

Tracking the evolution of causal cognition in humans

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Summary - We suggest a seven-grade model for the evolution of causal cognition as a framework that can be used to gauge variation in the complexity of causal reasoning from the panin-hominin split until the appearance of cognitively modern hunter-gatherer communities. The intention is to put forward a cohesive model for the evolution of causal cognition in humans, which can be assessed against increasingly fine-grained empirical data from the palaeoanthropological and archaeological records. We propose that the tracking behaviour (i.e., the ability to interpret and follow external, inanimate, visual clues of hominins) provides a rich case study for tracing the evolution of causal cognition in our lineage. The grades of causal cognition are tentatively linked to aspects of the Stone Age/Palaeolithic archaeological record. Our model can also be applied to current work in evolutionary psychology and research on causal cognition, so that an inter-disciplinary understanding and correlation of processes becomes increasingly possible.

Keywords - Causal cognition, Cognitive evolution, Tracking behaviour, Panin-hominin split, Causal grammar, Mindreading.

Introduction

In its simplest form, causal cognition allows us to do three important things: a) to predict outcomes based on observations, b) to affect and control events in the world around us, and c) ultimately, to predict causes from effects, even if the causes are not perceivable. Since Hume (1964 [1739]), philosophers have considered our abilities to gain causal knowledge, and to reason about outcomes based on it, key to the human way of thinking. Both humans and animals use basic associative mechanisms to learn about causal relations (e.g., Dickenson & Shanks, 1995). Nonhuman, tool-using primates have some comprehension of the association between a tool and its effects, but they generally do not grasp relationships between the underlying

physical principles of tool use (e.g., Povinelli, 2000; Blaisdell *et al.*, 2006; Penn & Povinelli, 2007). Humans, on the other hand, demonstrate a more profound understanding of causal relations, and a capacity for predicting causal interventions, which generally cannot be reduced to associative learning (e.g., Gopnik *et al.*, 2004; Waldman & Hagmayer, 2005).

Across disciplines, the evolution of causal cognition is thus progressively coming to the fore as a potential explanatory framework for what it is that makes us human. Work has focussed on the link between causal cognition and technology (e.g., Wolpert, 2003; McCormack *et al.*, 2011), the early origins of causal cognition in hominins (e.g., Stuart-Fox, 2014), and bridging the archaeological record with causal cognition (e.g., Haidle, 2014). Assessing levels of

causal understanding in animals and nonhuman primates also contributes to the discourse (e.g., Premack & Premack, 1994; Visalberghi & Tomasello, 1998; Povinelli, 2000; Blaisdell *et al.*, 2006), and currently it seems that the capacity for causal reasoning in chimpanzees is not much greater than in rats or corvids (McGrew, 2013). Povinelli & Bering (2002) suggested that a key advance in hominin cognitive evolution was the development of ‘a new representational system’, enabling our ancestors to ‘reinterpret’ the observable world by referencing unobservable physical and mental causes (also see Stuart-Fox, 2014).

Here we use the evolution of tracking behaviour (the ability to interpret and follow external, inanimate clues) in hominins and humans as a case study to hypothetically trace the roots and development of causal cognition. Tracking behaviour does not necessarily represent the sole performance demonstrating the presence of each grade, in many cases a range of technologies or social behaviours can be used similarly. We also do not imply that tracking was the main impetus for the development of every grade of causal understanding – almost certainly, a whole range of circumstances would have converged to hone each grade through time. Tracking is, however, a uniquely human behaviour that represents a continuous heuristic thread throughout the evolution of our causal cognition, which renders it a useful tool in its exploration. Partly following Woodward (2011), we see a development from thinking about your own actions as causes, *via* the actions of others as causes, to inanimate forces as causes. We present this development as a series of seven grades.

Grades of causal understanding

Woodward (2011) identified three levels of causal learning that could reflect variation in the complexity of causal thinking. The basic level is the ability to learn that one’s own physical actions can cause certain outcomes. For example, a baby will learn that kicking its foot will

move an object, such as a mobile. He refers to this as ‘egocentric learning’, based on ordinary operant or instrumental conditioning. On the second level is the ‘agent causal learner’, who also learns about cause from the actions of others. At this level, it is understood that there are causal relationships between one’s own actions, their outcomes, and interventions by either oneself or others. It is thus possible to integrate information so that it is understood that the outcomes of the interventions of others have implications for what would result from their own interventions and *vice versa* (Woodward, 2011). For example, a young chimpanzee is able to grasp, through observation, that if her mother is able to crack a nut by using a hammer stone, she too should be able to achieve a similar result by following similar actions. According to Woodward’s (2011) definition of this level of causal learning, the chimpanzee infant would grasp that other chimpanzees should be able to reproduce the same outcome based on making the same observations and following the same actions (agent causal learner).

On the third level is the ‘observation/action causal learner’. Woodward (2011, p.38) presents the following example: “Thus when I put water on plants and it grows, when I observe you put water on a plant and it grows, and when I observe rain falling on a plant and it grows, I assume that the very same sort of causal relationship between water and plant growth is present in all three cases and that observation of any one of these cases can furnish information about the other”. Such a learner is able to learn and understand relationships between their own actions and the potential outcomes thereof, the actions of others and their potential outcomes, as well as the fact that the observation of a range of natural signs or patterns can be integrated with the egocentric and action-causal observations, actions and outcomes. It is thus understood that all three causal-knowledge sets are able to inform on each other. Woodward (2011, pp.38-39) notes that the available empirical evidence suggests that apes are not observation/action causal learners (also see Tomasello & Call, 1997).

Building from Woodward (2011), we propose a more nuanced perspective on the emergence of causal cognition in humans, and focus on the degree to which the cause is perceivable, imaginable, purely abstract, and interchangeable between knowledge domains. Our framework partly follows the distinction between cued and detached mental representations introduced by Gärdenfors (1995, 2003), and builds on the model of events as mappings from force vectors to result vectors (e.g., Gärdenfors & Warglien, 2012; Warglien *et al.*, 2012; Gärdenfors, 2014), as well as on the concept of causal grammar (e.g., Tenenbaum & Niyogi, 2003). As a result, we distinguish seven grades of causal understanding, based on their level of detachment from egocentric learning or individual understanding, some of which (such as grades 3 and 4 below) might have evolved parallel to each other.

Grade 1: Individual causal understanding

The first grade involves a direct connection between a perceived force that an individual exerts and the resulting effect. Typical examples are a baby kicking its foot, learning the connection between motor commands and the resulting actions, or a kitten playing with a toy. In this case both the cause and the effect are directly perceived. The result is that the individual experiences its own agency. This grade need not involve strong cognitive mechanisms, but can be explained *via* learning by conditioning.

Grade 2: Cued dyadic-causal understanding

This grade involves two individuals who take turns in performing a similar action. One example is two children on a seesaw. One child first perceives that pushing with her legs on the ground makes her side of the seesaw go up and then she sees that when the other child pushes his feet in a similar way the other side goes up. The force of the other child is not directly perceived, but it is inferred *via* a simple mapping onto one's own force (mirror neurons are presumably involved in such an inference). Thus, I understand that your action causes an effect because it gives the same result as my action.

Another example is the rough-and-tumble play that all mammal juveniles (including humans) engage in (Bekoff & Byers, 1998). On this grade, I understand *your* agency.

Grade 3: Conspecific mindreading

Humans understand how our desires, intentions and beliefs lead to different kinds of actions. For example, when I am thirsty, I go to the refrigerator because I believe I will find something to drink. By watching your actions, I infer your state of mind under the hypothesis that your desires, intentions and beliefs are similar to mine. When I see you take out a bottle of juice from the refrigerator, I infer that you are thirsty. In this case, I do not perceive the cause of your action, but I use my understanding of your inner state as a hidden variable for the cause of your action (see Gärdenfors, 2007). On this evolutionary grade, desires, intentions and beliefs are seen as 'mental forces' causing the action.

One example of detached dual-causal understanding is gaze following, i.e., understanding that if someone is looking firmly in a particular direction, there is something worthy of attention in that direction. In other words, the onlooker infers that there is a cause for the gaze direction, even if the onlooker itself cannot perceive the cause. Conspecific co-orientation through following gaze direction provides adaptive advantages regarding predator awareness, food detection and/or for the monitoring of social interactions (e.g., Schloegl *et al.*, 2007, p.769). Gaze following is a behaviour that develops early during human infancy. At about 10-11 months old, infants become adept at gaze following, and by 12-18 months old, they engage in target sharing and joint visual perception (Metzloff & Brooks 2007).

There is an intensive debate among researchers in animal cognition concerning the extent to which non-human animals can read the minds of conspecifics. Some evidence for gaze following exists for a few bird species, dogs, seals and even goats (e.g., Schloegl *et al.*, 2007; Shepherd, 2010; Teglás *et al.*, 2012). Most nonhuman evidence, however, is generated from work with primates. For example, gaze following has been observed

in great apes such as chimpanzees, gorillas, and bonobos (e.g., Tomasello *et al.*, 2007), as well as in rhesus monkeys (Emery *et al.*, 1997) and lemurs (e.g., Sheperd & Platt, 2008). In gaze following, the gaze direction of the conspecific is seen as a cue to an object or event that is of interest. This can be interpreted as reasoning from the effect – the attention – to the cause – the object or event. When it comes to the capacity to understand the intentions of others, there is very limited research concerning animals (Tomasello *et al.*, 2005; Gärdenfors, 2007). Similarly, the evidence for non-human animals understanding the beliefs of conspecifics is very limited (but see Hare *et al.*, 2000; Tomasello & Call, 2006; Krupenye *et al.*, 2016).

A special case of mindreading is self-awareness, that is, reading the mind of oneself (Gärdenfors, 2003, 2007). Self-awareness involves the ability to imagine myself in the future and in the past, Grade 3 therefore includes early forms of mental time travel (e.g., Suddendorf & Corballis, 2007; Gärdenfors & Osvath, 2010; Osvath, 2015), basic episodic memory (e.g., Tulving, 1972, 1985; Osvath, 2010), basic working memory (e.g., Coolidge & Wynn, 2005), and priority scheduling (planning depth or extended thought-and-action sequences [e.g., Haidle, 2014; Haidle *et al.*, 2015]). Regarding episodic memory, Tulving (1985) argues that this kind of memory is not only directed to the past, but also makes it possible to imagine future situations and recombining elements from memories into new wholes (also see Osvath, 2015).

Grade 4: Detached dyadic-causal understanding

Sometimes we do not perceive another's presence, but only the traces of them. An example is when I come home and find your coat on a chair and infer that you have been in the room recently. The cause is detached from the present situation (Gärdenfors, 1995). I don't see you, but your presence in the past is the most plausible cause for your coat being there. I am familiar with you wearing your coat and have observed you leaving it on the chair repeatedly, so I easily form a 'mental image' of you doing so. I infer your agency,

which lead to the presence of the coat. This grade depends on the capacity to entertain two mental representations at the same time, that is, the current perceptual state of seeing your coat together with my imagination of you being present in the room, i.e., "observed effect, inferred cause, and the relationship between them" (Stuart-Fox, 2014, pp.261-262). In children, this capacity develops between 19 and 22 months (Gelman, 2009) and it shows up clearly in pretence play where the perceived world and the pretended interpretation must be available simultaneously (e.g., Leslie, 1987). Stuart-Fox (2014, p.256) writes that this opens "the way for conscious causal reasoning from observed effect to unobserved cause to develop in children during their third year of life" (see also Gopnik, 2000).

Several experiments and observations indicate that monkeys and apes often do not infer physical causes from their effects (e.g., Povinelli, 2000, but see Mulcahy & Call, 2006), hence they do not reach Grade 4. One example from Cheney & Seyfarth (1990) involves vervets. When these monkeys catch sight of a python or a leopard, they emit warning cries. To test whether they can interpret a 'sign' that there are predators in the vicinity, i.e., reason from the effect of a predator to its cause, Cheney & Seyfarth made a false python track in the sand that was later observed by a group of vervets. The monkeys did not react to the track, even though pythons are highly dangerous to them. A group of vervets was also observed passing a real python track without reacting. Yet, as soon as they came across the snake, panic broke out. Likewise, the monkeys did not react when the scientists suspended an antelope carcass from a tree, despite the fact that this was a clear sign of the presence of a leopard in the vicinity (Cheney & Seyfarth, 1990).

In our analysis, this is the grade where humans seem to be separated from other species. Being able to reason from effects to *non-present* causes seems to be unique to humans. In line with this, Tomasello & Call (1997) suggest that apes are not observation/action causal learners in the sense of Woodward (2011). However, to some extent, apes can reason from traces to

present causes. One example is that some apes have learnt to scribble with pencils and paint with their fingers. They understand the connection between the marks or paint on the paper and their actions (Persson, 2007, Ch. 10). Another example is the chimpanzee Austin who, when seeing his shadow on a wall would move in unusual ways and note the effects on the shadow (Savage-Rumbaugh *et al.*, 1998). These examples suggest that apes are at the brink of Grade 4. It is possible that future evidence about apes in the wild will show that they have achieved this grade.

Grade 5: Causal understanding and mindreading of non-conspicifcs

We sometimes have a dyadic-causal understanding of the actions and intentions of other species, although their motor actions and cognitive processes are different from ours. The most interesting case for the purposes of this paper is human detached causal understanding of non-human animals. For example, when I see an animal track, I can sometimes infer the cause. If I recognise the track as that of a springbok, I can form a mental image of the cause, since I have seen springbok many times. If the track is unfamiliar, however, I cannot conjure a corresponding mental image (cf. the Heffalump of Winnie the Pooh). With increased experience, I may also be able to infer the mental states of the animal, for example, if the tracks go in the direction of the waterhole, I draw the conclusion that the springbok is thirsty. The difference, between Grades 3 and 4 on the one hand, and Grade 5 on the other, is gradual and depends to a large extent on the experience of the behaviour of other species. The actions and mental states of other animals map less directly onto our own, since their bodies and presumably their inner worlds are different, but we can learn the mapping. The mapping is a matter of degree, though – we find it easier to read the causal forces in the mind of a chimpanzee or a dog than that of an iguana.

Grade 6: Inanimate causal understanding

We reach a more advanced grade of causal understanding when we can ascribe causal roles

to inanimate objects. I see an apple falling from the tree and at the same time I feel a gust of wind. I infer that the wind exerted a force on the ripe apple that made it fall off the branch – the cause has not been directly perceived, but is inferred. Unlike the previous cases, there is no animate agent that performs an action. For this grade it can be argued that causation is seen as *force transmission* (Povinelli, 2000; Wolff, 2007; Gärdenfors & Warglien, 2012) as an extension of agency. This could be proposed as a candidate for the new representational system suggested by Povinelli & Bering (2002).

In children one finds extensive forms of animistic reasoning, i.e., inanimate physical forces are ascribed to some hypothetical animate cause. For example, Piaget (1930, p.174) writes that the child “fills the world with spontaneous movements and living ‘forces’; the heavenly bodies may rest or move as they please, clouds make wind by themselves, waves ‘raise’ themselves, trees swing their branches spontaneously to make a breeze”. Inanimate objects are seen as agents, that is, in the terminology of Woodward (2011), children are only agent causal learners, but have not yet become observation/action causal learners. This tendency indicates that inanimate causal understanding takes time to achieve in human development.

From an evolutionary point of view an interesting question is what could represent the driving force behind the human capacity for inanimate causal reasoning. In our opinion, tool use or technology played an important role. Tools extend your peripersonal space – they allow you to act at a distance and to alter the force patterns generated by your body. When you hit a nut with a stone you magnify the forces acting on the nut compared to pounding on the nut with your hand and when you poke with a stick into a hole you extend the poking abilities of your fingers. Such tool use represents basic causal understanding that can be roughly associated with Grades 1 and 2. Even further extension of your peripersonal space is achieved when the tool leaves the direct control of your body and exerts its force at a distance. Throwing a stone may be

the first method of force transmission at a distance. During the evolution of the hominins, not only the shape of the hand but also the shoulder section changed in such a way that made throwing much more effective (Roach *et al.*, 2013). This ability to act with accuracy and speed at a distance was then expanded by technologies that allow a more concentrated form of the hitting force, such as the tip of a spear. Spear throwing can therefore serve as an example of well-developed inanimate causal understanding.

Grade 7: Causal network understanding

We suggest that the most complex grade of causal cognition is the understanding of how domain-specific causal node sets connect or link to inter-domain causal networks (e.g., Tenenbaum & Niyogi, 2003). The most advanced form of this kind of reasoning is science, but some developmental psychologists claim that children learn about the causal connections of the world much as scientists do. This is the so-called theory-theory of child development (e.g., Gopnik *et al.*, 1999).

Returning to our apple example, once it is understood that the wind can cause an apple to fall, causal network understanding will allow me to grasp that the wind can also cause other things to fall or move. I can also understand that counterforces will block causes. Such understanding could help me to find ways to secure objects, preventing them from being blown off, over or away by the wind. An abstract understanding of the fastening skills obtained during the above scenario can now be used in completely different contexts, for example, fixing a knife blade to a handle, or fixing a hide cover to a shelter framework made of branches. Abstractly understanding that 'wind exerts a force that causes movement' and that I can control movement by counterforces, for example through fastening technologies, enables me to transfer such knowledge into innovative solutions across problem domains. For example, my knowledge can be used to make things move, such as fixing a sail to a watercraft, to conceptualise and construct a windmill, or to design and build a helicopter, etc. *ad infinitum*. In addition, my

mindreading abilities will translate at least some of the ideas/actions above into the notion that I could apply the knowledge and/or technologies in a social context, securing reciprocity, status and/or another form of delayed or direct return/advantage for myself and/or my group. During this grade of causal understanding, aspects of all the previous causal understanding grades can be integrated and/or mapped onto each other into never-ending patterns of recursion and complexity.

It should be clear that we do not view causal cognition as independent of other forms of cognition. The first grade only involves perception of agency, but for later grades an increasing array of cognitive processes are involved, such as mind-reading, extended working memory, episodic memory, mental time travel and planning. Especially grades 6 and 7 build on a rich battery of cognitive capacities. Comparing ours with Woodward's (2011) classification; his egocentric learner corresponds to our Grade 1, his agent causal learner corresponds to our grades 2-4, Grade 5 is intermediary and his observation/action causal learner corresponds to our grades 6-7. We submit that our classification provides a more fine-grained understanding of the evolution of causal cognition. In particular, by splitting Woodward's agent causal learners into grades 2-4, we can conclude that non-human animals manage grade 2, do it less well than humans on grade 3 and are very limited when it comes to grade 4. One speculation concerning the difference is that non-human animals understand causation only in terms of agency, while humans can reason about causes also *via* force transmission across space (action at a distance) and time (detached representations).

Tracking behaviour and grades of causal understanding

We sometimes share behaviours, such as tool use or learning by imitation, with nonhuman animals, but responding to our own visual tracks, or to those of other species, seems exclusive to humans. Other terrestrial animals are dependent on scent when following a trail, or follow

sound and sight cues (i.e., reacting to noises or the movement of creatures). It thus appears that the aptitude for tracking, based on inanimate visual cues, developed only in the hominin clade (e.g., Calvin & Bickerton, 2000; Shaw-Williams, 2014; Stuart-Fox, 2014). Hewes (1994) refers to the activity of tracking, which originated from hominins observing the effects of their own hand- or footprints on suitable surfaces, as a uniquely human semiotic process that contributed considerably towards the selective evolution of *Homo sapiens* cognition. Shaw-Williams (2014, p.21) highlights three key differences between trackways and scent trails as cognitive systems, i.e.:

- 1) Tracks are intrinsically directional, with spatiotemporal orientation that reflects the direction of travel of those who left the marks.
- 2) Tracks are more durable than scent trails, which results in the 'scenting mind' being detained in 'here-and-now associative cognition'. The 'tracking mind' on the other hand uses detached representations and "is under selection to read the time stamp on every trackway, and respond appropriately".
- 3) In contrast to scent trails, tracks are combinatorial because they are both directional and durable. Multiple sets of overlaid tracks remain visibly detectible whereas the most recent scent trail tends to render older ones indiscernible. Tracks thus may contain layered sets of information, including past social behaviours. They can, for example, reveal the meeting of conspecifics, the nature of interaction (such as mating or fighting), and whether individuals subsequently travelled together or went their separate ways.

Shaw-Williams emphasises that the information gradient of tracking is open-ended and steep, so that increases in cognitive capacities associated with learning to read trackways would have augmented our social and ecological fitness. Also, because there is no proxy reward (such as a stronger scent as the prey is approached), and the reward is often delayed, "it is very hard for a purely associative mind to even begin to exploit a system

of natural signs with so much durability and information richness" (Shaw-Williams, 2014, p.23).

Liebenberg (1990, Ch. 3 and 2013, Ch. 6) reconstructs how tracking could have evolved through three levels of tracking complexity. He distinguishes between simple, systematic and speculative tracking. Simple tracking comprises following clear, easy-to-follow tracks under ideal tracking conditions. Such conditions would include prints that are not obscured by vegetation or many overlaying prints, left in soft barren substrates or snow. Systematic tracking is considered to be more refined than simple tracking, occurring under circumstances in which the tracks are not obvious or easy to follow. Such conditions require the tracker to recognise and interpret signs, i.e., to infer information about the animal s/he follows. Finally, speculative tracking culminates in the development of a working hypothesis based on the interpretation of the signs left by an animal, knowledge about the behavioural traits of the animal identified through its tracks and of the landscape in which the tracking is taking place. Once a hypothetical reconstruction is generated from the different knowledge sources in the mind of the tracker, s/he can look for traces where they can be expected – no longer bound to following individual signs doggedly (Liebenberg, 1990), i.e., no longer bound to a strictly linear tracking order. Both simple and systematic tracking require inductive-deductive reasoning, but speculative tracking requires much greater skill – it is based on hypothetico-deductive reasoning, which is similar to current-day scientific reasoning (e.g., Liebenberg, 1990, 2008; also see Carruthers, 2002). Below we use tracking behaviour as case study to hypothetically explain the development of the various grades of causal understanding on our evolution.

Grade 1: individual causal understanding and tracking behaviour

In terms of tracking behaviour, individual causal understanding simply requires that an animal or hominin is aware that it sometimes leaves a visible tread print. It needs not understand why

this is so, or that others share a similar awareness. Even though there are many examples that may serve as evidence for individual causal understanding in animals as well as in infants, for example their behaviour in relation to mirrors (Gallup, 1970; Marino *et al.*, 1994; Bard *et al.*, 2006; Prior *et al.*, 2008), we are not aware of any work demonstrating that nonhuman animals are aware of their own tread prints. Grade 1 causal understanding relating to tracking behaviour, represents very basic causal understanding, which was probably in the cognitive range of the last panin-hominin common ancestor. Yet, it seems to have developed only in hominin cognition. Because it is so basic, it is plausible to suggest that it evolved very early within our clade, possibly already during the Messinian, i.e., the final stage of the Miocene (e.g., Stuart-Fox, 2014). In the context of our model, initially becoming aware of tracks/prints might not have had any evolutionary advantage, but could have been a spin-off from general individual causal understanding.

Grade 2: Cued dyadic-causal understanding and tracking behaviour

This grade of causal understanding in tracking behaviour implies that an individual observes and understands that other conspecifics leave tread prints in the same way the observer does. Such causal awareness, in direct relation to the prints of others, has also not been observed in nonhuman animals. Yet, other activities that represent Grade 2 causal understanding have been recorded, for example in rough-and-tumble play in mammals (e.g., Bekoff & Byers, 1998), and in learning by imitation (e.g., Zentall 2004; Whiten *et al.*, 2005, 2009). For the next grades of causal understanding, basic cued dyadic-causal understanding is a requirement. We therefore suggest that this grade of understanding evolved prior to the following grades.

Grade 3: Conspecific mindreading and tracking behaviour

Mindreading can be argued to comprise several components that evolved gradually in animals as well as in hominins (Tomasello, 1999;

Gärdenfors, 2003, 2007), and it is therefore impossible to pinpoint in time when a general capacity emerges. Mindreading per se is not easily connected to tracking competence, but it is only in combination with Grade 4 that we can see the effects of tracking.

Conspecific mindreading allows me to infer the actions and motivations of others in the recent past and the present, without observing them directly. I am able to infer what tracking actions I need to follow, as well as the short-term sequence in which to follow them, with the goal to find social and/or physical reward amongst conspecifics, or avoiding enemies, which would increase my chances of survival. Shaw-Williams (2014) argues that the need to find out what kin were doing, or in which direction they were travelling, and assessing the imagined information against the individual's own needs for rewards such as pair bonding, food or safety, would have been a strong motivation for our hominin ancestors to invest in simple, conspecific tracking behaviour.

Grade 4: Detached dyadic-causal understanding

At this grade of causal understanding, it is understood that an imprint (track) indicates the previous presence of an individual, either the printmaker him-/herself or another conspecific. On a cognitive level, a limited time detachment (perception of the recent past) is introduced together with a mental image of someone being in a certain space, and the notion that conspecifics share a similar understanding. No extant species, other than humans, are known to follow inanimate visual cues such as tracks. For example, even when adult chimpanzees hunt conspecifics in a highly coordinated manner (e.g., Boesch & Boesch-Achermann, 2000), they do not display any awareness of the target individual's tracks (Shaw-Williams, 2014).

The 3.6 million-year-old Laetoli tracks (e.g., Leakey & Harris, 1987), are widely accepted to be that of australopithecines (but see Tuttle *et al.*, 1991). Whereas it is not yet certain whether the australopithecines are ancestral to living humans, work on the recently discovered *H. naledi* from South Africa indicates that it has certain

humanlike characteristics (i.e., stature, hand and wrist as well as foot and lower limb adaptations) and that its unique cranial morphology is most similar to early *Homo* species (Berger *et al.*, 2015). On the other hand, the small endocranial volume and some of the postcranial elements (e.g., trunk, shoulder, pelvis and proximal femur) are australopith-like. These findings led to the hypothesis that the common ancestor of *H. naledi*, *H. erectus*, and *H. sapiens* was intermediary between the australopiths and the *Homo* lineage (Berger *et al.* 2015).

The double trail of larger footprints from Laetoli are often interpreted to have been made by two individuals, one walking in front of the other, with the smaller follower stepping intentionally and exactly into the tracks of the larger one (e.g., White & Suwa, 1987; Agnew & Demas, 1998; Shaw-Williams, 2014). If this interpretation is correct, it represents the earliest known indication of detached dyadic-causal understanding through 'tracking' in the hominin lineage. It is impossible to say whether the follower was in visual proximity of the leader at the time, the most parsimonious inference would be that s/he was. Aiming to tread accurately in the footprint of someone else (whether with the aim to follow or as simple material engagement), however, requires centred attention on the prints left by another, rather than on their maker. A certain level of detachment is thus introduced.

Combining grades 3 and 4 leads to further expansions of tracking abilities. When an individual is able to understand and analyse their own causal motivations, and comprehends that tracks contain information about themselves and/or others, basic levels of inductive-deductive reasoning can be used to assess the information contained within a conspecific trail, and about the most likely consequences of following such a trail. For example, I understand the workings of the minds of others because I am aware of the workings of my own mind, and I can place myself 'on the trail' of another. Thus, when I see conspecific trails leading away from a water source, I might infer that those who made the tracks have quenched their thirst and are now looking for a

safe place to eat or rest. Depending on my own immediate needs, I might choose to go in the opposite direction of the trail to have a drink of water, or to follow the direction of the trail on the general assumption that I might find a group of conspecifics, whom I associate (consciously or subconsciously) with safety and/or food.

Grade 5: Causal understanding and mindreading of non-conspecifics and tracking behaviour

We have described the fifth grade as the causal understanding and mindreading of animals by humans. Placing causal understanding of human behaviour before causal understanding of other animals accords with Shaw-Williams' (2014) Social Trackways Theory. Whereas tracking behaviours up to this point were mainly focused on hominin conspecifics in the context of social manoeuvring, the benefits and dangers of strategic scavenging would have urged them to also apply their tracking skills to other animals. For example, the eminent danger of large predators might have drawn hominin attention to their tracks (Shaw-Williams, 2014). Similar to the understanding of non-kin conspecifics (e.g., Barrett *et al.*, 2010), becoming increasingly aware that other animals can be understood in analogous causal terms, would have been a complex, incremental process. Aspects in the evolution of human mindreading, probably overlapped with animal mindreading by humans through time and across space.

During the 2 million years preceding early evidence for spear hunting by ~500-300 thousand years ago (e.g., Thieme, 2000; Sahle *et al.*, 2013; Wilkins *et al.*, 2012), opportunistic hominin scavenging matured into well-developed strategic scavenging assisted by object throwing (e.g. Lieberman *et al.*, 2009), perhaps even killing naturally trapped or weakened animals through stoning. Such scavenging and/or rudimentary hunting techniques do not necessitate the tracking of animals. It would have benefitted, however, from all the previously mentioned grades of causal understanding including cooperation and competitive strategies through conspecific mindreading and the associated conspecific tracking skills.

On the other hand, the challenges and dangers experienced during such activities would have provided the selective pressures for our ancestors to become proficient in tracking animals. There is also little doubt that the long period between about 2 million years and 500-300 thousand years ago saw hominin meat-getting strategies advance from scavenging (probably including the foraging and killing of easy-to-catch prey such as tortoises and mud-stuck mammals) into hunting with rudimentary spears, which might have included simple tracking strategies.

Grade 6: Inanimate causal understanding and tracking behaviour

Whereas some groups probably already applied aspects of systematic tracking during earlier grades of causal understanding, we suggest that there is good circumstantial evidence for its practice after about 300 ka in combination with increasingly robust evidence for spear hunting (e.g., Sahle *et al.*, 2013). Systematic tracking would involve understanding that the direction in which grass is bent signifies the travel direction of a prey animal. Even in conditions where there are no visible tread prints, skilled systematic trackers are able to follow grass trails at a fast pace (Liebenberg, 1990). Whether in grass- or woodlands, animals often create and use paths when moving from one locality to another. Tread prints in exposed path patches or the paths themselves would have enabled systematic trackers to locate prey animals (Liebenberg, 1990). Thus, during systematic tracking, the emphasis is primarily on gathering empirical evidence in the form of tread prints *and* other inanimate signs, enabling the hunter to reconstruct an animal's activities (Liebenberg, 1990). By the time that *H. sapiens* appeared, at about 200 ka, it is thus possible that some groups were highly skilled systematic trackers, who were able to glean information associated with conspecifics and other animals, not only through their tracks, but also through understanding the related inanimate signs. Multi-stranded evidence for the production and use of hafted technologies during this phase (e.g., Mazza *et al.*, 2006; Rots & Van Peer, 2006; Rots *et al.*, 2011; Rots, 2013),

indicates clearly that early humans developed relatively high levels of inanimate causal understanding before 100 thousand years ago. To which extent such understanding was abstracted is, however, not clear from the archaeological record.

Grade 7: Causal network understanding or causal grammar and tracking behaviour

We suggest that speculative tracking as described by Liebenberg (1990, 2013) shows the ability to draw together domain-specific nodes into inter-domain networks of abstract causal understanding. Intimate knowledge of kin, non-kin and animal behaviour and their inanimate signs, are incorporated with knowledge about the landscape (its geographic features, water sources, vegetation, etc.), abstract causal understanding and the mental maps, thought processes and social contexts of the tracker. Speculative tracking demonstrates how humans create meaningful causal network hypotheses. For example, Liebenberg (1990, Ch. 4) suggests that speculative tracking requires the interpretation of signs in terms of creative/imaginative hypotheses to deal with complex, dynamic variables (Liebenberg, 1990).

For example, current-day Kalahari bow hunters create imaginative reconstructions to interpret the actions and states of the animals they intend hunting. Based on these reconstructions, the hunter creates novel predictions in endlessly unique/changing circumstances. Speculative tracking thus involves a continuous cognitive process of 'conjecture and refutation' to deal with complex, dynamic variables (Liebenberg, 1990). When expectations are confirmed, the hypothetical reconstructions are reinforced, but when expectations prove incorrect, the working hypotheses are revised and alternatives are investigated. With a hypothetical reconstruction of the animal's activities in mind, trackers can plan ahead and look for animals and/or their signs where they expect to find them (Liebenberg, 1990), no longer having to rely only on following visual cues – thus some of the tracking activity now happens abstractly, in the mind of the tracker. This way of thinking (i.e., hypothetico-deductive

thinking in tracking behaviour) is similar to scientific reasoning that is congruent with advanced forms of causal grammar.

The ability to generate inter-domain causal networks, use network understanding to speculate about potential outcomes, test and re-adjust our imaginative hypotheses, and to shift attention from one target to another, while keeping in mind the ultimate goal (e.g., subsistence) over an extended period of time is unique to the human mind of today. Even when Kalahari bow hunters use poisoned arrows, they often track wounded animals through the African bush for several days. Such extended pursuits will inevitably force them to deal with difficult tracking conditions and continuous terrain changes, such as those suggested by Liebenberg (1990), to have stimulated the development of speculative tracking.

Bow hunting is thus far exclusive to *H. sapiens* and could date to between 70 and 65 thousand years ago in southern Africa (e.g., Lombard, 2011; Brown *et al.*, 2012). This technology has been shown to demonstrate complex levels of cognition (e.g., Lombard & Haidle, 2012; Williams *et al.*, 2014; Coolidge *et al.*, 2016), is currently closely linked with speculative tracking (e.g., Liebenberg, 1990), and serves as another perfect example of the human ability for inter-domain causal understanding. In bow hunting, we see how the causal understanding of the advantages of hunting with a sharp projectile is married with the abstract causal understanding that the power of stored mechanical energy can overcome physical challenges, such as the limited reach of a spear, to brace subsistence and/or conflict strategies. What is more, ultimately we understood on abstract levels that the energy of a strung bow can be harnessed to drill holes (bow drills), make fires (fire drills) or to even play music (musical bows used by Kalahari hunters) (see Lombard, 2016). Taken together, this amounts to a causal grammar. As far as we are aware, none of these technologies are unambiguously represented in the archaeological records of anybody but *H. sapiens*. Advanced grades of causal grammar might thus be unique to us, and might have assisted our successful spread across the globe, outsmarting all others.

Concluding discussion

The theoretical framework of this paper is a 7-grade model for the evolution of causal cognition, based on the levels of detachment from egocentric learning or individual understanding. We submit that, compared to Woodward's (2011) classification, ours provides a more fine-grained understanding of the evolution of causal cognition, testable against empirical data from the palaeoanthropological and archaeological records. Similar to Shaw-Williams (2014), our model suggests that early stages of tracking behaviour evolved in the context on conspecific social behaviours. An increasing awareness of the rich body of information that can be gleaned from inanimate traces left by other creatures was then applied to improve chances of survival, for example, to avoid predators or enemies, and was subsequently mapped onto subsistence behaviours such as the scavenging and hunting of animals (also see, e.g., Stuart-Fox, 2014).

Both the social and subsistence scenarios have strong selective advantages that would have encouraged ever increasingly levels of complexity and flexibility in our tracking behaviours and causal understanding. For example, Shaw-Williams (2014) argues that the need to find out what kin are doing or in which direction they are travelling, and assessing the imagined information against the individual's own needs for rewards (such as pair bonding, food or safety) would have been a strong motivation for our hominin ancestors to invest in simple tracking behaviour, providing impetus for the evolution of systematic tracking. Furthermore, Stuart-Fox (2014, p.12) suggests that the evolution of causal cognition, associated with the 'reading' of tracks was likely "a significant driver in the evolution of language", a distinctly human social behaviour (also see Liebenberg 2013, Ch. 9). Barrett and colleagues (2010) also suggest that there is a co-evolutionary relationship between human cooperation and our skills in social causal cognition, including human mindreading (see also Gärdenfors, 2012). They propose, however, that unlike awareness amongst kin, detecting the internal states of non-kin

followed a prolonged and complex evolutionary path, incrementally improving our ability to “react strategically to the social world *via* progressively more fine-tuned capacities to detect and represent its hidden causal structure” (Barrett *et al.*, 2010, p.523).

If we accept that the initial grades of causal understanding in tracking behaviour were triggered socially, population increases and expansions would have shaped the evolutionary trajectory of hominin tracking behaviour. Initially, kin-based tracking would have been adequate for rudimentary social/survival rewards. However, as group and population sizes increased, and as bands of our ancestors started to move into previously unknown terrain, it would have been beneficial to develop strategies to manage cooperation, competition and hostility during intra- and inter-group engagement with non-kin conspecifics. One of these behaviours would have been inductive-deductive reasoning about the tracks and trails of non-kin, either to engage with them cooperatively, to compete with them for resources (such as food, mates or shelter), to avoid engagement which might result in conflict, or to establish territories by engaging in conflict. Regarding subsistence behaviour, Stuart-Fox (2014) suggests that the skill to glean the potentially rich information inherent in indirect natural signs (such as tracks and other associated visual signs) was probably very useful for the location of potential food sources and/or avoiding predators. Meat-hungry hominins would clearly benefit from understanding animal behaviours in a way that would either lead them towards or away from them, depending on perceived context.

By choosing ‘grades’ to discriminate between our categories it is implied that they probably phased into each other throughout our evolution. It is key, however, to recognise that even though the simpler grades of causal understanding support or scaffold the more complex ones, our framework does not necessarily denote a unilinear evolutionary trajectory (e.g., Haidle *et al.*, 2015; Lombard, 2016). Within each grade of causal understanding there might be several levels of complexity that developed at different times in different places and

or hominin populations. For example, basic, conspecific mindreading skills (Grade 3 above) might have been acquired early on in our evolution. However, enhanced levels of human mindreading, or theory of mind, that enable us to cope with the complexities of our current societies, might only have evolved at a much later stage, i.e., after we were able to understand and interpret the behaviours of non-conspecifics (Tomasello *et al.*, 2005; Gärdenfors, 2007). Thus, a newly identified grade of causal understanding does not automatically imply that all or some aspects of the previously identified grade stopped its evolutionary trajectory.

In summary, our suggested model progresses from an egocentric understanding of inanimate visual cues to an understanding that others leave similar signs, and that those signs obtain a wealth of information in the context of managing associations with conspecific kin and non-kin. Later, we came to understand that we could use the inanimate visual signs left by animals to avoid predators and to enhance our subsistence niche until we became the ultimate trackers and hunters, drawing on inter-domain causal networks to outsmart all other species. Tenenbaum & Niyogi (2003, p.1152) write: “A causal grammar defines a system for generating causal networks, by first choosing a subset of nodes in each class and then inserting links between those nodes in conformance with the link rules”. Causal grammar generates an infinite set of integrated networks for understanding, hypothesising and imagining. Grade 7 causal understanding therefore provides the principles that allow humans to create meaningful causal network hypotheses, which facilitate learning and reasoning about novel causal systems in a very effective manner (Tenenbaum & Niyogi, 2003). It enables the uniquely modern human trait of boundless behavioural and cognitive flexibility as expressed in current technological and scientific innovations.

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