisition since it depends on recursive reasoning, and recursive reasoning is impossible with STWM = 2 (Read 2006).

These data imply that we can assume a STWM = 2 ± 1 for the beginning of artefact formation by either *Pan* or pre-*Homo*. A simple striking of one cobble with another as a way to fracture one of the cobbles could be done with STWM = 2. However, flaking requires a consistent striking angle of less than 90°, and therefore it requires that one does not only conceptualize how the two objects are to be manipulated, but also that one keeps the angle of percussion active in working memory. Moreover, part of the working memory load for nut cracking is ‘scaffolded’ by having the objects in the visual field and by observing other individuals cracking nuts, but the task of keeping the striking angle less than 90° cannot be scaffolded. One must therefore conclude that even though nut cracking is achievable by *Pan*, flaking is not.

(b) Changes in cognitive capacity reflected in artefacts

Systematic artefact production requires control, if not conceptualization, by the (human or non-human primate) knapper of the actions that constitute artefact production. For artefact production, we make a distinction between an (abstract) concept and the instantiation of that concept in a material form, in which the conceptual level reflects what must be cognized in order for the artefact to be instantiated. Instantiation—the process linking concept with material object—need not account for all possible features or attributes of the material object (Read 2007), as some properties are inherent to whatever technology is involved. Stone knapping, for example, will leave scars on the object from which flakes are removed through knapping even if the ensemble of flake scars is mechanical and not intentional.

(i) Geometric and topological categories of artefacts

The simplest representation of a concrete object combines its geometry and topology, as abstracted from the artefact as object. From the geometry, we can ‘reverse engineer’ the concept–instantiation–object sequence to infer what minimal concept would be necessary to account for the production of an object that instantiates that concept. We will follow Pigeot’s (1991) argument that a combination of topological and simple geometric properties constitutes the conceptual system that has been instantiated. For example, Pigeot argues that an Oldowan chopper has the underlying geometry of a line with instantiation as the cutting edge of the chopper. The deviation of the actual edge from a line is due to iteratively removing flakes to induce an edge on an ‘edge-less’ cobble.

(ii) Time sequence for categories of artefacts

Since the size of STWM relates directly to the complexity of a sequence of actions that can be conceptualized and used to direct actions, we view the size of STWM as a cognitive constraint on the complexity of the artefacts that can be conceived and instantiated by the knapper until STWM = 7 had been reached during hominid evolution.³ We suggest that the following time sequence for the appearance of categories of artefacts also reflects increased demand on STWM.

Stage i. Dimensionality: none (pre-hominid divergence)

(a) *Concept: object attribute; action: repeated.* This category includes artefacts of which the functional attributes for the task at hand are already present on the object in its natural state. The object may be modified in order to enhance the attributes of interest prior to use. Modification may be repetitive. A chimpanzee’s preparation of a small branch to be used for obtaining termites by removing its leaves and small side branches is a prototypical example (see also electronic supplementary material, section 4).

(b) *Concept: relationship between objects.* This category includes examples such as the use of anvil and hammerstone in nut cracking. The functionality depends on the relationship between the entity being acted upon (e.g. the nut) and the instrument(s) (e.g. the anvil and the hammerstone) used in the action (see also electronic supplementary material, section 5).

Stage ii. Concept: imposed attribute; action: repeated; dimensionality: zero-dimensional (unknown dating, above 2.6 Myr BP)

This category would include instances where the attribute(s) that give(s) the object its functionality is (are) not present in the natural state of the object but is (are) introduced through simple modification of the object. The object may be modified more than once through repetition, but multiple modifications can be performed in any order (see also electronic supplementary material, section 6).

Stage iii. Concept: flaking; action: repetition; dimensionality: zero-dimensional (2.6 Myr BP)

This category includes true flakes (rather than debris from breaking one rock with another). Flaking requires comprehension that the striking table has a substantial effect on the breaking pattern of a stone, and that an incident angle of less than 90° produces a fracture known as conchoidal fracturing that is the basis for stone tool knapping. More than one flake can be removed from the same 'core', especially if the flake is the intended consequence of the action and not the fracture pattern left on the core. No dimensionality is involved, as the only conceptualization required is of the form: incident angle < 90° → flake, and the shape of the flake is happenstance from the viewpoint of the action. The functionality of the flake arises from the fact that the edge of the flake produced in this manner is suitable for cutting or scraping tasks without further modification (see also electronic supplementary material, section 7).

We consider stage iii to place greater demands on STWM than stages i–ii. Beyond all the conceptual requirements of stages i–ii, the knapper also needs to control for the striking angle. Knapping can be repetitive, though there need not be any overall plan or design (see Delagnes & Roche 2005). The fact that the knappers at Lokalelei 1 were primarily producing simple *débitage* implies that the repetitive flaking at Lokalelei 2C was cognitively more demanding than the simple, repeated flaking at Lokalelei 1.

Stage iv. Concept: edge; action: iteration; dimensionality: one-dimensional (2.0 Myr BP) = mode 1

The Oldowan industry and the Oldowan chopper, in particular, characterize stage iv. Whereas in stage iii, the core was the remnant of a cobble after flakes were removed, in the Oldowan industry, the core is the goal and the flakes removed may be incidental to this goal. This change in object versus remnant implies a conceptual shift (van der Leeuw 2000). The core has the property that it 'may be modified by flaking' (van der Leeuw 2000, p. 75), whereas a flake cannot be flaked (it can be retouched, but that involves a change in the scale for the flaking). The core conceptually shifts from being the remnant to the goal, and the flaking is aimed at producing a functional edge. Rather than being formed by repetitive removal of flakes (as in the case of the Lokalelei 2C 'organized *débitage*'), in the Oldowan case, the goal is to produce an edge, and so each flake removal is dependent on the previous one: 'It appears that the initial trimming had a tyrannical control on later trimming. The first blow seems to have anchored the rest; concepts of proximity, boundary and order then extended the trimming from this starting point' (Wynn & McGrew 1989, p. 387). The edge is thus formed by conceptually transforming repetitive flaking into iterative flaking aimed at imposing an edge on part of the cobble, and it is this edge that gives the Oldowan chopper its functionality.

According to Wynn & McGrew (1989, p. 387), the flaking of the edge also had a topological consequence as it 'divided the spatial field of the cobble into two realms'. But in our opinion, that is not quite correct.

While the edge begins to divide the total surface of the cobble into two, that division is not complete until the edge is self-intersecting. We are therefore observing an ambiguous situation: is the edge merely a 'line drawn on the (complex) surface of the cobble' (i.e. a one-dimensional feature) or is it the beginning of a two-dimensional approach that divides the cobble's surface into two separate surfaces intersected by a line? But such ambiguities are characteristic of all the transitions we are observing, such as the transformation of repetitive into iterative flaking, and that between knapping an intersecting edge that, in passing, encloses a surface and taking large flakes off a surface that then, in passing, produces an intersecting edge (see also electronic supplementary material, section 8).

Stage v. Dimensionality: two-dimensional

(a) *Concept: closed curve; action: iteration; edge as a generative element (1.5 Myr BP) = mode 2.* The next step fundamentally changes the topology by the simple expedient of continuing the edge until it intersects itself to make a closed curve. What was an irregular 'natural' surface (of a cobble) with a line (the edge) imposed on it is transformed into two surfaces, each having the topology of a surface inside a line closed upon itself. Thus, the surface of the stone (including cortex) is now divided into two surfaces, each inside a closed curve, and whose intersection is the closed curve. This allows for the two surface portions to be modified through flaking, and thus opens the conceptual pathway to bifaces, and to hand axes whose two surfaces are extensively flaked. In effect, by closing the edge on itself, the geometry of the topology is changed from one- to two-dimensional (see also electronic supplementary material, section 9).

(b) *Concept: surface; action: iteration (500 kyr BP) = mode 2.* As noted by Wynn (2002), beginning ca 500 kyr BP, hand axes shift from a focus on edges (where the surface is largely determined by flaking aimed at producing an edge) to a focus on two (top and bottom) surfaces bounded by an edge. The surface is no longer a 'residual category' but its shape and form becomes the intent of the knapping (Graves 1994). The shift is from *débitage* technology in which the flaking has to do with 'l'aménagement final d'un bord et de l'extrémité en outil' ('forming the edge and end of the tool'; Boëda 1991, p. 55) to *façonnage* technology in which the flaking is used to form a desired shape, in this case the shape of the biface: '*façonnage* is predominantly manifest as bifaces, based around a plane of intersection separating two interdependent surfaces that may be hierarchical or non-hierarchical, biconvex or plano-convex, depending on the precise operational chain and type of blank used (Boëda *et al.* 1990)', where 'the two surfaces are organized in relation to each other' (White & Ashton 2003, p. 604, emphasis added; see also electronic supplementary material, section 10).

Stage vi. Concept: surface; action: algorithm;

dimensionality: two-dimensional (300 kyr BP) = mode 3

We suggest that a major conceptual shift occurs with the introduction of Levallois flaking in the Middle

Palaeolithic. The surface as a concept instantiated in hand axes is formed using the same flake technology as occurs in earlier stages. The difference between the earlier approaches and Levallois knapping resides in a shift from viewing flaking as a means to produce an object or to form an edge, to viewing flaking as a means to form a surface through control over the location and angle of the flaking. The surface of the flake is now brought under the control of the knapper.

Moreover, this technique optimized the efficient knapping of surfaces by ensuring that removing one flake is at the same time the preparation for the next removal. Product and object are identified with each other in the knapper's conceptualization. The characterization of the Levallois method given by Boëda (1995) clearly shows the sense in which this method becomes an algorithm for the production of flakes, rather than simply a particular method for the removal of a flake (see figure B of the electronic supplementary material, section 11). It allows for repeated, but not recursive, application of the algorithm to the same core so as to produce a number of flakes whose characteristics are under the control of the knapper (see also electronic supplementary material, section 11).

The technique is, in Pigeot's (1991, pp. 184–186) view, the culmination of the development of control over flaking causing the shape of the original nodule to become less important.

Stage vii. Concept: intersection of planes; action: recursion; dimensionality: three-dimensional (less than 50 kyr BP) = mode 4

Prismatic blade technology replaces Levallois methods wherever it occurs (primarily North Africa, northern and western Asia and Europe; Bar-Yosef & Kuhn 1999), but is not a transformation of the latter. Boëda (1986), in a comparison of Levallois and Upper Palaeolithic nuclei, distinguishes the two technologies by arguing that the Levallois technology is based on two crosscutting surfaces that form a functional hierarchy. This limits productivity because the production of a predetermined flake is at the detriment of one of the two surfaces (the 'true' Levallois surface), hence it recedes systematically during flake production (see also electronic supplementary material, section 12).

Prismatic blade technology, on the other hand, controls the flaking technique in such a way that the removal of a blade maintains the form of the core from which it is removed, so the next step simply acts on the output (the form of the core volume) of the previous step. Since the location of the next blade detachment is determined by the previous detachment and the previous detachment preserves the form of the core, the blade production process (namely begin with a striking surface at right angles to the exploited surface, then detach a blade of controlled width through percussion) is directly enacted on the core that is the output of the previous instance of blade production.

Thus, what seems to be different about prismatic blade production is that it is based upon recursive application—to the core volume—of the algorithm that determines the process by which the blades are obtained: 'Each blade is produced by the same process

as the one preceding it, a monotonous process. As with other skilled knapping, it also requires rhythm ...' (Clark 1987, p. 268, emphasis added). The Levallois method, in contrast, allows only for repetition since the surface from which a flake is to be detached must be reformed, thus the flake removal process must start anew for the next flake.

We suggest that the recursion of stage vii may be an exaptation of cognitive changes that had already led to neurological capacities of the brain that enabled recursive logic.

(c) *Implications of the changes in working memory*

(i) *The relationship of technological change to change in STWM*

Although we do not have any direct evidence on the relationship between encephalization and working memory, we can make the following indirect argument. Encephalization is presumed to relate to the ability to deal with more complex reasoning, among other capacities. There is a strong correlation between general fluid intelligence (reasoning and problem-solving ability) and working memory (Engle *et al.* 1999b; Engle 2002), hence we can assume that the STWM component of working memory and encephalization are correlated. Let us make the assumption that the relationship is linear as a first approximation (see also electronic supplementary material, section 13).

We can graph change in the encephalization quotient (EQ) during hominid evolution from a common ancestor with *Pan* and rescale the change in the EQ to a STWM scale, assuming STWM=2 for *Pan* and STWM=7 for modern *H. sapiens* (see the left and right vertical axes in figure 2). We can then determine the implied STWM for a fossil hominid group based on its estimated encephalization. Finally, we place a vertical 'fuzzy bar' (in order to emphasize measurement imprecision) at the estimated time for the appearance of each of stages iii–vii, based on archaeological and palaeontological data (figure 2).

(ii) *Implications of change in STWM*

We offer the following interpretation of changes in encephalization, STWM and stone tool technology over hominid evolution. Beginning with STWM=2 for *Pan*, stage iii (control of flaking) occurs when STWM=3, which is consistent with the fact that stage iii conceptually requires STWM=3 as discussed previously. Stage iv (control of an edge) occurs after increased encephalization when STWM=4, again consistent with the increased conceptualization involved in using iterative flaking to form an edge. Stage v (forming a closed boundary, hence a surface) occurs after a slight increase in encephalization and increase in STWM to STWM=4.5, which is consistent with the argument we made previously that the change from stage iv to stage v is more of an elaboration on stage v (closure of an edge) rather than the introduction of a qualitatively new concept. Stage v(a) (conceptualization of a surface as a two-dimensional concept) occurs with STWM=5, but this is only a small change from stage v (STWM~4.5). The change from stage v to stage v(a) is thus conceptually not a major change.

Figure 2. Graph of encephalization quotient (EQ) estimates based on hominid fossils and *Pan*. Early hominid fossils have been identified by taxon. Each data point is the mean for hominid fossils at that time period. Height of the 'fuzzy' vertical bars is the hominid EQ corresponding to the date for the appearance of the stage represented by the fuzzy bar. Right vertical axis represents STWM. Data are adapted from as follows: triangles, Epstein (2002); squares, Rightmire (2004); diamonds, Ruff *et al.* (2004). $EQ = \text{brain mass} / (11.22 \times \text{body mass}^{0.76})$ (Martin 1981).

This is consistent with the change primarily from making a hand axe using the *débitage* technique to making a hand axe using *façonnage* technique. Stage vi (Levallois method) occurs after a period of rapid encephalization with STWM=6, consistent with the Levallois method involving a new concept, namely an algorithmic approach to knapping based on the relationship between a solid and a method for flake removal, with producing the flake as the goal of the method. Finally, stage vii (prismatic blade technology, recursion) also occurs after a period of rapid encephalization with change in STWM to STWM=7; that is, a change in STWM to the value that occurs in modern *H. sapiens*. Prismatic blade technology leads to a florescence of kinds and forms of stone tools, which appears to build off the level of conceptualization possible with working memory the same as it is for humans today. With respect to language, Coolidge & Wynn (2007, p. 709), for example, have postulated that 'enhanced working memory [working memory comparable to that of modern humans], by way of recursion, may have allowed the speaker to 'hold in mind' a much greater number of options, and as such, give the speaker a greater range of behavioural flexibility and even creativity' and suggest the origin of what they call EWM via a 'genetic neural mutation, sometime within the last 100,000 years' (p. 710), a conclusion consistent with the scenario we have postulated for the shift from stage vi to stage vii.

3. PART TWO: MODERN HUMANS

Once this stage has been reached, there is no reason to impute further evolutions in working memory, but we see an 'innovative explosion' in the evolution of artefact technologies. In effect, if we observe the technologies developed in the last 25 000 years or so, we are quickly convinced that a threshold has been crossed, and that modern humans have entered a different era, in which a very different dynamic is occurring between humans and the material world. In the following sections we describe that transition and the first stages of the new dynamic. The sheer multitude of different kinds of artefacts and logical operations that emerge forces us to change our focus and the language we use. We have to move a level of generalization up and focus on rather broad categories of change, hence losing direct connection between specific sequences of manufacture and the conceptual operations they entail.

The hypothesis that we propose to explain this sudden acceleration in the pace of technological change is the fact that it is no longer constrained by the capacities of working memory. Indeed, even superficial observation of modern technologies, languages and other human achievements indicates that modern humans' current STWM of 7 seems adequate to deal with very complex operations indeed.

But that introduces other questions, such as 'are there other constraints that come into play?', 'what are

some of the consequences of this acceleration?', etc. We will try to answer some of them along the way.

(a) New kinds of tools, new materials

(i) *The end of the Upper Palaeolithic and Mesolithic (25–10 kyr BP)*

During this period, we see numerous important new techniques emerge almost simultaneously.⁴ One is the manufacture of 'microliths', small stone tools testifying to the control toolmakers have over finer and finer details in the production process and *extending the range by orders of magnitude for the volume* manipulated by toolmakers. These microliths occur in an increasingly wide range of shapes, which implies that there is a closer match between individual objects and their intended functions. Toolmakers must have acquired an improved capability to analyse the requirements their artefacts should meet in order to be most effective, and a *more versatile spatial topology*.

Although it is unlikely that this time period includes the first use of non-stone materials in tools, one now observes a substantive number of instances of the use of other materials (wood, bone, antler, etc.) alongside stone in making tools. This implies the development of a wide new range of (motor and other) skills and tools to work all of these materials.

A closely related innovation is the introduction of *composite tools*, consisting of a number of microliths hafted together in objects of wood or bone. This implies the *conceptual reversibility of scalar hierarchies*: not only are tools made by reducing a larger piece of stone into one or more small flakes, which are retouched to give them the required shape, but also these small pieces are then assembled into something larger.

(ii) *The Neolithic (ca 10 000–7000 yr BP)*

New artefact making techniques

Beginning in the Neolithic, stone tools are transformed beyond recognition by the introduction of grinding. This development completes the mastery of stone—working scales going from the macro- to the microscopic. Neolithic stone axes and adzes are first roughly flaked out of appropriately fine-grained blocks of stone. Next, they are refined by removing smaller and smaller flakes. And finally, the toolmaker removes microscopically small particles by pecking or grinding. The resulting objects have a completely smooth surface, which can be as flat, rounded or irregular as desired. *Control over the final shape is complete, as is the use of different scales of removal from the initial stone block—from very large flakes to individual grains.*

The making of *containers* was introduced between 12 000 and 9000 yr BP (depending on the material and the world region), made of wood, leather, stone and pottery. In each case, the manufacturing technique is different. Nonetheless, some conceptual innovations are the same:

— The introduction of a different topology—a *surface around a void*. This requires the conceptual separation of the surface of an object from its volume, and making the distinction between the outside and inside surfaces. Neither is conceivable in the absence of a true three-dimensional conception of objects.

Natural containers may have served as examples, but recreating them conceptually was nevertheless an important innovation.

- The inversion of the sequence of manufacturing—*beginning with the smallest particles and assembling them into larger objects*. In basketry and weaving, small fibres combine into longer and thicker strands and are then coiled or woven into two- or three-dimensional objects. Pottery making uses naturally coherent small particles, but early techniques combine them into long and thick linear objects (coils), and these into three-dimensional shapes.
- Closely related is the *correction of errors* by undoing work and returning to a point earlier in the manufacturing sequence. This presumes that *control loops link the past with the present and the future*, but also that *actions are conceived of as being reversible*.
- In the case of pottery, metallurgy and other complex techniques, the *separation between different stages of production* is pushed a step further. Resource procurement, paste preparation, shaping, decoration and firing occur sequentially, and the maker has to keep all these stages in mind during the whole process. This involves tracking a large number of embedded control loops in working memory.

A changing relationship with the environment

These and other conceptual advances opened up new realms of problem-solving and invention, including the transformation of subsistence risks—from a daily concern over which people had little control, to a seasonal or pluriannual concern over which they had a little more control. This was achieved

- (i) by combining a mobile lifestyle with the breeding and herding of domesticated animals and/or the seasonal cultivation of wild plants, or
- (ii) by sedentism and cultivating domesticated plants.

Spatially, this required a *two-dimensional 'map' of the landscape* and, in the case of cultivation, the conceptual distinctions between 'inside' and 'outside' marked by the perimeter of gardens or fields—as well as between 'self' and 'other', which was acquired as part of the conceptualization of kinship systems. *Temporally* speaking, cultivation and herding stretched the temporal sequences and temporally separate parts of a 'manufacturing' sequence much further than is the case in artefact manufacture.

When cultivating and herding, people no longer cull and harvest nature for their subsistence, but *intervene and invest* in their natural environment in the expectation that they can change it, even if only locally. This *limits the adaptive flexibility of the people involved*. Whereas gathering and hunting involve intermittent, almost instantaneous (albeit periodic) interactions between the temporalities of the natural environment and the rhythms of human subsistence needs, herding, cultivation and domestication necessarily involve a *longer-term conception of the symbiosis* between humans and their food sources. This in turn involves a change in the relationship between people and their environment from being reactive to the environment to being interactive with it.

Box 1.

Problem-solving structures knowledge → more knowledge increases the information processing capacity → this in turn allows the cognition of new problems → creates new knowledge → knowledge creation involves more and more people in processing information → enables and triggers increases in group size and degree of aggregation →; these increases create more problems → augment the need for problem-solving → problem-solving structures more knowledge, etc.

Survival continues to depend on the adequacy of subsistence and survival techniques, but is no longer defined by just the capability to find and harvest wild resources. Increasingly, it is defined by the ability to control the environment through means such as

- simplifying the environment, for example by homogenizing it locally, replacing natural vegetation by more homogenous planted vegetation,
- optimizing and narrowing the range of dependencies on the natural environment, for example by focusing on particular crops or particular animals for subsistence, and
- diversifying technical know-how to closely match the resources available in the local and regional environment in which they live.

In this process, the coupling between humans and their environments became much tighter, initiating a true coevolution between the two. The investments made in the environment and in one's social and technological adaptation to it encouraged increased investment in known environments and subsistence strategies. But it thereby also introduced long-term risks inherent in following a single survival strategy, as well as the need to deal with those risks.

Increasing demographic aggregation

Consequently, problem-solving rather than moving to a new location became the key to survival. This set in motion another positive feedback loop in which problems prompted a search for solutions, leading to more problems, etc. This feedback loop explains in our eyes the exponential growth in both innovation and population density over the last 10 000 years, which is summarized in box 1 (cf. van der Leeuw & McGlade 1997; van der Leeuw & Aschan-Leygonie 2005):

The result is the continued accumulation of knowledge, and thus of information processing capacity, enabling a concomitant increase in matter, energy and information flows through the society, the growth in the number of people participating in that society and the subsequent need to reduce the time involved in communication which, in our opinion, led to urbanization (cf. Read & LeBlanc 2003). But that is another story (cf. van der Leeuw 2007).

4. CONCLUSION

Returning to the beginning of this paper with the benefit of hindsight, we can now answer the questions posed there by describing the emergence of the human species as a dominant player on Earth as a bootstrapping process in which we can distinguish two phases.

The first of these is predominantly biological and consists of the growth of human cranial capacity, the

development of the frontal lobe and the increase in working memory capacity. These three developments prepared the way for a second phase, in which humans slowly gained an edge over other species and over their physical environment by developing the faculty that distinguishes modern humans from all other species: the capacity to learn and to learn how to learn.⁵ This capacity allowed them to categorize, to make abstractions and to hierarchically organize them, and thus to develop the capacity to identify and solve ever more complex problems by inventing suitable conceptual tools. They learned various kinds of (symbolic and other) means to communicate among themselves, and they increased their capacity to transform their natural and material environment in many different ways, and at many spatial and temporal scales.

Hence, from *ca* 12 kyr BP, we observe a drastic acceleration in the speed of invention and innovation. Many new categories of artefacts emerge, new materials are used, new techniques are introduced and new ways to deal with aspects of the material world are 'discovered' in the comparatively short time span of a few thousand years. The acceleration is so overwhelming that the way of life of most humans on Earth changes: rather than live in small non-sedentary groups, people concentrate their activities, invent different subsistence strategies, and in some cases become sedentary.

This 'invention explosion' of the Mesolithic and Neolithic is the result of the fact that human beings have internalized the conceptual apparatus necessary to conceive of space in nested dimensions (zero, one, two and three) across a wide range of spatial scales (from the individual fibre or grain to the landscape), to separate a surface from the volume it encloses, to use different topologies, to distinguish and relate time and space, to distinguish between different sequences of cause and effect, to plan, etc.

From the perspective of the development of working memory, a threshold has clearly been crossed. With a STWM of 7, innovation was no longer an additive process, but became an exponential one because combinatorial possibilities of existing concepts now could be the basis for generating new concepts. Human beings achieved an exponential increase in the dimensionality of the conceptual hyperspace ('possibility space') that governed their relationship with the external world. This afforded them a quantum leap in the number of degrees of freedom of choice they had in dealing with their material and ideational environment.

Once that stage has been reached, working memory (and with it, biological changes in humans' information processing capacity) no longer constrained the introduction of more and more, and more complex, 'tools for thought'. We have reached a critical point, where

human-induced generation of new concepts and new relationships (physical, environmental and social)—and thus cultural evolution—takes over from biological evolution in the development of humans' means of adapting to their physical and social environment.

Together, these advances greatly increase the number of ways at people's disposal to tackle the challenges posed by their environment. This allows them to meet more and more complex challenges in shorter and shorter time frames. Hence, it triggers a rapid increase in our species' capability to invent and innovate in many different domains.

But the other side of the coin was that these solutions, by engaging people in the manipulation of a material world that they only partly controlled, ultimately led to new, often unexpected, challenges that required the mobilization of great effort to be overcome in due time. In this process, human societies invested more and more in control over their environment (such as by building infrastructure) and anchored them more and more closely to the territory in which they lived. The symbiosis that emerged between different landscapes and the life-ways invented and constructed by human groups to deal with them eventually narrowed the spectrum of adaptive options open to the individual societies concerned, and thereby drove them to devise new (and more complex) solutions, with increasingly unexpected consequences. Overall, increasing control over the material and natural environment was balanced by increasing societal complexity (Read 2002), which was not always possible to keep under control.

ENDNOTES

¹The term 'working memory' is a bit of a misnomer as the cognitive function that is involved does not just involve memory but also includes attention (Baddeley 1993). Baddeley was expanding on the earlier notion of short-term memory to include what he referred to as an executive function coupled with a phonological loop and a visuospatial sketchpad (Coolidge & Wynn 2005).

²Theory of mind refers to 'the ability to attribute mental states—beliefs, intents, desires, pretending, knowledge, etc.—to oneself and others and to understand that others have beliefs, desires and intentions that are different from one's own' (Wikipedia 2007; cf. Premack & Woodruff 1978).

³This is no different from what has been argued in linguistics. According to Just and Carpenter, for example, while in principle there is no limit to the amount of embedding that can occur with relative clauses, the comprehensibility of sentences with multiply embedded relative clauses is directly related to the size of working memory (Just & Carpenter 1992).

⁴In archaeology, it is often very difficult to determine the sequence in which phenomena appear, in part either owing to a lack of dates or because dates have a wide margin of errors, but also because our record is often so fragmentary that it is very easy to miss the first manifestation of a phenomenon.

⁵Their capacity to process information is genetically encoded, but the information they process, and the ways in which they do so, is not. It is socio-culturally and self-referentially developed and maintained.

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