The Cognitive Implications of Controlled Fire Use by Early Humans

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This article proposes a framework for investigating the cognitive implications of controlled fire use by Middle Pleistocene humans. By identifying the simplest strategies they could have used to control fire, given the constraints individuals had to overcome, we can establish a behavioural basis for making inferences about cognition. Accessing, maintaining and benefiting from fire involved a range of behaviours that imply future-directed planning, response inhibition and group-level cooperation. I argue that we can infer human cognitive abilities such as an extended working memory, episodic memories, collective intentionality and intersubjective communication from these fire-related behaviours.

Although fire use has implications for understanding the cognitive capacities of early humans (Burton 2009; Clark & Harris 1985; Gowlett 2006; 2010; James 1989; Karkanas *et al.* 2007; Peris *et al.* 2012; Wrangham & Carmody 2010), these implications have not been investigated in detail. This article provides a framework for investigating the cognitive demands of controlling fire and argues that we can infer important features of human cognition from fire-related behaviours. Archaeological and biological evidence suggest regular use of fire emerges between 400–800 thousand years ago (kya). Controlling fire would have entailed solving problems related to accessing, maintaining and benefiting from fire. I propose that the simplest sufficient strategies early humans could have used would have involved planning ahead, inhibiting prepotent responses and future-directed group-level cooperation. These criteria indicate episodic memory, extended working memory, collective intentionality and protolanguage, from which we can infer increased degrees of cognitive control, social awareness and communicative abilities relative to non-human apes. The term 'extended working memory' is intended to complement the concept of 'enhanced working memory' (Coolidge & Wynn 2009, 255). The working memory associated with fire use may have been extended relative to other apes, but not enhanced to a modern human degree. It is important to recognize that these cognitive skills may be a matter of degree rather than kind (Shettleworth 2012). My claim is that fire use implies degrees of planning depth, self-control and cooperation that are features of human cognition today, but not generally evident in other animals.

I begin by outlining my approach to inferring cognition from palaeoanthropological evidence and discussing the evidence for early human fire use. I then model the behaviours required to control fire and discuss the constraints early humans had to overcome. From this I identify the least cognitively demanding strategies that would have sufficed to control fire. I then relate these strategies to the criteria for human cognitive abilities. In conclusion, I propose a model of early human cognition based on the cognitive demands of controlled fire use.

Controlling fire does not entail being able to make fire. Fire making is considered the final stage in the transition from no use of fire, through opportunistic use to controlled use of fire. The evolution of fire use is generally modelled this way (Burton 2009; Frazer 1930; Gowlett 2010; Rolland 2004). These stages probably formed 'a mosaic of continuous graduations' (Gowlett 2010, 352). Current evidence suggests the common ancestor of the Neanderthals and *Homo sapiens* probably needed fire to survive (Gowlett 2010; Wrangham 2009), and by implication regularly used fire.

Rossano (2009) has argued that fireside rituals involving focused attention and response inhibition may have been implicated in the evolution of human

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cognition. While this is an important consideration, I am concerned with the practical aspects of fire keeping. My focus is the behavioural and cognitive demands of regularly using fire prior to the invention of ignition technologies. While it is important to acknowledge the cognitive significance of other early human behaviours associated with tool use (Hallos 2005), cooperative foraging and social organization (Stiner *et al.* 2009; Vaesen 2011), the behavioural and cognitive implications of these have been extensively investigated and debated. Controlling fire added a layer of behavioural complexity to these other activities that would have increased the cognitive load on early humans. While it may turn out that fire use makes greater and more constant demands on planning, response inhibition and cooperation than these other activities, I am not suggesting it was the prime mover in our cognitive evolution. It would have been the combined complexity of cognitively demanding adaptations that drove the evolution of human cognition during the Pleistocene. One aim of this article is to introduce fire use into the debate and provide a foundation for further discussion.

Inferring prehistoric cognition

A credible argument from palaeoanthropological evidence to cognition must be based on a sequence of explicit and persuasive inferences (Wynn 2009, 9544). We need to identify behavioural criteria that can be inferred from evidence and that reliably indicate cognitive processes (Wynn & Coolidge 2007, 81). Behaviours should be explained in terms of the minimum necessary competence required to produce them (Coolidge & Wynn 2009, 177). Accordingly, I aim to focus on the least cognitively demanding strategies early humans could have used to control fire given their circumstances. Cognition is not always defined clearly or operationally in relation to the adaptive behaviours which it governs (Ardila 2008; Aunger & Curtis 2008; Barkley 2001; Botha 2000; 2006; Gershenson 2004). In light of this I will focus on behavioural criteria that are generally accepted to indicate distinctively human cognitive abilities. These are planning for a future need, inhibiting prepotent responses and future-directed group-level cooperation.

Planning ahead requires representing an intended outcome in the absence of any direct reference to the goal (Deacon 2011; Gärdenfors 2008). Representing information about absent or displaced phenomena is a feature of modern human cognition that enables our ability to inhibit responses and plan ahead (Sterelny 2003). Preparing for a future need without any proximate extrinsic or intrinsic stimulus motivating and sustaining attention on the future goal implies the ability to form episodic memories (Tulving 2001; 2005; Suddendorf & Corballis 2007; 2010).

Inhibiting prepotent responses or 'future-directed self-regulation' is the hallmark of our executive functions (Barkley 2001, 5; Verbruggen & Logan 2008, 418). Inhibiting responses to proximate opportunities in favour of future benefits is cognitively demanding because the future benefit must be represented and the discomfort of delaying or suppressing gratification tolerated (Osvath & Osvath 2008, 663). Behaviours involving response inhibition imply cognitive control governed by an enhanced working memory capacity (Wynn & Coolidge 2007).

Cooperation directed at future goals and involving complimentary roles requires complex social cognition (Tomasello 2009). I need to know the role which fellow collaborators intend to perform and they need to know my intentions directed at the future state *we* intend to bring about (Pettit & Schweikard 2006, 23; Tuomela 2007, 5). These are rational constraints on cooperation directed at future benefits (Tuomela 2007). Human cooperation also implies intersubjective communication involving individuals jointly attending to, and communicating information about mutually beneficial future states (Gärdenfors 2008; Hurford 2007). It requires representing roles and mutual objectives (Gärdenfors 2008), and keeping one's own intentions distinct from those of others (Knoblich & Sebanz 2009).

Cooperation is also cognitively demanding if it provides a public good and is open to free-riding. Evidence demonstrates that unconditional cooperation is not adaptive and that public goods will be undersupplied without additional incentives (Hauert *et al.* 2008; Hawkes 1993; Ofek 2001; Shinada & Yamagishi 2007; De Silva *et al.* 2010). Common goods present individuals with a social dilemma because each person is better off acting selfishly, but if everyone does, everybody will be worse off (Van Vugt & Van Lange 2006, 238). Effective cooperation directed at future rewards and an ongoing mutual benefit requires that free-riders can be identified and discouraged.

Humanlike cooperation implies informational theory of mind, joint attention, collective intentionality and intersubjective communication. Informational theory of mind refers to understanding the knowledge and beliefs of others, as against inferring their intentions from what they can see and hear or from contextual cues. Only informational theory of mind seems to be uniquely human (Emery & Clayton 2009), and enables human modes of cooperation directed at future rewards (Gärdenfors 2008). As with planning and response inhibition, humanlike cooperation requires conscious cognitive control and goal mainte-

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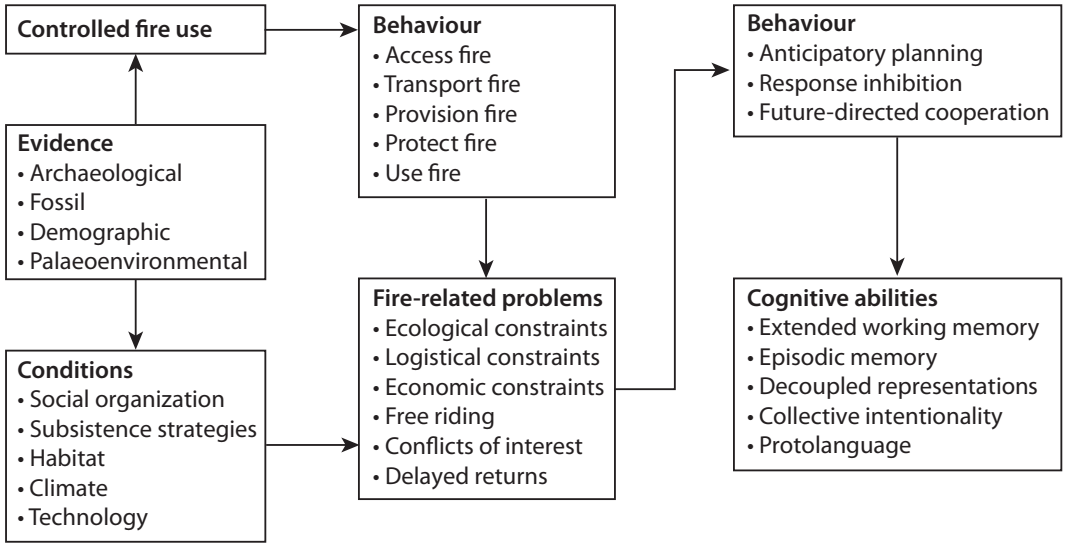


Figure 1. *Inferential structure of an argument from controlled fire use to cognitive abilities.*

nance that is associated with our enhanced executive functions.

Based on our current understanding, behaviours that involve planning ahead, inhibiting responses and future-directed group-level cooperation imply degrees of episodic memory, working memory and social cognition that are not clearly evident in other animals. The structure of my argument from prehistoric evidence to cognitive abilities is outlined in Figure 1.

Evidence for early human controlled fire use

Domestic fire

Evidence for domestic fire implies controlled fire use and is common after 200 kya (Klein & Edgar 2002; Roebroeks & Villa 2011; Rolland 2004). The ability of the Neanderthals and early *Homo sapiens* to control fire is not at issue. Gesher Benot Ya'aqov in Israel, dating to around 790 kya, is currently the earliest site with evidence for domestic fire that is suggestive of controlled fire use (Alperson-Afil & Goren-Inbar 2010). Despite concerns that this site may indicate opportunistic rather than controlled fire use (Roebroeks & Villa 2011), the case for habitual fire use at Gesher Benot Ya'aqov is strong (Alperson-Afil & Goren-Inbar 2010).

Evidence for Early Pleistocene controlled use of fire is rare and equivocal (Rolland 2004). A few Early Pleistocene sites have good evidence for anthropogenic fire (Bellomo 1994; Pickering *et al.* 2008), including recent evidence from Wonderwerk Cave in South Africa dated to about one million years ago (mya) (Berna *et al.* 2012). The Middle Pleistocene sites listed below that predate 200 kya have compelling evidence for domestic fire. See Rolland (2004) for a more extensive list including sites with suggestive, but less-conclusive evidence. The dates for Zhoukoudian Locality 1 are based on revised age estimates for this site.

- *Gesher Benot Ya'aqov, Israel:* Domestic fire evident in Layer 11-6 from Levels 1 through 7 between 800–700 kya (Alperson-Afil & Goren-Inbar 2010)
- *Zhoukoudian, China:* Domestic fire evident at Locality 1, Layer 10 dating to between 780–680 kya (Boaz *et al.* 2004; Rolland 2004; Shen *et al.* 2009)
- *Beeches Pit, East Anglia:* Domestic fire evident in area AH from around 400–350 kya (Gowlett 2006; Preece *et al.* 2007)
- *Schöningen, Germany:* Domestic fire evident in Horizon 13, Levels 11–4 at around 400 kya (Thieme 2005)
- *Qesem Cave, Israel:* Domestic fire evident in the lower sequence from around 400–200 kya (Karkanas *et al.* 2007)
- *Bilzingsleben, Germany:* Domestic fire evident at around 370 kya (Mania & Mania 2005)
- *Orgnac 3, France:* Domestic fire evident in Levels 2 and 6 at around 300 kya (Moncel *et al.* 2005)
- *Menez-Dregan 1, France:* Domestic fire evident in Layers 5c and 5e around 200 kya, and in Layers 7 and 9. The date range of these older layers is uncertain, although Layer 9 may date to about 400 kya (Mercier *et al.* 2004; Monnier *et al.* 1994)
- *Hayonim Cave, Israel:* Domestic fire evident throughout the Mousterian sequence from Layer F beginning around 250 kya (Albert *et al.* 2003)

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- *Bolomor Cave, Spain:* Domestic fire evident from Level XIV around 230 kya (Peris *et al.* 2012)
- *Misliya Cave, Israel:* Domestic fire evident in the Upper Terrace around 200 kya (Yeshurun *et al.* 2007)

Excluding the revised dates for Zhoukoudian Locality 1 (Shen *et al.* 2009), there is currently no evidence for domestic fires between about 400–700 kya (Roebroeks & Villa 2011). This would be expected even if using fire were common because clear evidence for domestic fire will only survive in exceptional preservation conditions (Preece *et al.* 2007; Sergant *et al.* 2006). Fire must have been used at many sites over the last 250 thousand years where there is no direct evidence for it (Wrangham 2009, 88). Therefore, the direct evidence for domestic fire probably cannot tell us when controlled fire use first emerged, or how widespread it may have been during the Pleistocene. However, other lines of evidence suggest some humans were using fire regularly throughout the Middle Pleistocene.

Indirect evidence for regular fire use by early humans

Wrangham argues (2009) that *Homo erectus* was adapted to eating cooked foods. In particular, the metabolic demands of evolving, developing and maintaining our relatively large brains suggest improvements in diet breadth and quality that imply cooking (Schoenemann 2006). Middle Pleistocene human brain evolution required a considerable increase in net energy input (Navarrete *et al.* 2011). While it is debatable if early *Homo erectus* required regular cooking to survive (Leonard *et al.* 2007, 319), the rapid increase in relative brain size that occurs during the Middle Pleistocene (Holloway *et al.* 2004) probably required the regular consumption of cooked foods (Aiello & Wells 2002; Schoenemann 2006; Wrangham 2009). This is because while the metabolic demands of Middle Pleistocene humans would have been similar to or greater than modern foragers, the former were less equipped to meet these demands (Hockett 2012). Even when differences in body size are considered, brain evolution to within the modern human range between about 200–750 kya suggests that the common ancestor of the Neanderthals and *Homo sapiens* regularly ate cooked food. This implies that effective populations of controlled fire users have existed for about 700 thousand years.

Modern humans have a universal sleep pattern that is unique among apes (Burton 2009; Gowlett 2010). Human adults sleep an average of eight hours a day no matter where they live. We depend on artificial light to do this. Other diurnal primates usually sleep when it is dark. Our particular circadian rhythms have a biological basis that suggests a deep evolutionary history (Burton 2009; Gowlett 2010). Firelight would probably have been required for this adaptation to evolve (Burton 2009). Nocturnal activities would also have been important for humans migrating into temperate regions during the Early and Middle Pleistocene. Our distinctive sleep patterns and the probable need for some Middle Pleistocene humans to extend the day support the view that they could control fire.

Some Middle Pleistocene humans occupied seasonally or permanently cool environments in which fire was probably required to survive (Klein & Edgar 2002; Mania & Mania 2005; Preece *et al.* 2007; Shen *et al.* 2009; Thieme 2005). Humans today cannot survive without heating, effective clothing and shelter when temperatures drop below tolerant levels (Gilligan 2007). While no doubt hardy people, '*Homo erectus* did not come as a naked savage into these regions' (Mania & Mania 2005, 103). We now have evidence that some humans could survive in cold environments from the beginning of the Middle Pleistocene (Shen *et al.* 2009; Parfitt *et al.* 2010). Fire would have been important for the survival of many Middle Pleistocene human societies living in the temperate zones of Europe and Asia during cool or cold periods (Gilligan 2007).[1]

Despite the sparse direct evidence for domestic fires prior to 200 kya, the direct and indirect evidence taken together suggests populations of fire-using humans have existed since at least the beginning of the Middle Pleistocene. This is not to say all humans at this time controlled fire or that fire use did not evolve much earlier in some human populations. However, it is reasonable to think that some humans were regularly using fire throughout the Middle Pleistocene.

Modelling early human controlled fire use

My model of Middle Pleistocene fire use is derived from the universal properties of fire and assumes that people could not make fire. The distinction between controlling fire with or without ignition technologies is important because the behavioural and cognitive implications are different. Fire making reduces some of the cognitive demands associated with fire use because individuals need not worry about accessing it, conserving the fire or transporting it. However, fire making is arguably more cognitively demanding in terms of cultural transmission and technological reasoning (Twomey 2011, 87–90). There is no evidence to suggest Middle Pleistocene fire users could make fire and circumstantial evidence suggests they could not (Gowlett 2006; Ofek 2001; Rolland 2004). We can also be sure controlled use of fire without fire making preceded the invention and diffusion of ignition technologies (Goudsblom 1992; Ofek 2001), although we

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cannot say for certain that all fire users of the Middle Pleistocene could not make fire.

If early fire users could not make fire then controlling it involved accessing, conserving and using fire. Accessing fire is not necessary if individuals can keep a fire going indefinitely. Fire may have been 'inherited' without ever having to access it. While ongoing maintenance would have been important, this idea scenario is unlikely. Bad weather, unforeseen contingencies or neglect could have resulted in a fire going out (Ofek 2001). Perpetuating fire also requires failsafe contingency plans and maintenance strategies that presuppose human cognitive abilities beyond those which I am proposing. Even if fire only had to be accessed occasionally, for humans who needed it to survive access was a problem that had to be solved if long periods without fire were to be avoided. This difficulty is not fully appreciated by those of us with easy access to matches (Ofek 2001, 151).

Observing and interacting with natural fires would have been important in the initial stages of fire domestication (Burton 2009). However, natural fires would not always have provided individuals with a reliable ignition source (Twomey 2011, 91–4). If Middle Pleistocene fire users could not afford to wait months or years for a fortuitous wildfire or lightning strike and did not live near an active volcano, then natural fires were not really an option for them. In an effective population of fire users domestic fires would have provided a more readily available ignition source. This suggests that before the invention of fire making fire users often relied on other domestic fires to regain fire.

If access was difficult, then provisioning, protecting and transporting fire were necessary to ensure individuals could regularly benefit from fire. Controlling fire also involved using fire adaptively. Keeping fire would have been a costly behaviour relative to other activities (Ofek 2001; Twomey 2011). Costly adaptations do not evolve unless they provide individuals with some benefit (Dunbar & Schultz 2007, 1344). It follows that fire use was favoured because it conveyed some advantage. Cooking would have provided a regular net-energy return relative to fire-keeping costs (Wrangham & Conklin-Brittain 2003). Nightlight and warmth would sometimes have provided a substantial energy return and may have been critical for survival in some contexts. While nightlight and warmth would have been important, many fire users experienced conditions when these were not required, such as temperate summers or tropical climates. As such, cooking probably provided the consistent motivation and return for effort needed to encourage early humans to keep a fire going from day to day (Burton 2009; Wobber *et al.* 2008; Wrangham 2009).

Controlling fire would have involved accessing fire from natural or domestic fires, maintaining, transporting and protecting fire, and using fire adaptively. The primary benefit of fire was probably cooking, with warmth and light being important at certain times. While there is scant direct evidence for these behaviours, they were necessary if individuals could not access fire easily or make it.

The conditions of Middle Pleistocene fire use

I now consider some of the constraints associated with fire-related behaviours. Middle Pleistocene humans lived in a range of habitats including grassland, woodland and forest in tropical and temperate regions (Elton 2008, 387). They would have experienced seasonal changes that varied according to latitude such as tropical cycles of monsoon and dry periods or temperate summers and winters. Some fire users lived in environments with low fuel loads, and all would have had to deal with rain.

Evidence suggests Middle Pleistocene humans lived in small local groups of 15–30 individuals (Henry 2003; Lalueza-Fox *et al.* 2011; Marlowe 2005), had low population densities (Premo & Hublin 2008) and were distributed over large areas (Stiner 2002). This means fire was controlled and used by individuals in a local group social context and that local groups were sometimes isolated from each other. Middle Pleistocene humans probably foraged from a central location (Rolland 2004), thereby delaying the consumption of fuel and food. This affected the logistics of fire provisioning because fewer trips with heavy loads are more efficient than many trips with light loads (Olsson *et al.* 2008). Therefore, gathering fuel to last for several hours or days was more efficient than gathering enough to last an hour or two.

The amount of daylight and availability of resources are major constraints on the time budgets of diurnal foragers (Hill *et al.* 2003). Early humans would not always have had enough time in the day to forage for food, maintain social relationships, rest, compete for mates, avoid predators, make tools and conduct fire-related tasks. All social primates spend a large percentage of our time maintaining social relationships (Dunbar & Schultz 2007), and modern human foragers regularly face seasonal food shortages (Jenike 2001). Some Middle Pleistocene humans had to deal with increasingly poorer-quality habitats as populations extended further into northern Europe and Asia (Grove *et al.* 2012). We have no reason to think early humans were better than modern foragers at

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avoiding nutritional stress. On the contrary, it is likely that humans who lacked the cultural supports and technologies of modern foragers spent relatively more time and energy meeting their metabolic requirements (Hockett 2012). This means other needs and desires would often have conflicted with the motive to engage in a fire-related task.

Early humans would have used mostly low-quality fuels, such as deadwood, brushwood and dry grass (Ofek 2001). They may have logged and cured firewood. However, this would not always have been practical for mobile foragers with only hand-held stone tools and assumes complex cooperation and planning abilities beyond the minimum necessary competence required to control fire. They also could have used bone as many prehistoric humans did (Théry-Parisot 2002). A heavy reliance on bone as a fuel source is unlikely however, because this could have led to the curious situation of people having to hunt for fuel (Théry-Parisot 2002). A fire burning continually and fed largely on poor-quality fuels would have quickly used up the combustible material in its vicinity, meaning the time and energy required to find sufficient fuel each day increased relative to length of occupation (Ofek 2001). Fires also needed to be relatively large to be effective for cooking, light and warmth (Lioubine 1992). Given these conditions, it is reasonable to think that large amounts of fuel were required to control fire before the advent of fire making. Ofek has suggested (2001, 157) that finding sufficient fuel supplies would always have been difficult in these circumstances, and Gowlett suggests that controlling fire presupposes a 'considerable investment in fuel' (2010, 352). Evidence from some Middle Pleistocene sites suggests large amounts of wood fuel were brought in from remote locations (Gamble *et al.* 2011; Gowlett 2006).

I am assuming that local groups kept communal fires that serviced all members, rather than individuals keeping fires for private use. Evidence for large fires from Late and Middle Pleistocene sites suggests that the fire serviced all members of a local group (Gowlett 2006). Private fires would have been more socially disruptive because group members would have competed for fuel resources. Several private fires would also have been less efficient because they would have used up local resources more quickly for about the same return to individuals as a communal fire could have provided. A private fire scenario in a local group context also suggests modern human forager modes of social organization and levels of social restraint. While we cannot rule out a private fire scenario (Ofek 2001), this would have been no less cognitively demanding and less efficient.

A fire burning continually in a local group context has all the elements of a public good (Ofek 2001, 159). Unless prevented, individuals can use a private or communal domestic fire as an ignition source and to cook or keep warm without incurring fire-keeping costs. This would put free-riders at an advantage over those in the group who provided the fire (Ofek 2001; De Silva *et al.* 2010). We have no reason to think Middle Pleistocene humans were more cooperative or less inclined to free-ride than people today. We also know that non-human apes are good at using social knowledge towards selfish ends (Hirata 2009, 3), but not generally inclined to use this knowledge in collaborative ways (Tomasello 2009, 5). This means that controlled fire use presented early humans with a social dilemma. Individuals were better off avoiding the cost of fire keeping while enjoying the benefits, but if everyone acted this way then the fire would be undersupplied. Controlled fire use before the invention of ignition technologies implies that mechanisms were in place to discourage free-riding because 'providing a public good in the ordinary business of human life must contend with free-ridership' (Ofek 2001, 159). Cooking also delays the consumption of food, which increased the opportunity and temptation for individuals to steal food (Wrangham 2009). Free-riding by stealing food would also have undermined fire-keeping efforts.

Fire users would have faced a range of environmental, demographic, economic, logistical and social fire-related problems. They had to delay gratification, deal with environmental fluctuations and contingencies, and overcome conflicts of interest, free-riders and social dilemmas. They had to meet the cost of keeping fire and coordinate fire-related behaviours with other necessary activities.[2]

Possible fire-related strategies

I now consider simple strategies that would have sufficed to access, maintain and benefit from fire in light of fire-related problems. While we cannot know if the strategies I am suggesting were employed, we can identify the least cognitively demanding strategies that would have sufficed. These can stand as a logically sound behavioural basis for grounding inferences about cognition because fire users must have adopted these or more cognitively demanding solutions.

Accessing fire

Individuals could have accessed fire by stealth or force from hostile groups. They could have waited in hiding for an opportunity to access fire undetected. Alternatively, individuals could have collaborated by

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creating a diversion that allowed others to make off with a burning log. Another option was using force by intimidating those with fire into allowing access or fighting with them to gain access. Either stealth or force was risky because it increased the chance of injury or death and may not always have been successful. While these would have been the least efficient and effective ways to regain fire relative to alternatives, individuals may have had no choice if neighbours were hostile and natural fire was unavailable.

Fire could have been accessed through more amicable negotiations if those with fire allowed unhindered access. Free access would have been a safer option for both parties and more reliable. So long as borrowers were not in direct competition with donors, individuals with fire lose nothing by providing an ignition source and avoid the potential costs associated with guarding and defending their fire. Individuals without fire gain a great deal by being able to access it without conflict or risk. A problem with free access would have been if close neighbours did not bother to conserve fire because they knew they could access it when they needed to (Ofek 2001). If free-riders did not have to travel far and could access fire without costs then they would be at an advantage over diligent fire keepers, so this behaviour was probably not viable (Ofek 2001, 161). However, if local groups were widely distributed and population densities low, individuals who lost fire may have had to travel for several days in order to find another group and would spend more time without fire if they lost it regularly. In these circumstances borrowers would not have been at an advantage over donors. In cold conditions when individuals could not afford to be without fire for long, social networks of local groups who helped each other out by allowing free access would have been adaptive for all individuals in an effective population (Gowlett 2006, 306).

Provisioning fire

One way to avoid the problems associated with accessing fire is to conserve it. Maintaining a fire would have involved provisioning, transporting and protecting fire. Provisioning a fire involved gathering fuel and feeding it to the fire. Individuals in a local group may have contributed equally to the cost of provisioning or some individuals may have dedicated more energy to keeping the fire going. They may have gathered fuel as a group or remotely from each other. We do not know if early humans tended to stay together as a group during the day or foraged separately. Their subsistence strategies may have involved group participation (Kuhn & Stiner 2006), or they may have split up to forage (Foley & Gamble 2009; Grove *et al.* 2012). Given that either strategy may have been used at different times or places, we need to consider both.

We do not know if early fire users stockpiled fuel for the long term. This would have been an efficient and adaptive strategy in some contexts, but impractical in others.[3] It also implies planning depth and group contingency planning beyond the minimum necessary competence required to control fire. If we exclude long-term stockpiling, then early humans had three basic fuel-gathering options available, each with a short-term stockpiling option. Short-term stockpiling refers to gathering enough resources to last a few days or perhaps a week. Individuals could have gathered fuel together as a group or remotely from each other, with everyone in the group making roughly even contributions. Alternatively, members of local group could have divided their labour, with some individuals dedicating more time and effort to gathering fuel and tending the fire.

Transporting, protecting and using fire

Before the invention of fire making, controlling fire involved transporting fire when a group relocated. Early humans could have used a burning log or stick to do this, or carried hot coals in some form of natural container. There are many ways to move fire around when making a fire is impossible, difficult or impractical. However, modern fire totes involve complex technologies that we usually associate with modern human cognition and I will assume early humans did not use them.

The main constraint on moving fire is distance. The further a fire had to be moved, the longer an individual had to attend to the task and the greater the risk that the fire might go out. At an average walking speed of about five kilometres per hour, transporting a fire over five kilometres would take more than an hour. Evidence suggests Middle Pleistocene *Homo* sometimes travelled ten kilometres to procure lithic resources (Marwick 2003), and that large amounts of meat were sometimes carried several kilometres (Dubreuil 2010; Stiner *et al.* 2009). If fire users were central-place foragers, then they would need to travel twice the radius of the patch they had exhausted when relocating (Grove 2009, 223). Seasonal migrations may have involved travelling for weeks. Therefore, it is reasonable to think fire sometimes had to be carried for several hours. While early humans could have moved around incrementally or shared the task to avoid carrying fire for long durations, whenever they moved someone had to carry the fire unless they knew that an ignition source would be available upon arrival at a new location.

Protecting a fire from rain would have been difficult without access to natural or fabricated shelters.

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A large fire may survive a shower, but large fires are inefficient and will not survive in persistent heavy rain. We do not know if Middle Pleistocene humans regularly made huts or not. There is little evidence for living structures prior to the Late Pleistocene. However, we do have evidence from Bilzingsleben in Germany for fires kept in huts (Mania & Mania 2005).

Caves and rockshelters will protect a fire. However, living in a cave would not always have been logistically viable (Ofek 2001), and many early humans would not have had access to caves. For these people sheltered huts or devices designed to protect the fire in an emergency may have been required. If individuals did not prepare in advance to protect a fire in the open they would probably have lost their fire in bad weather. Caves and constructed shelters were probably the two main ways Middle Pleistocene humans could have protected fire from rain.

Cooking involves taking fire to the food or bringing food to fire. Cooking also involves a method. Food items could not always have been simply placed on the fire. Large items could smother a small fire and small items could be burned or difficult to retrieve. Special cooking fires of hot coals or skewers may have been required to cook food. We have evidence of a 400,000-year-old wooden tool from Schöningen in Germany that was probably used for cooking (Thieme 2005, 126). Apart from these practical difficulties, the main problem was that cooking increased the opportunity and temptation to steal food.

The strategies suggested above were not the only means available. However, I propose that they are the least cognitively demanding that would have sufficed to control fire under the conditions with which early humans had to contend. Whichever way we consider it, controlling fire involved several tasks that required overcoming various difficulties. It was not simply a matter of accessing fire when it was needed and keeping it burning until it was not. Economic, environmental and social constraints had to be considered. I now discuss the cognitive implications of accessing, maintaining and using fire in relation to the criteria for cognition discussed above and the problems fire users had to solve.

The cognitive implications of controlled fire use

Accessing fire

Accessing fire from nature or other groups implies planning and cooperation directed at a future reward. If individuals tried to regain fire from a remote source then they were focused on a goal that may not have been realized for days. However, the need and motivation to regain fire was probably persistent for individuals that usually had fire, even if the goal itself was remote in time and space. Accessing fire by stealth or force was more likely to succeed if individuals planned ahead and cooperated because, unlike cooperative hunting in other animals, other humans who were intent on preventing you had to be negotiated. Alternatively, fire could have been accessed from others through more amicable negotiations. This is interesting from a cooperative point of view because it implies cooperation between local groups, as is common in modern human forager societies. A single individual could access fire by stealth, force or amicably. However, this still implies cooperation if the fire was then shared with others. Cooperating by assisting others to access fire or sharing an acquired fire implies that the future goal and intentions toward it are understood.

Accessing fire in these ways would have established the potential for strategic cooperation between members of a local group or cooperative interactions between local groups. Ofek argues (2001, 161) that the problems associated with accessing fire before the invention of fire making would have demanded an incipient form of market exchange involving specialist fire keepers who traded fire for other goods or services. If this were the case then complex humanlike social cognition, concepts of value and executive functions would have been required.

Provisioning fire

Gathering fuel or tending a fire at times when the fire was not needed or about to go out implies planning for future need. Sometimes individuals would have needed to plan ahead because they would not always have been able to gather fuel in response to proximate needs. A motivational problem for early fire users was that there were no regular intrinsic or extrinsic cues that clearly indicated the best time to gather fuel. Information about when to gather fuel was sometimes cognitively 'translucent' or 'opaque' (Sterelny 2003, 12, 17). While the procedures associated with fuel gathering and tending a fire are not complex, unlike food- and tool-provisioning systems, fire provisioning is a detached system whereby the act of gathering fuel is not clearly associated in time and space with the benefits fire provides (Ronen 1998, 443). This means that fire tending and fuel gathering involved 'deferred gratification' because they were not always performed in an individual's immediate interest (Goudsblom 1989, 165). Needing to use the fire or the fire going out could not always have motivated fuel-gathering behaviours because these cues would often have occurred at times when fuel was difficult or impossible to gather. If the fire or fuel was needed

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at night, in extreme weather conditions or when other contingencies demanded attention then fuel might not be gathered. Similarly, if fuel loads were low or supplies had been cleared from around the fire then leaving fuel gathering to the last minute is risky because there may not be enough readily available fuel to sustain the fire. Planning ahead was perhaps the only way to ensure the fire was provisioned thereby guaranteeing regular access to fire's benefits.

Cooking could have provided early human fire users with a regular cue that motivated fuel gathering. Individuals could have foraged for food and gathered fuel as they returned to home base, thereby reducing the need to plan ahead. This strategy may have worked in some contexts if individuals collaborated to carry food and fuel. However, it would have been inefficient and difficult if fuel was not close to food, food was scarce or both were unevenly distributed, because food would have to have been carried around or guarded while fuel was gathered. This could also further delay the consumption of food, implying a capacity to inhibit responses to eat the food raw or cook it before fuel was gathered. Once food was cooked and eaten, then the need to cook food could no longer serve as motivation to gather fuel. Whichever way we imagine it, sometimes fire users had to gather fuel or tend the fire when there was no immediate need to do so.

If gathering fuel conflicted with other interests, then individuals would sometimes have needed to inhibit their response to more immediate rewards in order to ensure that fuel was gathered. Fuel gatherers would often have had to inhibit responses to proximate intrinsic and extrinsic motives because they did not always live in ideal conditions, and other behaviours would sometimes have been preferred. While gathering fuel leads to a substantial reward, it offers no immediate reward in itself. It is a laborious task that takes time and energy, and may have exposed individuals to an increased risk of injury or predation. It is perhaps the least desirable thing an early human might do compared to foraging for food, seeking mates, socializing, playing, resting or tool making. All these activities, except perhaps tool making, offered individuals an immediate and desirable reward. Fuel gatherers would often have had to choose between one of these activities and gathering fuel. In situations when food was scarce individuals may have had to abandon a food search to ensure sufficient fuel was gathered to last through the night. This is not to say that individuals always faced conflicts of interest, that they could not take advantage of a mating opportunity or eat some food on the go and then return to gathering fuel. However, given their social and ecological context, conflicts would have occurred often enough to undermine fuel-gathering efforts if individuals never inhibited responses because fuel gathering would often be left to the last minute or neglected altogether. Furthermore, an individual might forego fuel gathering without the fire going out if others in the group gathered fuel, thereby increasing the temptation to avoid the task. Inhibiting prepotent responses was required in order to ensure fuel-gathering behaviours were initiated and sustained despite interference from motivations towards more immediate rewards.

Provisioning a domestic fire would have required future-directed group-level cooperation. It is unlikely that one or a few individuals could maintain a fire for everyone in the group to use without some additional incentive (Ofek 2001). A few altruistic fire providers would have found it difficult to feed both the fire and themselves when food and fuel were hard to find. These individuals would also have been at a disadvantage relative to their beneficiaries who spent no time and energy gathering fuel. All else being equal, providing a fire for others was probably not a viable evolutionary strategy because the free-riders would be at an advantage over fire providers. In the long run you end up with all free-riders, no providers and no fire (Ofek 2001, 161). Given the importance of fire to everyone in the group, it is reasonable to think individuals cooperated to ensure that enough fuel was gathered and the fire was tended, even if some individuals were happy to do more of the work. Cooperation also greatly improves the efficiency of fire provisioning, which would have been important when time budgets were constrained or finding sufficient fuel supplies was difficult. Ten individuals might gather in ten minutes the same amount of fuel that an individual would take about one and a half hours to find.

If individuals cooperated to gather fuel that would be used later in the day, throughout the night or the next day, then they were cooperating to secure a future reward. This would have required planning ahead, inhibiting responses and understanding the intentions of others towards the future benefit. Similarly, if individuals cooperated to tend the fire then they would need to know each other's intentions towards it. I would need to know that you intend to tend the fire in my absence and that you know I expect this of you, suggesting three orders of intentionality.

Individuals from a local group could have gathered fuel together. This would have made free-riding more difficult as everyone could see what the others were doing. Conflicts of interest may also have been easier to overcome if everyone else was doing the

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same thing at the same time and place. However, this strategy would have been the least efficient and required group-level coordination of daily activities. If fuel and food were widely distributed, then travelling as a group from food to fuel to fire could have been a costly strategy. A group-gathering strategy implies consideration and communication of information about the location and proximity of food and fuel before setting out to procure resources.

Individuals or small foraging parties could have gathered different resources in different locations by engaging in complementary roles synchronically. This would have been more efficient as the efforts of the group as a whole could be distributed over time and space. Fuel and food could be gathered from different places without everyone in the group having to travel to each patch. Someone could carry food while another carried fuel, thereby reducing the distances which individuals needed to travel, distributing foraging costs and reducing the potential delay between finding food and cooking. This strategy would have reduced fire-keeping costs and the risk that the fire would go out relative to a group-foraging scenario. However, this makes free-riders more difficult to monitor and would have increased the temptation to avoid fuel gathering. Individuals would need to understand the intentions of remote others and trust that others were gathering food or fuel and that resources would be shared later. Individuals would be unlikely to gather resources that benefited others unless they knew others would reciprocate. This would not have required a strict division of labour. Individuals might have gathered fuel one day while on another they gathered food or tended the fire. While either of these strategies would have sufficed, the cost and logistics associated with using fire in a forager society combined with the inefficiency of group gathering and the problem of free-riding, suggest that controlling fire may have required socially constructed divisions of labour (Goudsblom 1992; Gowlett 2010, 325; Ofek 2001; Ronen 1998) that presuppose complex social cognition.

Free-riding is recognized as a major constraint on the evolution of human cooperation (Dubreuil 2010, 53; Gamble *et al.* 2011, 118; Shinada & Yamagishi 2007, 330) and would have undermined cooperative fire provisioning. Gamble and colleagues identify (2011, 118) the need to monitor and deal with free-riding as a primary evolutionary driver of human social cognition associated with a theory of mind, increased cognitive load and demands on memory. The public nature of a domestic fire implies that coalitions of individuals actively guarded their fires, or that a credible threat of punishment and social norms encouraging cooperation were in place. Transmitting information about future goals, intentions, responsibilities and free-riders implies collective intentionality and intersubjective communication. When we consider the social and logistical constraints, controlling fire would have been very difficult without future-directed group-level cooperation to minimize free-riding and maximize efficiency.

Transporting and protecting fire

Transporting fire implies planning, response inhibition and cooperation directed at a future goal. An individual carrying fire may have needed to focus attention on the task and ignore distractions for hours, or be relieved by others lest the fire go out. Decisions had to be made as to who would carry the fire whenever the group relocated. Even if only one individual carried the fire this still implies cooperation because the behaviour benefited everyone in the group.

Individuals no doubt would have rallied to prevent a fire from going out in the rain. Trying to save a dying fire would be responding to an immediate and urgent need, although the benefit would still be in the future. However, trying to keep a fire burning continually without shelter or contingency plans would have been difficult. Early humans may have kept fires in caves to prevent them from going out. While caves would have provided other benefits, we have reason to think fire protection was a primary factor motivating cave use (Gowlett 2006; Ofek 2001; Rolland 2004). Although we cannot be certain this is why early humans exploited caves, using caves for this purpose implies group contingency planning, which is associated with enhanced executive functions (Wynn & Coolidge 2007, 82).

Benefiting from fire

Early humans would have used fire for cooking, warmth and light. The main constraint on having light and keeping warm was that large amounts of fuel needed to be gathered during the day for a fire to be effective at night. However, an individual can benefit from fire in these ways without doing much, other than being near the fire. Cooking was different because it required special social arrangements.

Delayed consumption increased the opportunities for individuals to steal food. Dominant or cunning individuals could simply wait for food to be brought to them or roam from fire to fire stealing what they could (Wrangham 2009, 158). It would be difficult to prevent strong individuals from stealing food unless coalitions cooperated to prevent them. 'Central place provisioning presupposed respect for property. It cannot evolve if those bringing resources back are likely to lose them to stronger individuals' (Sterelny 2003, 137).

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Table 1. *Behavioural and cognitive implications of problems early human fire users would have encountered.*

Fire-related problem	Implication for behaviour	Cognitive implications
Access fire from other fire users in hostile or amicable contexts	Anticipatory planning and future-directed cooperation	Executive functions including episodic memory, extended working memory and decoupled representations
Ensure fire provisioning when time and energy budgets were constrained		
Exhausting local fuel supplies, running out of fuel at night and rain	Anticipatory planning	
Conflicts of interest between fire-related tasks and motivations towards more immediate rewards	Inhibiting prepotent responses	Social cognition including informational theory of mind, collective intentionality and intersubjective communication
Motivations to steal food		
Sustain attention on fire-related tasks such as transporting the fire or gathering fuel		
Maintain sufficient levels of provisioning efficiency	Future-directed group-level cooperation	
Monitor the intentions of fellow group members to tend the fire and gather fuel		
Identify and discourage individuals that free-ride by avoiding fire-related tasks or stealing food		

Even dominant uncooperative individuals would have needed help to maintain a fire and would therefore need to avoid stealing food from those upon whom they relied. This suggests that individuals were able to inhibit inclinations to steal food or that mechanisms were in place to discourage food stealing. It implies that groups or coalitions of individuals cooperated, tolerated and trusted each other.

Controlled fire use established a context that would have provided strong motivation for individuals to form coalitions capable of excluding or punishing bullies and the uncooperative. Cooking in a group context implies the kind of trust, tolerance, restraint and social awareness associated with modern human societies. In this respect, the social skills of other apes would not have been conducive to controlling fire (Tomasello 2009). Recent evidence suggests our closest ape relatives are either unable or unmotivated to inhibit responses when presented with opportunities to steal food (Kaiser *et al.* 2012). While some other animals form coalitions, punish individuals and display restraint directed at social cohesion, these behaviours are usually directed at proximate rewards (West *et al.* 2011). Similarly, ape cooperation seems to be directed at immediate gratification (Call 2009), and cognitive constraints may account for this (Stevens & Hauser 2004). Cooperating to maintain a public good is not evident in other ape societies and most likely a derived human adaptation.

In summary, controlled fire use would have involved planning, inhibiting responses and cooperation directed at future rewards for the following reasons. Planning was required to access fire, to ensure sufficient fuel supplies were gathered before nightfall, and to prepare for contingencies such as rain or exhausting local fuel supplies. Being able to plan ahead would have been important for coordinating fuel gathering with other daily activities, when transporting fire and if fire had to be accessed from hostile neighbours. Using fire implies that individuals regularly had to consider uncertain future contingencies, and plan for tomorrow and beyond. In their day-to-day activities they often had to consider and engage in tasks directed at future rewards. While there is evidence other animals can plan ahead to a limited degree (Raby & Clayton 2009), controlling fire implies regularly preparing for future needs and planning depth extended into tomorrow. Similarly, the hunting and tool-making behaviours of early humans do not imply the depth or consistency of foresight implied by fire use.

Inhibiting responses would have been required to focus and sustain attention on future-directed fire-related tasks. Self-control was needed to overcome interference from conflicts of interest that undermined the initiation or continuation of fire-related tasks such as transporting fire, gathering fuel and tending the fire. Inhibiting motivations to steal food or avoid fire-related duties would also have been important.

Future-directed cooperation was required in order to ensure that the fire was maintained and to discourage free-riding. Controlling fire in a local group social context required relatively even contributions to fire-keeping costs by all group members or a division of labour involving delayed reciprocity. Social norms, enforcement coalitions, trust, tolerance and understanding each other's intentions towards future states would all have been important. Cooperation between

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group members would have greatly improved the efficiency and effectiveness of fire-related tasks, and cooperation between local groups would have ensured all individuals in an effective population could regularly access fire. Individuals who could plan ahead, inhibit responses and cooperate with the future in mind would have been better able to solve fire-related problems and enjoy regular access to fire's benefits. This has evolutionary implications that require further investigation because those with regular access to fire would have been at a distinct advantage over those with limited or no access.

Conclusion

In conclusion, controlled fire use implies planning for a future need, which suggests that Middle Pleistocene fire users were not stuck in time. They could plan for tomorrow and probably beyond. Some humans of the Middle Pleistocene may have stockpiled fuel for the long term, which implies a planning depth of weeks or even months. Controlling fire implies response inhibition that suggests a high degree of self-control. Both planning and response inhibition indicate cognitive control governed by episodic memories, decoupled representations and an extended working memory capacity. While not suggestive of modern human degrees of future-directed self-regulation, this does suggest that executive functions were well developed in the common ancestor of the Neanderthals and *Homo sapiens* relative to other apes.

Controlled fire use implies future-directed group-level cooperation. From this we can infer an informational theory of mind, collective or *we-mode* intentionality (Tuomela 2006) and intersubjective communication involving predication and displacement. Controlled fire use implies degrees of social cognition not evident in the cooperative behaviours of other animals.

The cognitive demands of controlled fire use are not consistent with the view that human cognition evolved suddenly during the Late Pleistocene from an apelike precursor. Fire use by Middle Pleistocene *Homo,* and maybe earlier humans, adds weight to the increasing evidence that suggests human cognition has been evolving gradually or in stages since we diverged from our common ancestor with chimpanzees (Barnard *et al.* 2007; Donald 2001, 268). Successfully controlling fire implies important cognitive precursors, such as protolanguage, forethought, enhanced cognitive control and complex social cognition that were required for modern human cognition to evolve.

The ideas and arguments presented here require further qualification, testing and development. While modelling the costs, conditions and consequences of early human fire use is difficult, the reward in improving our understanding of how, why and when important features of human cognition evolved would be substantial. Fire use could well have facilitated the evolution of human language, consciousness, social complexity and cooperation. It can help us understand the roots of our humanity because by domesticating fire we domesticated ourselves (Goudsblom 1992).

The approach I have outlined above establishes a heuristic framework for investigating the cognitive implications of controlled fire use. Controlling fire provides a behavioural basis for making inferences about cognition that can complement and enhance what the evidence for other early human behaviours tells us. Pyrotechnology is a uniquely human behaviour that is very likely implicated in the evolution of our distinctively human cognitive faculties.

Notes

1. These are empirical issues that are open to testable hypothesis. Regular fire use by humans can be inferred from metabolic and palaeoenvironmental evidence. We need to determine if large-brained human foragers living during the Middle Pleistocene could have survived and reproduced without regularly consuming cooked food and if humans were living in conditions that exceeded the limits of their tolerance to cold. Wrangham has argued (2009) that a suite of biological adaptations associated with *Homo erectus* suggest their predecessors regularly ate cooked food. This suggests controlled fire use may have emerged between 1.5–2 mya. While I tend to agree with Wrangham's hypothesis, in this article I am adopting the more conservative approach that cooking was required to meet the increased metabolic demands associated with human brain evolution during the Middle Pleistocene.
2. Modeling the logistics and cost of early human behaviours is a feature of palaeoanthropological research (Aiello & Wells 2002; Dubreuil 2010; Grove 2009; Grove *et al.* 2012; De Silva *et al.* 2010; Stiner 2002; Théry-Parisot 2002), and Ofek (2001) has considered the economic conditions of early human fire use in some detail. While beyond the scope of this article, the logistic, economic and social conditions associated with early human fire use are amenable to quantitative analysis. By using archaeological evidence, relevant comparisons, realistic parameters and conservative estimates when variables are unknown, we can develop viable models of fire-related costs. This would provide an empirical basis for further testing my general claims that keeping fire was relatively costly and that fire related problems are cognitively demanding. A feature of this approach (Twomey 2011) is that it provides a framework for comparing the relative effectiveness and efficiency of hypothetical strategies in a range of different environmental and social contexts.

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3. Concentrations of lithic material discovered at archaeological sites in East Africa dating to 1.5–2 mya have been interpreted as possible stockpiling by early *Homo*. However, this hypothesis is controversial (Shick 1987), and there is no clear evidence that Middle Pleistocene humans stockpiled resources for the long term. Evidence for storage facilities is only associated with *Homo sapiens* of the Late Pleistocene and is considered to require advanced executive functions (Wynn & Coolidge 2007).

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