**Not just a virtue: the evolution of self-control**

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**Not just a virtue: the evolution of self-control**

We rely constantly on self-control in every aspect of our lives. Although it is not an ability unique to humans, our elevated levels of self-control may have played a key role in our evolution. Self-control is likely to have been key to many of the traits such as prosociality, that define modern humans. Despite this, attempts to study the evolution of self control through characteristics of the archaeological record have been few. Studies of related concepts such as inhibitory control have often been vague and do not reflect the whole scope of self-control. Defining self-control as arising from a combination of cognitive abilities including inhibition and the conscious regulation of emotions, this paper sets out a novel approach. We identify links between material culture, behaviours and the cognitive–emotional processes underlying them and produce testable predictions of what increases in these abilities might look like in the archaeological record. Using an example, we consider how late Acheulean handaxes (bifaces) demonstrate five characteristics that can be related to forms of self-control: deliberate practice, forward planning, time and energy investment, hierarchical processing, and distress tolerance. This provides some initial insights and lays the groundwork for future research in this area.

Keywords: self-control; inhibition; human evolution; self-domestication; cognitive evolution; Acheulean; bifaces; handaxes

# Introduction

We live with a constantly shifting set of drives and emotions and our ability to choose whether and how to act on these can have huge implications. Our self-control – that is, our ability to subdue immediate impulses in order to achieve long-term goals – is the cognitive capacity which takes the longest to develop and can be the most challenging. Yet this capacity also affects almost all areas of our lives, not only health and social success (Moffitt et al. 2011) but also emotional well-being and achievement (Tangney, Baumeister, and Boone 2004). Patience is not only a virtue, it’s also a considerable advantage.

Selection pressures on self-control may have been particularly important in human evolution (Hare 2017). Self-control plays a role in collaborative practices, such as hunting and food sharing, and reciprocal altruism (Spikins 2012; Stevens and Hauser 2004). All these abilities contribute to human hypersociality. Despite this, self-control has been relatively underexplored in evolutionary archaeology. It is a nebulous term that is often used without being defined. Previous discussions of cognitive evolution have touched on aspects of self-control (e.g. Wadley 2013; Wynn and Coolidge 2017), but an exploration of its behavioural, cognitive and neural architecture demonstrates the gaps left by this research. This paper will address self-control directly and suggest ways that archaeological evidence may help to answer questions about its evolution.

# The evolutionary significance of self-control

Self-control can be a selective advantage across many different realms of survival and reproductive success. Most obviously self control can have a direct effect on the exploitation of resources. Common marmosets (*Callithrix jacchus*) for example, who exploit gum which exudes slowly from trees, demonstrate higher levels of self-control than cotton-top tamarins (*Saguinus oedipus*) who largely exploit insects (Stevens, Hallinan, and Hauser 2005). Marmosets who were unable to withstand the frustrations of waiting would, it seems, have been at a selective disadvantage in the past. Likewise hunting prey often demands a certain level of self-control over immediate response. However, the advantages of elevated levels of self-control are particularly seen in the realm of social collaboration. Without high levels of self-control, wolves for example would be unable to share food effectively. Being able to overcome immediate drives to compete for access to meat in order that food is shared equally make collaborative hunting and provisioning of the young sustainable (Marshall-Pescini, Virányi, and Range 2015). Beyond direct effects on subsistence practices self-control is also key to enabling collaborative parenting (Koski et al. 2017). Moreover individuals in highly social groups need elevated inhibitory control to negotiate their complex social relationships and avoid conflict (Amici, Aureli, and Call 2008; Beran 2015).

Self-control is likely to have been under selective pressure in early humans for a number of different reasons. Both high levels of predation (Hart and Sussman 2011) and moving into an ecological niche which involved greater degrees of meat-eating (Ferraro et al. 2013; Domínguez-Rodrigo and Pickering 2017) will have placed selective pressures on more in depth collaboration entailing increasing self control in early humans. Whilst self-control itself is not an indicator of pro-sociality, the increasing significance of social selection pressures will have added additional selective advantages to individuals who are better able to inhibit their immediate drives and responses (Hare 2017). Furthermore, the significance of language to human communication and collaboration may have placed additional pressures on the evolution of capacities for self control (Shilton et al 2020), particularly in the context of cumulative culture (Laland 2017).

# A material record of self-control?

The relationship between self-control and material culture is far from straightforward, and presents an even greater challenge in an evolutionary context. Nonetheless, the archaeological record offers a novel route to explore the evolution of self-control by pinpointing evidence for behavioural or technological innovations that would have required increased capacities.

Here we will use the theoretical scaffolding of evolutionary cognitive archaeology (ECA) to explore insights that can be gleaned from a specific archaeological assemblage and lay the groundwork for a new method for studying the evolution of self-control through material culture. This will allow further research to explore key questions such as the relationship between phylogeny and ecology (e.g. the role of meat eating and collaborative parenting, as discussed above) and the relationship between conscious and unconscious inhibition.



Figure 1: Forming bridging arguments between arguments between archaeological evidence and cognitive abilities, via behavioural interpretations (after Coolidge et al. 2016).



Figure 2: Archaeological evidence results from an interaction between behavioural, mental and neural systems (after Barnard 2010). In the behavioural architecture of tool-making (A), self-control is a component (C) of the individual knapper’s abilities (B). Self-control is the result of multiple cognitive capabilities interacting within the overall mental architecture.

Evolutionary cognitive archaeology involves constructing strong “bridging theories” between archaeological evidence, behavioural interpretations and cognitive and neural architecture (see figs. 1 and 2) (Haidle 2014; Garofoli and Haidle 2014; Barnard 2010). As self-control is a very loose term, we first need to have a better understanding of the cognitive and neural architecture of self-control. The next section explores the range of psychological concepts that make up this architecture. We then suggest ways that a chaine operatoire approach can be used to find evidence of self-control in material culture, using as an example Acheulean handaxe manufacture at Boxgrove, which has already been linked to aspects of self-control (Stout et al. 2011; Wynn and Coolidge 2010b).

# What is controlled and how? Understanding self-control

## Executive functions

The term self-control is often used without being precisely defined (e.g. Hare 2017; Moffitt et al 2011). Although an intuitively simple idea, psychological research in the area can be confusing as it uses many different terms to refer to overlapping concepts (Diamond 2013). Broadly, self-control refers to the ability to resist temptations and exercise control over one’s own emotions and behaviour (Diamond 2013). A more restrictive definition has also emerged in psychological literature, referring to specific tasks involving a choice between rewards of different values (Beran 2015). For the purposes of this paper, we view self-control as a behavioural phenomenon that emerges from a core set of cognitive abilities, including both inhibition and emotion regulation, and their interaction with other abilities within the broader cognitive architecture.This is not intended as a critique of the use of more restrictive definitions. It is merely to aid discussion, as this appears to be the way the term has previously been used in the context of cognitive evolution (e.g. Hare 2017; MacLean et al. 2014).

Establishing the relationships between the different abilities we refer to and their behavioural measures can be difficult, especially as there is often a circular logic to the defining of concepts based on tests designed to measure them (Stout 2010; Addessi et al 2013; Glassman et al 2016). Functional brain imaging provides one way to substantiate these relationships, although it is easy to be reductionist in mapping functions directly onto one brain region or network (Stout 2010; Stout et al. 2018). For the purposes of this paper, therefore, we will treat these different terms as part of the same core of abilities except where they have been separated based on multiple lines of evidence. However, future research into the evolution of self-control will need to take into account any further differentiation of neural networks.

An important concept that overlaps with self-control is inhibition or inhibitory control. This can refer to the ability to inhibit actions and desires, such as learned or automatic responses to stimuli, or to focus attention on one thing and ignore distractions (Diamond 2013). It is often included under the umbrella of the executive functions. Executive functions, also known as cognitive control, are the conscious processes that are thought to underlie “higher-level” thinking, when effortful reasoning is required rather than automatic responses (Beaman 2010, S31; Diamond 2013). Together, they work to flexibly process information and organise goal-oriented behaviour (Diamond 2013; Stout 2010; Wynn and Coolidge 2010a). Various lines of evidence have associated these with areas of the prefrontal cortex (PFC) (see fig. 3) which – through their connections with widely distributed networks across the rest of the brain – control attention, action and emotions (Miller and Cohen 2001; Stout 2010).

Figure 3: the Prefrontal Cortex (PFC) highlighted in red. BodyParts3D/Wikimedia Commons (2010a, b) [© The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan.](http://lifesciencedb.jp/bp3d/info/userGuide/faq/credit.html)

Other important executive functions are working memory and cognitive flexibility. Though inhibition is most directly relevant to self-control, it cannot be treated as separate from the other executive functions and later sections of this paper will build on existing archaeological theories which cover all of these. For instance, one such theory (e.g. Wynn and Coolidge 2010b) has followed a model which characterises working memory as a broader concept within which the other executive functions exist as one component known as the central executive. However, we will use the more limited definition of working memory followed by Diamond (2013). Working memory involves holding and manipulating information in active attention (Diamond 2013, 7; Wynn and Coolidge 2010b, 86). It is closely related to inhibtion and the two usually function together in the achievement of complex goals: while information relating to the goal is held in working memory, irrelevant information must be inhibited. A simple, everyday example of this is reading, which involves processing information contained in the text while avoiding getting distracted by extraneous thoughts (Diamond 2013, 144). They also seem to activate the same brain regions (Diamond 2013). Cognitive flexibility, which refers to the ability to change perspective and switch between different tasks, rests on both inhibition and working memory; information and actions relevant to the old task must be inhibited while information relating to the new one is held in working memory (Diamond 2013, 148).

## Emotion regulation

Self-control is often discussed in a fairly “cold” way, focussing on planning or the control of actions or attention. This is especially true of previous approaches to working memory or inhibition in evolutionary archaeology (Beaman 2010, S34). However, being able to control our emotions is just as important. Unfortunately, this sort of “hot” inhibition has largely been studied as a separate field, using the terms emotion regulation or self-regulation (Diamond 2013).

There have been a number of attempts to divide the executive functions into distinct parts based on their different neural networks (Bari and Robbins 2013; Stout 2010). This is very useful for approaching executive functions from an evolutionary perspective, as it can be asked whether these distinct networks evolved separately. A common distinction is between “hot” and “cold” inhibition, the former most associated with the medial prefrontal cortex (mPFC) and the latter with the lateral areas (lPFC). However, although these different areas clearly play different roles in inhibitory networks, the relationship is not so clear.

While some evidence has suggested the mPFC – in particular the ventromedial PFC (vmPFC) and orbito-frontal cortex (OFC) – is more important to emotion regulation (Bari and Robbins 2013; Stout 2010), this is only true in certain forms of regulation which do not involve a conscious effort. A conscious self-control of emotions – i.e. deliberately seeking to change how you feel or control how you express your feelings – uses the same lPFC inhibitory control networks as the more “cold” control of action and attention (Etkin et al. 2015). Therefore, the distinction seems instead to be between an unconscious processing of emotions - such as fear extinction, when an initial fear response to something is dampened by repeated exposure (Etkin et al. 2015, 695) - and more effortful, deliberate self-control.

Emotion regulation is complex to understand from a behavioural perspective. Conscious and unconscious regulation are difficult to separate as the two usually work together (Etkin et al. 2015). In addition, other forms of emotion regulation are confounding factors. An individual’s development and the society they live in has a strong influence on what emotions they feel and express (Markus and Kitayama 1989; Gross and Barrett 2011; Mesquita et al 2014). However, emotions are part of everything we do so it would be impossible, especially given the neuroanatomical overlap, to look at inhibition without considering how emotions are controlled. Therefore, we will make efforts to do so when discussing the archaeological evidence.

## Addressing the sequence of development

Comparisons between our two closest extant primate relatives suggest that the evolutionary histories of conscious and unconscious emotion regulation might be very different even though they typically may work together. Chimpanzees perform better on tests of inhibition (Herrmann et al. 2007; Rosati et al. 2007; Stout 2010), while bonobos appear more socially tolerant and are better at cooperative tasks (Stevens and Hauser 2004; Stout 2010; Steklis and Lane 2012). This probably relates to differences in their brain anatomy: chimpanzees have a larger lPFC and bonobos a larger vmPFC (Stout 2010). A host of other differences compared to chimpanzees, including more grey matter in the pathway linking the amygdala to the ventral anterior cingulate cortex (vACC) and changes in neuroendocrine balance (lower levels of androgens and higher levels of seratonin), make unconscious regulation in bonobos stronger (Hare et al. 2012; Rilling et al. 2012, Hare and Yamamoto 2017). This dampens their “fight-or-flight” or stress reactivity response to their conspecifics and so allows them to cooperate more effectively.

Conscious inhibition and unconscious emotion regulation can evidently be subject to different selection pressures and adaptive responses. A key characteristic of hominin adaptation may however be chimpanzee-like inhibitory skills combined with bonobo-like social tolerance. Quite how this adaptation may have occurred remains a subject of debate. Hare (2017) argues that, in humans, an increase in conscious inhibition – as a side-effect of allometric brain size increase – came first, followed by our own “self-domestication”. In other words, being able to consciously control our emotions created a general bias towards being less emotionally reactive. Spikins (in press) adds to this discussion by arguing for different pathways in late human evolution towards or away from various elements of domestication.

Studying the archaeological evidence for inhibition as well as social tolerance can therefore hopefully cast light on both the significance of conscious and unconscious self-control and the sequence of development of different elements.

# Cognitive theories: previous research

The field of evolutionary cognitive archaeology (ECA) has yielded important insights into diverse areas of cognitive evolution (see for example Overmann and Coolidge 2019) Within this field there has been some attention to inhibition as one element of the emergence of modern human cognitive complexity. This research generally makes use of insights from experimental studies that demonstrate the complexity of the processes evidenced by archaeological materials. Although the modern-day humans carrying out these experiments may not be perfect analogies for earlier hominins, this is the best available approach and already allows for confident discussion of a number of aspects of cognitive evolution.
 Most of this research discusses inhibition as a component of an overall cognitive architecture. Such “macro-theories” of cognitive evolution are important, as they allow for more valid interpretations of archaeological evidence (Garofoli and Haidle 2014; Barnard et al. 2017). We view self-control as a behaviour that emerges, not from specific abilities alone, but from the interactions of the abilities discussed above (inhibition and emotion regulation) with other components of the cognitive architecture. As such, we will build on these broader discussions, with a more precise interpretation of material evidence and a focus on emotional aspects of self-control.

As already mentioned, inhibition is a component of theories which treat working memory as a broad concept central to, if not synonymous with, intelligence (Martín-Loeches 2010; Wynn et al. 2017). For instance, Coolidge and Wynn (2005) argue that a relatively recent mutation led to the evolution of what they call enhanced working memory (EWM) in Homo sapiens. EWM involves an enhanced capacity for inhibition, as can be seen in later Palaeolithic examples of long-term planning. They believe the first evidence of this is bone and antler points where there has been clear investment in design to maintain long-term effectiveness, putting the date of the emergence of EWM no earlier than 90,000 BP (Coolidge and Wynn 2005, 17).

Similarly, Wadley (2013) discusses innovations that she believes require “complex” cognition, in which she includes abstract reasoning and multi-tasking alongside enhanced executive functions. These innovations involve planning and decision-making during activities that combine multiple different tasks, each of which can depend on a careful balance of factors and take hours or more to complete. They include the heat treatment of lithics for pressure flaking (first evidenced c.75kya), of ochre to create pigments (at least c.135kya and possibly up to 250kya), and in the creation of glues (c.45kya), and the use of compound adhesives (c.70kya) and paints (c.100kya). This presents a potentially slightly earlier date for the emergence of modern human cognition.

Other studies offer a diachronic approach, showing the development of complex cognition over time. Stone tools have been a particular focus of this research. The role of inhibition in tool manufacture clearly increases as more complex manufacture processes require more expertise. Important steps in the evolution of expertise are the development of prepared-core technologies around 500kya, followed by composite tools from around 200kya, which place more demand on working memory due to the extra steps involved (Wynn et al. 2017). Inhibitory skills such as the ability to avoid getting distracted and to be able to move between tasks (i.e. cognitive flexibility) are key parts of this evolving expertise. Wynn et al. (2017), for instance, point to the task-switching inherent in composite tools as an additional demand on inhibition.

Functional imaging studies of tool manufacture also demonstrate the role of inhibition in stone tools. In such studies, the manufacture of highly refined Acheulean handaxes activates the right inferior frontal gyrus (rIFG), where earlier Oldowan flake-based tool manufacture does not (Stout et al. 2011). The rIFG, which includes the ventrolateral PFC (vlPFC), is associated with computational functions including inhibition and task-switching. The reason these areas are involved is likely the hierarchically organised nature of late Acheulean handaxe manufacture (Stout et al. 2011; Stout et al. 2018). Processes where an ultimate goal is kept in mind while multiple sub-goals are worked on (Beaman 2010; Vaesen 2012), require an individual to choose between actions and inhibit those that are inappropriate for the ultimate goal (Stout 2010). To achieve the thinness of late Acheulean handaxes, striking platforms must be carefully prepared, resulting in a more complex sequence of actions than required for earlier tools (Stout et al. 2011; Stout et al. 2014; Stout et al. 2018).

Previous research into cognitive evolution has yielded insights, especially functional imaging studies. However, the evolution of self-control is still poorly understood. Certain inferences seem reasonable. Self-control was likely increasing among early hominins as brain size increased allometrically for example (Hare 2017). Moreover both social and technological complexity are likely to have placed selection pressures on greater levels of self-control through time. However, important questions remain, which also have significance for understanding other areas of cognition and social relationships. The final section of this paper suggests how self-control might be approached in a more nuanced way, which takes into account the *chaîne opératoire* (see Soressi and Geneste 2011) of emotional self-control involved in the creation of material evidence, and develops testable predictions.

# Making testable predictions: an archaeological approach to self-control

Interpreting cognitive abilities and how these change through time from archaeological evidence is always a challenge. ECA is inevitably subject to the constraints imposed by limited or biased evidence, as well as those imposed by our understanding of cognitive processes and how they affect behaviour and in turn the material record. Through a careful theoretical scaffolding, however, it is possible to access the “minimum capacity necessary” to produce evidence as we find it (Wynn 2002).

In order to create bridging arguments between archaeological evidence and cognitive abilities, we need to first establish the behavioural architecture in between (Haidle 2014). Forming a *chaîne opératoire* of an artefact type allows us to then analyse the sequence of cognitive-emotional processes involved in the production of material artefacts. For example, the processes involved in preparing cooked meat for consumption include collaborative hunting, gathering the raw materials to create a fire, cooking meat and sharing food. These include not only forward planning and an investment of time and energy in a future reward, both of which rely on the ability to inhibit current desires (Coolidge and Wynn 2005), but also inhibitory control over fear and other instinctive responses when collaboratively hunting and over hunger when sharing food (Wood and Gilby 2017; Boyette 2019). It is also a hierarchical process (see above), where multiple steps contribute to the ultimate goal of cooked meat.

Being specific about the behaviours and cognitive abilities involved allows us to draw analogies with not just the abilities of modern-day humans, but also of other primates. We can use this to make predictions about evolutionary trajectories. After exploring the *chaîne opératoire* of stone tools from one site, we will discuss some of the analogies that can be drawn.

# Boxgrove: evidence of an increase in self-control?

As an example of how such an analysis might work, we will briefly discuss elements of self-control in examples of highly elaborate and standardised handaxes from the late Acheulean site of Boxgrove, UK. Previous analysis of this assemblage has already explored evidence for aspects of complex cognition and executive functions, some of which was discussed earlier. However, we use the cognitive and neural architecture outlined above to highlight further lines of evidence and outstanding questions.

Bifacial handaxes characterise archaeological sites in Europe and Africa for a period from 1.8mya until 125kya (de la Torre 2016). Though often seen as an exceptional period of stasis, numerous studies have shown a trend towards handaxes appearing in assemblages generally dating later than c.900kya that are smaller, thinner, more standardised and more symmetrical (see Hodgson 2015 for a review; Iovita et al. 2017; Shipton 2018). Others have questioned the existence of this trend, arguing that the evidence from limited samples may disguise an overall more variable picture (McNabb and Cole 2015; Cole 2015; though see Underhill 2007 for a critique of methodology). However, whether they represent a technological development within the Acheulean industry or simply part of its wider variability, the existence of elaborate and carefully designed handaxes has inspired lengthy debates about the motivations (if any) behind them and hence the cognition and emotions of early Homo (Kohn and Mithen 1999; Gowlett, 2006, 2011; Hayden and Villeneuve, 2009; Hodgson, 2015; Malafouris, 2010; Machin et al, 2005; McNabb et al., 2004; Spikins, 2012).

Leaving aside questions of motivation, various aspects of their production can be broken down and related to self-control. Here we focus on the particularly refined examples (see fig. 4) found in the assemblage at Boxgrove, dating to Marine Isotope Stage 13 (524,000-478,000 BP) (Roberts and Parfitt 1999). In broad terms, there are many moments in the process of making these handaxes that might involve forms of inhibition in ways that are variable and unpredictable. For example, not getting distracted by interruptions would be an important skill that is difficult to measure archaeologically. However, there are certain aspects of the archaeological record that do provide evidence or characteristics against which specific predictions can be tested. These are deliberate practice, forward planning, time and energy investment, hierarchical processing and distress tolerance.



Figure 4: Two handaxes from area Q1/B at Boxgrove (Pope et al 2006, 52) Reproduced with the kind permission of the UCL Institute of Archaeology.

## Deliberate practice

The production of any highly symmetrical or elaborate handaxe is a result not only of momentary capacities but also of knowledge accumulated over a lifetime. Replications of handaxes from Boxgrove showed that these had most in common in handaxes made by expert knappers with decades of experience, while it took novice knappers sixteen hours of practice to even produce recognizable handaxes at all (Stout et al. 2014). This represents a considerable investment of time and energy in something which does not provide immediate rewards (see below).

Additionally, experimental replications suggest that this skill would have been acquired through a process of social learning and deliberate practice (Edwards 2001; Stout et al. 2011; Stout 2010). The form of social learning involved demonstrates a range of socio-cognitive and motor skills as well as attentional control (Stout et al. 2011). It would also rely on a certain amount of social tolerance (Stout 2010; Vaesen 2012), something which emerges from a mixture of conscious and unconscious emotion regulation.  Deliberate practice is an effortful activity directed at honing skills. It is a cognitively complex process that relies on all the executive functions (Rossano 2003). It requires that an individual maintain focus on their goal – e.g. creating a better handaxe – while constantly monitoring and altering their behaviour in service of that goal. As part of this, automatic responses must be controlled and replaced with new ones (Rossano 2003, 11).

 We do not know what form the process of skill acquisition took. It is worth noting that, unlike most modern knappers, flint knapping would have been present in the lives of the hominins at Boxgrove from childhood. In addition, the presence of a formal system of apprenticeship (Stout 2005) would require very particularl socio-cognitive skills. Regardless of this uncertainty, it would likely have been a conscious process that involved certain forms of self-control.

## Inhibitory control at the planning stage

Stone tool manufacture involves not just complex planning during the process of manufacture (see *hierarchical processing*) but also plannnig over the longer term. Forward planning and mental time-travel have long been considered important to human evolution (Corballis 2013; Suddendorf et al. 2009; Suddendorf and Coraballis 2007). It has been suggested, for instance, that Middle and Upper Palaeolithic technologies rely on planning that emerges from working memory abilities and developments in autobiographical memory (Coolidge and Wynn 2005; Coolidge et al. 2016). Self-control is also a key part of forward planning as immediate drives must be inhibited in the service of more long-term goals. For instance, *delay* and *effort discounting* are measures of self-control that recruit areas of the brain associated with conscious inhibition (Beran 2015; Diamon 2013; Massar et al. 2015; Ochsner and Gross 2014). Both involve a choice between a smaller, immediate reward and larger but more costly reward.

Acheulean technologies also demonstrate clear planning in the selective procurement of raw materials and transport of raw materials and both unfinished and finished tools(see e.g. Goren-Inbar 2011; Herzlinger et al. 2017; Shipton et al. 2009). At Boxgrove, flint nodules are tested at the nearby cliffs before being carried away to be worked elsewhere, while tools at various stages of development transported around the landscape, seemingly according to specific rules and immediate needs (Pope and Roberts 2005; Roberts and Parfitt 1999). However, these transport distances are small, at most 250m (Pope and Roberts 2005). Elsewhere, raw materials at Acheulean sites have been transferred several kilometers at most (Shipton et al. 2009), although chert potentially transported from 40km away has been found of Gesher Benot Ya’aqov (Delage 2007). The time depth of the planning may therefore not be large. However, all the instances of activities carried out in anticipation of future need at Boxgrove represent a choice of a relatively demanding task without an immediate reward over more short-term rewards.

## Time and energy investment

In addition to the time invested in practice and raw material procurement, experimental replications indicate how long handaxes took to make. Unfortunately, this data is not available for Boxgrove. However, for replications of handaxes from Kalambo Falls, Edwards (2001, 609) gives manufacture times from thirty minutes to several hours, depending on raw materials. This significant range makes it difficult to make conclusions about how long the Boxgrove handaxes, made with flint, would have taken. However, a manufacture time of at least half an hour represents a short but not insubstantial investment. The ability to stay focussed for this length of time and inhibit distracting urges clearly demonstrates some self-control. In addition, that handaxe manufacture is a cognitively effortful task shows some level of effort discounting (see Massar et al. 2015). It is worth bearing in mind, however, the reward value potentially attributed to handaxe manufacture itself: it would seem churlish to imagine that hominin knappers did not to some extent enjoy knapping. However, this does not invalidate the point that making a handaxe represents an effortful and time-consuming choice.

## Hierarchical processing

Perhaps the most obvious way of measuring self-control in tool manufacture is hierarchical processing. As already described, the link between hierarchical processing in late Acheulean handaxe manufacture and vlPFC function is well-established (Stout et al. 2011; Stout et al. 2018). Refitting analysis (Wynn and Coolidge 2010b; Stout et al. 2014) and experimental replications (Stout et al. 2008) can be used to detect this archaeologically. For example, refitting of a knapping episode from area 4b at Boxgrove shows a knapper working on a local goal, in this case fixing a break surface, while also holding multiple long-term goals - creating a handaxe as well as obtaining usable flakes for later use - in mind (Wynn and Coolidge 2010b). Faceting scars on handaxe debitage at Boxgrove directly evidence the extra steps involved in the careful preparation of striking platforms (Stout et al. 2014). This is required in order to remove the large thinning flakes that produce a handaxe that is thinner without losing breadth. Thus, handaxe manfacture at Boxgrove was a hierarchically organised process that demonstrates inhibitroy abilities on the part of the hominin knappers in a way that earlier tools do not.

## Distress tolerance

Anyone who has tried flint knapping will know how difficult it can be. As demonstrated by the figures for practice time quoted above, making an elaborate and highly symmetrical handaxe is not easy. This is often true even for experts. For instance, Edwards (2001) emphasises the intense concentration involved in the last stages of working. Partly, this concentration is due to the high error rate at this level of refinement, even for skilled knappers. This includes step- and stack-fractures, which may be preserved on flakes removed to correct them, and end-shock, which causes the full breakage of the core (Edwards 2001, 609). Step-fractures are common and can be removed from the final product, something that takes up a great deal of time in the later stages of production (ibid.: 608). End-shock was a common problem at Boxgrove; the refitted core mentioned earlier from area 4b shows a knapper recovering a broken core (Wynn and Coolidge 2010b).

It is, of course, impossible to interpret the precise emotions of past hominins (Tarlow 2000; 2012). However, the capacity to persevere in the face of frustration is a key part of how self-control contributes to modern life. Though less well-studied than other aspects of emotion regulation, studies have, for instance, shown that *distress tolerance* is something that children with ADHD (a disorder which particularly affects executive functions (Barkley 1997)) struggle with compared with controls (Seymour et al. 2019). Importantly, this is an issue of regulation, not reactivity; the children with ADHD reported no higher levels of frustration, yet were more likely to give up on the task.

It is clear from experimental replications and refitting that overcoming failure was part of making handaxes. Measuring the rates of errors in archaeological assemblages might be one way of studying distress tolerance. This is tricky to interpret, however. Error rates are usually seen as a measure of skill (e.g. Grimm 2000; Stapert 2007), but even experienced knappers make mistakes or suffer from problems (Hovers 2009). Large error rates for a given site may represent unskilled knapping, but it may be simply that a lot of tools were being made and only the unusable remains were left behind. Averaging of error rates across contemporary sites may be one way to resolve these interpretative problems.

These five characteristics - deliberate practice, forward planning, time and energy investment, hierarchical processing, and distress tolerance - present specific measures of self-control that can be related to established psychological concepts. Their presence and extent can be identified through archaeological signatures, such as platform preparation, or experimental replications. All recruit forms of conscious inhibition or emotion regulation, but these operate within the wider context of tool manufacture.

This context includes the wider cognitive architecture that supports tool manufacture. For instance, forward planning involves response inhibition and delay discounting alongside mental time-travel. The context also includes a range of environmental, social and individual factors (see Haidle 2014). This context is particularly important when thinking about emotion regulation. For instance, each individual will differ in the extent to which they are stimulated by tool manufacture in itself, and this might be shaped by developmental and social factors. Effort discounting and distress tolerance therefore play a role in tool manufacture, but the extent of that role may differ greatly among individuals. However, there is still a minimum requirement for both that can be used to study the evolution of emotion regulation.

# Comparative evidence

Using these characteristics, we can trace evolutionary changes through diachronic comparisons of different technologies. Their specificity also allows us to make analogies with comparative behavioural evidence. Evidence from other primates suggests what the minimum abilities of our last common ancestor (LCA) might have been. Tests show that other apes struggle to inhibit automatic responses compared to even children as young as four (Boysen and Berntson 1995; Herrmann et al. 2007, S43). This suggests they would certainly have difficulties with deliberate practice and hierarchical processing. Studies have shown evidence for forward planning in chimpanzees (Bourjade et al. 2014; Osvath and Osvath 2008), and chimpanzee tool-making certainly involves some level of this (Roberts 2002). Studies of delay discounting show that chimpanzees are even better than humans at waiting for food rewards, although this is probably due to different values being placed on food vs monetary rewards (Rosati et al. 2007).

None of these lines of evidence, however impressive, show abilities equal to the self-control evidenced at Boxgrove. The effort discounting and distress tolerance abilities of other primates have not been explicitly studied. However, given its relative simplicity, chimpanzee tool-making behaviour would certainly seem to be easier and less effortful han that of Acheulean handaxes (Haidle 2014). Therefore, we can already see that, by c.500kya, the minimum capacity of self-control visible in the archaeological record was greater than that evidenced by other apes.

In addition, this specificity allows us to explore questions about the evolution of different abilities. Key questions concern the relationship between self-control and sociality. Self-control is an important part of collaboration and may have selected for by increased sociality in human evolution. However, there is also some dissociation between self-control and collaborative skills when comparing across primates. Understanding these different abilities allows us to test hypotheses about the relationship between phylogeny and ecology. For instance, their dependence on collaborative parenting and food sharing has led to elevated capacities to share in marmosets for example (Burkart and Finkenwirth 2015). Meanwhile, self-control abilities are predicted by social complexity (Amici et al. 2008) and body size (MacLean et al. 2008). Exploring inhibition and emotion regulation alongside other abilities such as collaboration and social tolerance will hopefully help untangle these relationships.

Highly symmetrical and elaborately produced handaxes are rare if even present before 600ka. This is coincident with a point in hominin evolution where relative brain sizes first appear to grow larger than would be predicted by body size (Ruff et al. 1997). This period that sees the emergence of large-brained Homo erectus, followed by Neanderthals and Anatomically Modern Humans, is also a period that sees evidence for emergent sociality (Carbonell and Mosquera 2006; Gamble et al. 2011, 123-125; Spikins et al. 2010). The coincidence of these three lines of evidence – increased levels of self-control in handaxe manufacture, relative brain size increases, and social collaboration – demonstrates the emergence of the broad cognitive complexity that defines modern humans. The earlier appearance of refined and symmetrical handaxes as early as 900ka (Iovita et a. 2017), along with early evidence for other activities requiring self-control such as the controlled use of fire (Sandgathe and Berna 2017), lends credence to the hypothesis that an early increase in self-control may have led to the social selection of further increases in self-control, socio-cognitive abilities and encephalization (Hare 2017). This and other hypotheses can be pursued further by future research.

Table 1: Aspects of late Acheulean handaxe manufacture and how they can be related to forms of self-control

|  |  |
| --- | --- |
| **Aspects of handaxe manufacture** | **Forms of self-control implicated** |
| Deliberate practice – as evidenced by experimental replications | All executive functions including inhibition of inappropriate actions |
| Forward planning – e.g. raw material transfers | Delay discounting and executive functions |
| Time and energy investment – in raw material sourcing, skill acquisition and manufacture | Delay and effort discounting |
| Hierarchical processing – e.g. platform preparation | All executive functions |
| Distress tolerance – perseverance despite difficulty and frustration | Emotion regulation |

## Conclusion

This paper has discussed the concept of self-control and how archaeological evidence can contribute to an understanding of its evolution. Though self-control is a significant part of human socio-cognitive evolution, there has been little discussion of how it evolved. It is often poorly defined and, while evolutionary cognitive archaeology has addressed related concepts, this has often been vague and there has been no exploration of the wider, emotional aspects of self-control.

Studying such a complex cognitive ability using archaeology requires establishing strong links between the socio-cognitive capacities, archaeology and behavioural measures and archaeological signatures. Using cognitive and neurological evidence, we define self-control as a behavioural phenomenon that results from a combination of cognitive capacities, most importantly inhibitory control and emotion regulation. These are not two distinct abilities but overlapping psychological concepts based on overlapping neural networks that involve the same areas of the prefrontal cortex.

Five archaeological measures of self-control are put forward, based on Acheulean handaxe manufacture and generalisable to other stone tool technologies (see table 1). These are deliberate practice, forward planning, time and energy investment, hierarchical processing and distress tolerance. These are analogous to various behavioural measures of self-control and recruit a combination of inhibitory control and emotion regulation as part of a wider cognitive architecture. Deliberate practice and hierarchical processing have already been discussed extensively and represent the more “computational” aspects of response inhibition, while evidence for distress tolerance and delay and effort discounting reflect the broader scope of the term self-control and are related more to emotion regulation. Having established these measures, the next step will be to further explore their cognitive and neural architectures to make sure that we have valid bridging arguments.Some outstanding questions remain. For instance, it would be useful to interrogate the “self-rewarding” (Beaman 2010, S35) nature of flint knapping; that is the question of the enjoyment that hominin knappers might have taken from knapping and how this factored into decision-making alongside self-control. Following this, we can begin making and testing predictions based on comparative evidence and exploring how they might have evolved in relationship to other cognitive abilities and to ecological factors.

The example discussed here of Acheulean handaxe manufacture at Boxgrove suggests that an increase in self-control must have occurred by c.600ka at the latest. Apart from further demonstrating the importance of the Middle Pleistocene, this has significant implications for theories of cognitive evolution. It potentially lends credence to the idea that an increase in self-control at this time preceded selection for socio-cognitive abilities and encephalization. This paper, therefore, offers a tantalising glimpse of the insights future research into self-control might offer.

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