

The brain–artefact interface (BAI): a challenge for archaeology and cultural neuroscience

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Cultural neuroscience provides a new approach for understanding the impact of culture on the human brain (and vice versa) opening thus new avenues for cross-disciplinary collaboration with archaeology and anthropology. Finding new meaningful and productive unit of analysis is essential for such collaboration. But what can archaeological preoccupation with material culture and long-term change contribute to this end? In this article, I introduce and discuss the notion of the brain–artefact interface (BAI) as a useful conceptual bridge between neuroplasticity and the extended mind. I argue that a key challenge for archaeology and cultural neuroscience lies in the cross-disciplinary understanding of the processes by which our plastic enculturated brains become constituted within the wider extended networks of non-biological artefacts and cultural practices that delineate the real spatial and temporal boundaries of the human cognitive map.

Keywords: Cognitive archaeology; material culture; brain–artefact interface; extended mind; plasticity

INTRODUCTION

It cannot be too strongly emphasized that, to an important extent, all social, cognitive and affective neuroscience is cultural neuroscience. The reason for that is simple enough, at least for cognitive archaeology and anthropology: the human brain, for some million years now, is an extremely plastic, profoundly embodied, materially engaged and culturally situated bio-psycho-social artefact (Donald, 1998, Donald, 2001; Clark, 2003; Knappett, 2005, 2006; Gamble, 2007; Renfrew, 2007; Malafouris, 2008b; Malafouris and Renfrew, 2008; Mithen and Parsons, 2008; Wheeler and Clark, 2008; Renfrew *et al.*, 2009). It may not be as widely recognized, in the sciences of mind, as it should have been but few if any of the phenomena studied under the label of cognitive, social and affective neuroscience exist outside culture. The concepts of culture, brain, body and mind, are simply terms used to separate analytically what has been evolved and can only exist as an inseparable ontological unity. I do not mean, of course, to imply here that the brain, in general, is not a meaningful unit of analysis. Instead, I want simply to emphasize at the outset, that when it comes to the question of the relationship between cognition and culture we should take extra care to avoid falling into the trap of reductionism and neurocentrism which can easily lead us to mistake the properties of culture for the properties of the individual brain (for a more extensive critique, see Malafouris and Renfrew, 2008; Renfrew *et*

al., 2008; Malafouris, 2009). Thus rather than seeing culture as some kind of replaceable software for our genetically fixed computational hardware, I suggest we should see culture as the enactive process that brings forth, envelops and partially constitutes human cognitive and emotional lives. It follows, that any attempt at developing cultural (Nisbett *et al.*, 2001; Nisbett and Miyamoto, 2005; Chiao and Ambady, 2007; Han and Northoff, 2008) and critical (Choudhury *et al.*, 2009) perspectives that will help us understand better the reciprocal interaction between brain and culture, is the way forward but also a big challenge for neuroscience. Naturally, we are still a long way from arriving at more a holistic but also empirically testable formulation of the key issues involved in the neuroscience of culture. Any attempt to bridge the gap between ‘supposedly culture-invariant neural mechanisms and psychological evidence of culture-sensitive cognition’ (Han and Northoff, 2008, p. 646) raise a number of questions: for instance, what would constitute a meaningful and ecologically valid analytic unit for transcultural comparisons in neuroscience? How can the cognitive properties which arise from the interaction of person with social and material world best approached and described?

In this article, I want to explore those issues from the perspective of cognitive archaeology. I will be asking what is it that archaeology can bring to this new emerging field of cross-disciplinary research and how can it help us to develop common relational ways of thinking at the cross section between brain and culture? To answer that, I shall be focusing on the hypothesis of the constitutive intertwining of cognition and material culture (Malafouris, 2004, 2010). To encompass the complex recursive relations between brains, bodies and things in a single analytic unit; I will introduce and discuss the notion of the brain–artefact

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interface (BAI). I will argue that the BAI offers to cultural neuroscience a useful conceptual bridge between neuroplasticity and the extended mind which is applicable across the scales of time.

PROSTHETIC BODIES, SITUATED MINDS: THE PRIMACY OF MATERIAL ENGAGEMENT

Despite the growing consensus in many disciplines about the important role that the material world plays in the structuring of human cognitive operations (Latour, 1992, 1999, 2005; Hutchins, 1995, 2005, 2008; Sterenly, 2004; Knappett, 2005; Clark, 2008; Sutton, 2008) the precise question of the causal efficacy of things in the human cognitive system, has, surprisingly, evoked limited collaboration between archaeology, anthropology and neuroscience (e.g. Costall and Dreier, 2006; Renfrew, 2006; Renfrew *et al.*, 2009; Gosden, 2008; Knappett and Malafouris, 2008; Mithen and Parsons, 2008; Coolidge and Wynn, 2009; de Beaune *et al.*, 2009; Malafouris and Renfrew, 2010). This attitude of what we may call ‘epistemic neglect of the object’, is symptomatic of a more general tendency in the mainstream cognitive sciences to leave material culture outside the cognitive equation proper. Even embodied and situated perspectives in cognitive science (for a review of the field, see Clark, 2001, 2007, 2008; Anderson, 2003; Wheeler, 2005), which explicitly recognize the intrinsic relationship between brain/body and environment, often seem oblivious to the actual material medium that envelops and shapes our lives. Although material culture is recognized as a ‘causal influence’ it is rarely seen as playing a ‘constitutive’ role. On this construal, the cultural object may be the stimulus that triggers or mediates some cognitive process but is not seen as having any important role or as being a part of the cognitive network. It seems that retaining a substantial dose of residual cognitivism, the situated cognition paradigm failed to develop a systematic research framework concerned with figuring out the effects of materiality in the enactment and constitution of a cognitive system or operation. Despite stretching the mind as far as the body’s surface, the conventional use and understanding of the embodiment and situated cognition remains trapped inside the biological boundaries of the individual (for a more detailed critique and discussion, see Malafouris, 2004, 2008c; Malafouris and Renfrew, 2010). I believe this is, potentially, a serious methodological drawback at the heart of cultural neuroscience that we need to overcome. As Donald points out ‘we cannot have a science of mind that disregards material culture as we cannot have an adequate science of material culture that leaves out cognition’ (Donald, 1998, p. 186). The notion of the BAI nicely exemplifies the above synergy signifying the point of intersection between cognition and material culture. It also offers a useful and widely applicable analytical unit for doing away with some deeply misconceived assumptions about the mind’s function, ontology and location.

THE BRAIN–ARTEFACT INTERFACE (BAI)

But what precisely is a BAI and how can it help us to redefine the place and effect of material culture in the human cognitive system? In its broad sense an interface is essentially any natural or artificial mediational means or prosthesis that enables, constrains and in general specifies communication and interaction between entities or processes. The human body, language and gesture are some obvious examples of such an interface, as it is also, the handheld rake used by a monkey to retrieve distant food rewards in captivity or the stick used in the wild by a chimpanzee digging for food (Iriki, 2005; Iriki and Sakura, 2008). However, the notion of the BAI introduced here, carries some distinctive features that differentiate and delineate its meaning and applications both from an ontological and epistemological perspective. Starting from the ontological standpoint, the term BAI is introduced to denote in particular the kind of technological mediations (material structures, processes, objects or other socio-material apparatuses and practices) that enable the configuration of a dynamic alignment or tuning between neural and cultural plasticity. This sort of bidirectional dynamic coalitions that lie at the heart of BAIs can take many different forms [e.g. hard assembled (stable)/soft-assembled (reconfigurable), epistemic/pragmatic, invasive/non-invasive, representational/performative, transparent/non-transparent, constitutive/instrumental, etc.] and can be empirically observed through diverse examples ranging from the early stone tools (e.g. Oldowan choppers, Achelean handaxes, blade and microlithic technology), specialized hunting, art and personal-decoration (Foley and Lahr, 2003; d’Errico *et al.*, 2003; McBrearty, 2003; Gamble, 2007; Mellars *et al.*, 2007), to the more recent symbolic or ‘exographic’ (Donald 1991) technologies such as calendars, writing, and numerals as well as pencils and papers (Ifrah, 1985; Schmandt-Besserat, 1992; Hutchins, 1995, 2005; Kirsh, 1995; Sterenly 2004). To this long list of BAIs, one could add the case of the most recent brain–machine interfaces (BMIs) that make now possible for a monkey or human to operate remote devices directly via neural activity (Nicoletis 2001, 2003; Donoghue, 2008) or simply the QERTY keyboard of my laptop that I use to write this article. Obviously a detailed taxonomy of BAIs and discussion of their respective differentiating features and properties would be beyond the scope of this brief article. What follows is simply a summary of the principal ways in which the effects of BAIs in the human cognitive system can be understood. These can be broadly classified according to three major and closely interrelated categories: mediational, temporal and plastic:

(1) Mediational effects

- *Enactive prosthetic enhancement*: BAIs enable the mind to make maximal use and/or transform the structure of information in the environment in ways that would have been impossible for the naked organism to achieve.

- *Co-evolutionary material engagement*: BAIs as dynamic perturbatory channels drastically change and reconfigure the nature of the relationships between humans, and between humans and their environments. The presence of BAIs means that people no longer react or passively adapt to their environments, instead they actively engage and interact with it in feedback circles which run across evolutionary time. This idea resonates and to a certain extent emanates from ‘niche construction’ (Laland *et al.*, 2001; Oyama *et al.*, 2001) but it goes beyond the short of cumulative ‘epistemic engineering’ (Sterelny, 2004) that such view might imply (see also Wheeler and Clark, 2008).

(2) Temporal effects

- *Temporal anchoring and binding*: BAIs have a critical role for the integration and coordination between processes that operate at radically different timescales (e.g. neural, bodily, cultural and evolutionary).

(3) Plastic effects

- *Effective connectivity*: BAIs are a powerful mechanism for culture and activity induced plasticity in the human cortex. They effect extensive structural rewiring either by fine-tuning of existing brain pathways or by generating new connections within brain regions (see discussion of *metaplasticity* below).
- *Extended reorganization*: BAIs extend the functional architecture of the cognitive system either by adding new processing nodes to the system or by changing the connections among existing nodes. More importantly, they are capable of transforming and rearranging the structure of a cognitive task. This is possible either via a simple reordering in the sequence in which the steps of a task are performed or by delegating part of a cognitive process to another agent (human or artefact). Neurobiologically this shift in the cognitive processes underlying a given task performance is reflected as a change in the actual location of brain activations (Kelly and Garavan, 2005). Thus extended reorganization does not simply refer to an activity-dependent change in the neural architecture (whether by adding new processing nodes or connections among them). Instead, it refers to an outward expansion of the cognitive system as to forge and incorporate extra-neural connections and nodes realized through bodily action and cultural practices (see example of numerical thinking below).

The last point brings us back to the second part of our initial question concerning the epistemological function of the BAI as an analytic tool. That is the question about how can this notion help us to redefine the place and effect of material culture in the human cognitive system? The answer is twofold: on the one hand, the BAI as an object-oriented methodology shifts the focus of research explicitly upon the elementary processes of material engagement that

mediate and constitute thinking as a cultural process. On the other hand, it enables us to think about interfaces in a new way, i.e. to think about their function in terms of mutual permeability, binding and structural coupling rather than separation. The underlying working assumption behind the operation of the BAI is that *the functional structure and anatomy of the human brain is a dynamic construct remodeled in detail by behaviourally important experiences which are mediated, and often constituted, by the use of material objects and cultural artefacts which for that reason should be seen as continuous integral parts of the human cognitive architecture* (Malafouris, 2008b, 2010). No doubt, from the perspective of neuroscience, understanding the precise effects of things on the functional anatomy of the human brain is not an easy task and the evidence that bears on this question is hard to come by, especially in humans. Nonetheless, recent studies exploring the effects of the temporary or permanent incorporation of inanimate objects and tools into the ‘body schema’ (Iriki *et al.*, 1996; Berti and Frassinetti, 2000; Farne and Ladavas, 2000; Maravita *et al.*, 2001; Holmes and Spence 2004, 2006; Holmes *et al.*, 2004; Maravita and Iriki, 2004; Farle *et al.*, 2007; Cardinali *et al.*, 2009a) offer plenty of neuroscientific evidence about how even the simplest BAIs may change the way the human brain perceives the size and configuration of our body parts. These studies may well be seen as already articulating some very interesting points of intersection between archaeology and neuroscience. Seen in this context, the concept of BAI attempts to delineate, in an empirically accessible manner, the hybrid space at the intersection between ‘personal’, ‘peri-personal’ and ‘extrapersonal’ space (Cardinali *et al.*, 2009b), where mediated action takes place and where neural and cultural plasticity meet and exchange properties.

TOOLS FOR A PLASTIC MIND

There are a number of archaeological examples that one could use to illustrate the above premises. The example of early tool use and manufacture offers one of the earliest archaeologically identifiable examples of BAIs. We should remind ourselves that from an evolutionary perspective stone knapping, i.e. using a tool to make another tool (Wynn and McGrew, 1989; Ambrose, 2001; Roux and Bril, 2005; Stout *et al.*, 2008), is generally considered, together with language, learning by instruction (Frith, 2008), and possibly theory of mind (ToM) and ‘shared’ or ‘we’ intentionality—i.e. the human ability to participate in collaborative activities with shared intentions (Tomasello *et al.*, 2005)—a unique feature of human cognition. Although some chimpanzees may display tool use abilities in the wild and monkeys can be trained to use simple tools in captivity (Iriki, 2005; Iriki and Sakura, 2008), even some of the most highly trained and ‘enculturated’ chimpanzees, like Kanzi, could not manage to equal the abilities seen in the earliest hominin stone tool makers (Davidson and McGrew, 2005).

Most archaeologists would agree that the first intentionally modified stone tools appear, more or less, at the same time with the origins of our genus *Homo* and prior to any fossil evidence of significant hominin brain expansion, in the archaeological record of Africa at least 2.6-million-years-ago (Holloway, 1999). About 90% of this time, what we call in archaeology the Early Stone Age (also known for the regions outside Africa as the Lower Palaeolithic), in terms of brain evolution, we witness a nearly threefold increase in hominin brain size—from the high end of the chimpanzee range to the low end of the modern human range (Stout and Chaminade, 2009). In terms of technical evolution we see a progression from simple ‘Oldowan’ stone chips to the skillfully shaped ‘Acheulean’ cutting tools (McPherron, 2000; Lycett and Gowlett, 2008; Stout *et al.*, 2008).

The question that naturally follows, given what we previously suggested concerning the function of BAIs, is the following: Should we perceive these early stone tools as BAIs capable of transforming and extending the cognitive architecture of our hominid ancestors? Or, is it more plausible instead, to see them simply as a passive ‘external’ mechanical aid for cutting meat with no real, or in any sense important, cognitive bearing in the developmental trajectories of our species? This is a question that extends beyond the domain of stone tools and relates also to more recent symbolic processes and social practices that appear well after the appearance of *Homo sapiens*, between 200 000 and 70 000 years ago, arguably with major implications for our conventional archaeological understanding of the origin of human cognitive modernity.

Until recently, our understanding of the brain mechanisms and of the functional architecture of tool use in humans came primarily from the study of *apraxia* or similar behavioural deficits resulting from brain damage. For example, patients with ideomotor and ideational apraxia are able to name and describe a tool but are unable to grasp the tool and use it—the reverse deficit can also be observed. Moreover, some patients may show inability to use a tool unless the target of the tool’s action is present (Johnson-Frey, 2004; Holmes and Spence, 2006). However, with the new developments in functional neuroimaging and evolutionary neuroscience the situation is rapidly changing (e.g. Johnson-Frey and Grafton, 2003; Schaefer *et al.*, 2004; Frey, 2008; see also discussion of body schema above). From the perspective of archaeology a series of pilot imaging studies of stone-tool making (Stout *et al.*, 2008; Stout and Chaminade, 2007, 2009) offer a good example to the point, providing the first concrete imaging evidence about the possible neural correlates of the changing lithic technologies in the human brain. For instance, Stout and his colleagues using positron emission tomography PET display evidence of increased sensorimotor and cognitive demands related to the changing nature of expert performance and to the complexity of toolmaking methods (Stout and Chaminade, 2007). In particular, two findings are of special

interest: On the one hand, the presence of sensorimotor activations and absence of prefrontal recruitment during ‘Oldowan’ knapping argues against the predominant prefrontal or ‘executive’ bias that characterizes most research in human cognitive evolution. On the other hand, the increased anterior frontal and right hemisphere activations observed in Late Acheulean knapping methods are indicative of practice effects which raise the question of how technological change and innovation can be related with human brain anatomy and function. Lastly, new imaging data (Stout *et al.*, 2008; Stout and Chaminade, 2009) show that neural circuits supporting stone toolmaking partially overlap with language circuits, which suggests that these behaviors share a foundation in more general human capacities for complex, goal-directed action and are likely to have evolved in a mutually reinforcing way. Further evidence for this important link between complex tool use and language are also offered by Frey (2008). His research combining data from brain-injured patients and functional neuroimaging studies indicate a possible brain network participating in the representation of both familiar tool-use skills and communicative gestures. Although from an evolutionary perspective these correlations cannot demonstrate the direction of cause and effect, they constitute a significant development in the long-standing issue of the possible relations between language and tool use in human evolution. The above proposed relationships between early Stone Age (ESA) technological change, evolving hominin brain size, functional lateralization and language capacities support the argument that human brains and technology have been co-evolving for at least 2-million-years. It remains less clear, however, how precisely this co-evolution might have led to the emergence of our species, *H. sapiens*, in Africa between 70 000 and 200 000-years-ago.

I suggest that approaching tool use as a BAI enables us to think about cultural cognition and its evolution as a transformative interplay of neural, bodily and material recourses rather than in terms of ‘set of pre-specified adapted functions, performed in the triggering context of variable non-neural structures and cultural forces, by relatively static, genetically based forms of neural encoding and processing’ (Wheeler and Clark, 2008, p. 3563).

METAPLASTICITY

The view of the brain as an inherently plastic and environmentally contextualized adaptive system has been around in neuroscience for many decades and should come as no surprise (Wexler, 2006). More recently the rapid development of new imaging technologies offered a new means for exploring the effects of culture on the human brain and understanding the mechanisms of activity-dependent plasticity (Quartz and Sejnowski, 1997; Poldrack, 2000; Pascual-Leone *et al.*, 1993, p. 379; Kelly and Garavan, 2005) and ‘environmental enrichment’ (for review, see Nithianantharajah and Hannan 2006). Social and

developmental neuroscience can now confirm that plastic changes (functional but also structural/anatomical) occur throughout the human lifespan (for recent review, see Sowell *et al.*, 2003; Blakemore and Choudhury, 2006; Blakemore, 2008). Our minds and brains are (potentially) subject to constant change and alteration caused by our ordinary developmental engagement with cultural practices and the material world.

Naturally, exploring the long-term effects of culture on the brain (and vice versa) is a far more difficult task. Despite years of research in many disciplines (for a good summary, see Tomasello *et al.*, 2005) the precise links between ontogeny and phylogeny remain far from obvious or straightforward. At present, learning and practice-related developmental plasticity appear as the most promising areas of research in helping us to build some analytical bridges between the short- and long-term aspects of human cognitive becoming. Of course, neural plasticity, *in itself*, is probably not the best place to look for signs of human uniqueness. For one thing, neural plasticity, exaggerated as it might be in humans, is something that like ‘mirror neurons’ we share with other species. For another, there are no definable points in human cognitive evolution after which one may be able to measure and compare plastic changes. Having said that however, it is indeed the property of plasticity which possibly, more than any other feature, makes change and alterability, especially in a cultural setting, the natural state of human intelligence more than anything we see in other animals. We have a plastic mind which is embedded and inextricably enfolded with a *plastic culture*. And it is this truly distinctive feature of the human cognitive system, what we may call *metaplasticity*, that I suggest should occupy, more than anything else, the research focus of cultural neuroscience and cognitive archaeology. In fact, I want to suggest, that a common challenge, for archaeology, anthropology and cultural neuroscience, should concern the mechanisms that mediate those plastic changes, not at the level of the individual, but at the broader systemic level of deep enculturation, material engagement (Malafouris, 2004, 2008a, b) and ‘profound embodiment’ (Clark, 2008). It is in this connection that the usefulness of the BAI as an analytic tool becomes more obvious. At this broader level of human/non-human interaction, that underlies the constant and dynamic reorganization of human cognitive architecture, material culture competes, equally with any other brain region, for a place in the human cognitive system. It should be noted that there are, at present, no *a priori* reasons to believe that the mechanisms at play during cross-modal plasticity (i.e. the partial takeover of lost function by neighboring systems) differ from those involved in intra-modal plasticity (Bavelier and Neville, 2002). From the perspective of archaeology and material culture studies it makes good sense to extend this point further exploring cultural change as a form of extra-neural or extra-modal plasticity. A good way to illustrate further these points is by drawing on

the recently proposed hypothesis of *cultural reconversion* or ‘*neuronal recycling*’ (Dehaene, 2005, p. 147). This hypothesis essentially refers to the capacity of human cerebral architecture to transform what was initially a useful function in our evolutionary past into another function which is currently more useful within the present cultural context. To illustrate that consider two recently developed human cognitive capacities, i.e. arithmetic and reading. In both cases, humans learn to attribute meaning to conventional shapes (Arabic digits or the alphabet) using brain areas which turn out to have a significantly related function in primate evolution and present consistent and highly reproducible brain activations. In the case of arithmetic there seems to be a genuine precursor of number knowledge in primate evolution, i.e. the intraparietal cortex (Dehaene, 1997; Piazza and Izard, 2009). In the case of reading, however, the evolutionary precursor of the visual word form area, i.e. object recognition, is a function significantly different from the mapping of written language onto sound and meaning and thus initially unrelated to reading. The recycling hypothesis in short predicts that (Dehaene, 2005, p. 147): (i) our inherent brain circuits constrains the set of learnable cultural objects, (ii) that learning difficulty depends on the distance between the initial function and the new one, and finally (iii) that cultural learning may reduce the cortical space available for previous abilities.

Hypotheses like that of neural recycling offer valuable avenues of research in trying to elucidate some of the learning associated changes that can be observed on the neurological side of the cognitive equation. Nonetheless, from the perspective of the BAI, we advance here, one may also identify a serious drawback in the above model. This drawback primarily emanate from the misleading reductionist basis which, as we discussed at the beginning, following the general tendency in the mainstream cognitive sciences leaves material culture outside the cognitive equation proper and attempts to explain cognitive change solely on the neural level.

To illustrate that let us return again to the example of the development of arithmetic thinking we mentioned above and approach it this time from a ‘neuroarchaeological’ perspective. In neuroscience there seems to be broad agreement that human numerical abilities can be seen as rooted on two core systems with a long phylogenetic history that account for humans’ basic ‘number sense’. The first system refers to our ability to approximate large numerical magnitudes, while the second system to our capacity to identify the exact numerosity (the number of objects in a set) of small numbers of individual objects (oneness, twoness and threeness) (Dehaene, 1997; Feigenson *et al.*, 2004). Although most people today take the notion of abstract number for granted, we should not forget the mental leap required to go from counting specific things (concrete counting) to the abstract concept of number as a representation of quantity. The making sense of an exact, large cardinal value,

presupposes cognitive processes that children take many years to learn and that people may perform in different ways in different cultures or even lack altogether (Ifrah, 1985; Pica *et al.*, 2004; Frank *et al.*, 2008). Although we share a common numerical basis with many other animals, none of them seem capable of making that mental leap even after years of training in a controlled environment (e.g. see Biro and Matsuzawa, 2001). The crucial question then, from a long-term perspective, is ‘what drives humans beyond the limits of the core system?’ (Feigenson *et al.*, 2004, p. 313)

One possibility, proposed by many researchers, is that it is language (the presence or absence of number words) that provided the necessary link that enabled humans to move beyond the threshold of approximation (Gelman and Gallistel, 2004; Gelman and Butterworth, 2005; Neider, 2005). But from a long-term archaeological perspective the above premise cannot easily account for the development of numerical thinking in those early cultural contexts where such verbal numerical competence and counting routine did not yet exist (cf. Lakoff and Núñez 2000; Gordon, 2004). The question I am trying to underline here does not concern the neural mechanisms and developmental processes by which we learn to associate, for instance, the word ten with the quantity 10, but rather about how you conceive the quantity of 10 when a number word or symbol to express it is not available in your ‘zone of proximal development’ (Vygotsky, 1978; Wertsch, 1998). Despite the evident association between language and exact arithmetic, language lacks in itself the necessary ‘representational stability’ (Hutchins, 2005) that would have made possible such a transition. Following that, I have used elsewhere the example of the Neolithic Near Eastern system of counting (Schmandt-Besserat, 1992, 1996) (Figure 1) to argue that it was the clay token system that drove the Sapiens mind beyond the limits of ‘approximation’ in the long-term development of ‘exact’ numerocity during that period and this specific cultural context (Malafouris, in press). The clay token system offered a novel BAI able to transform, ground and simplify the problem of number. More specifically, it can be argued that the process of engaging and grasping the number as a tangible physical clay token offers a cultural scaffold able to restructure the cognitive task thus forging

an *extended reorganization* in the neural connectivity of the critical intraparietal areas associated with approximate numerocity that would have been impossible to achieve by the naked biological brain. In other words, the tangible material reality of the clay token as an ‘epistemic’ artefact made possible that the parietal system previously evolved to support approximate numerosity gets re-organized, and thus partially ‘recycled’, to support the representation of exact number (cf. also Piazza and Izard, 2009). No doubt the representational properties of neural networks, like those that subserve numerical thinking, become realized inside the head, but in the case of BAIs the systemic properties of the cognitive structures from which they derive extend beyond skin.

To illustrate further these premises let us use also the example of navigation in a cultural setting. The study of the navigation-related changes observed in the hippocampi of London taxi drivers by Maguire *et al.* (2000) offers a good example. The comparison of the structural MRI scans obtained from the taxi drivers and the control subjects showed on the one hand, that the posterior hippocampi of taxi drivers were significantly larger, and, on the other, that hippocampal volume correlated with the amount of time spent as a taxi driver (positively in the posterior and negatively in the anterior hippocampus). Maguire’s interpretation was that this structural change was clearly due to taxi drivers’ extensive training and experience in navigating inside the city of London. We should point out that an alternate ‘selectional’ interpretation could interpret the above findings as meaning, that people with increased hippocampal grey matter volume are innately better navigators and thus may be more likely to become taxi drivers. However, in a follow up study of navigation expertise among non-taxi drivers no differences in grey matter volume were found (Maguire *et al.*, 2003) indicating that plastic change was actually effected due to experience and practice rather than innate factors. Moreover, another study comparing taxi drivers with bus drivers further supported these findings (Maguire *et al.*, 2006). But how all these can be interpreted in relation to our present considerations? One question, given that hippocampus activation was associated both in taxi drivers and in control subjects,



Fig. 1 Plain clay tokens, Mesopotamia, ca. 4000 BC. The cone, spheres and disk represented various grain measures; the tetrahedron stood for a unit of labor. (Courtesy: Denise Schmandt-Besserat.)

would be discerning the basis and precise causes of the changes recorded in taxi drivers (Maguire *et al.*, 2003, p. 214). Obviously taxi drivers are not the only successful navigators and thus navigation accuracy cannot be what be argued as the difference that made the difference in their case. The answer to that according to Maguire *et al.* is that although our hippocampi are probably more than able to cope with our typical navigational needs without recourse to structural change ‘there may be a threshold (either in terms of detail or duration of use) beyond which storage and elaboration of a large scale spatial representation induces hippocampal plasticity’ (Maguire *et al.*, 2003, p. 216). Thus while much remain to be understood about the long-term aspects of neural plasticity, it becomes increasingly clear that it is upon identifying these mediational thresholds and discerning the possible links between behavioural innovation, cultural practice and brain architecture is one of the key areas where cultural neuroscience should focusing upon.

Indeed, seen from the theoretical angle advanced in this article, simply to ask about how and why London cab drivers’ ‘gray matter’ enlarges in order to enable the storage of a detailed mental map of the city of London is not enough. The question is rather, on the one hand, how do we compare between the plastic effects of different navigational practices, and on the other hand, how do we account for the transformative effect that the various mediational technologies and artefacts have on these cultural practices and by extension on the human brain. To give a simple example, with the introduction of modern GPS devices London taxi drivers no longer need to expand their hippocampus in order to succeed in their complex navigation tasks. The cognitive objective remains the same, i.e. navigating from point A to B, but the process involved has changed. From the broader ‘system’s view’ (Norman, 1991) no potential increase in ‘gray matter’ is any longer necessary. The GPS not only has amplified the drivers’ biological memory but, like many other BAIs in human evolution, it has drastically reshaped or changed the nature of the cognitive operations involved in the navigation task and as a consequence the selective pressures placed on human hippocampus.

CONCLUSION: EXPLORING THE ‘CULTURE EFFECT’

It is common wisdom in anthropology and archaeology that the human mind is as much the product of biology and evolution as it is of culture. In sort, culture shapes our brains and extends our minds. There are, by now, numerous studies exploring different aspects of this ‘culture effect’: learning to read and write (e.g. Castro-Caldas *et al.*, 1998; Paulesu *et al.*, 2000); learning arithmetic (e.g. Tang *et al.*, 2006); meditating (e.g. Vestergaard-Poulsen *et al.*, 2009); playing the piano (e.g. Hyde *et al.*, 2009); driving a taxi (Maguire *et al.*, 2000), etc. Cultural neuroscience research tries to make this ‘culture effect’ more explicit and tangible at the level of the human brain. In this way,

it is hoped that long-standing anthropological and archaeological debates, such as those over the nature of symbolism, the mechanisms of social memory or the effects of literacy in the human cognitive system can now be seen in a new light. Naturally, as a new approach to cultural variation and difference, cultural neuroscience raises a number of important questions and methodological challenges: for instance, what is the meaning of the term ‘cultural difference’ in cultural neuroscience? What does the measurement of blood-oxygen-level dependent (BOLD) signals using fMRI can actually tell us about these differences? What is the most productive way to assess cultural influences on the neural substrates of our perceptual, emotional and embodied cognitive processes? Where does embodiment, sociality and material culture comes in? What is the neurological meaning of cultural mediation and what would constitute a meaningful analytic unit for cross-cultural comparisons in neuroscience?

There can be no doubt that transcultural neuroimaging opens a new window on the human mind and offers a whole new set of possibilities for exploring brain’s hidden functional architecture. But the phenomenological price for capturing the ‘ghost in the machine’ inside the scanner is heavy. The static ‘snapshot’ view of localized brain activity can easily mislead us to a sterile neurocentrism that has no place in the study of cultural cognition. I have argued in this article that to tackle successfully the challenges of cultural neuroscience a change of focus and a new conceptual vocabulary is needed. Explaining how cultural differences influence the human brain entails close examination of the way physical artefacts and embodied cultural practices are enacted, transformed and transmitted across the scales of time. In other words, the key question does not concern simply the hemodynamic couplings between blood-flow, metabolism and activity, but also the dynamic structural coupling of brains, bodies and the material world. So how can we proceed to visualize and explore that in concrete empirical terms? Admittedly, none of the usual radionuclide tracers would be of any help here. The question is not about the changes in cerebral blood flow, the question is about the ‘leaks’, to use Clark’s term (1997), of this flow into the external world. The challenge for us lies, in other words, in figuring out how our plastic brains and the associated patterns of *reorganization*, *redistribution* and *scaffolding* (Quartz and Sejnowski, 1997; Petersen *et al.*, 1998; Poldrack, 2000; Kelly and Garavan, 2005) can be understood within the wider networks of non-biological scaffolds and social practices that delineate the spatial and temporal boundaries of the human cognitive system as a cultural artefact. This demands a cross-disciplinary synergy aiming at discerning the possible ways that observed brain changes (functional or anatomical) can be associated with the various ‘complementary’ strategies and culturally situated tasks that humans recruit when ‘adapting the environment instead of Oneself’ (Kirsh, 1996). To visualize that, a different,

‘epistemic’, kind of tracer is needed. Adopting a long-term and rather object-oriented archaeological perspective, I proposed the notion of the BAI as a useful analytic unit for integrating the different temporalities of cultural, evolutionary and neuronal time and for bridging the gap between neural and cultural plasticity.

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Conflict of Interest

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