Thinking a Bow-and-arrow Set: Cognitive Implications of Middle Stone Age Bow and Stone-tipped Arrow Technology

Marlize Lombard & Miriam Noël Haidle

For various reasons increased effort has recently been made to detect the early use of mechanically-projected weaponry in the archaeological record, but little effort has yet been made to investigate explicitly what these tool sets could indicate about human cognitive evolution. Based on recent evidence for the use of bow-and-arrow technology during the Middle Stone Age in southern Africa by 64 kya, we use the method of generating and analysing cognigrams and effective chains to explore thought-and-action sequences associated with this technology. We show that, when isolated, neither the production of a simple bow, nor that of a stone-tipped arrow, can be reasonably interpreted to indicate tool behaviour that is cognitively more complex than the composite artefacts produced by Neanderthals or archaic modern Homo. *On the other hand, as soon as a bow-and-arrow set is used as an effective group of tools, a novel cognitive development is expressed in technological symbiosis, i.e. the ability to conceptualize a set of separate, yet inter-dependent tools. Such complementary tool sets are able to unleash new properties of a tool, inconceivable without the active, simultaneous manipulation of another tool. Consequently, flexibility regarding decision-making and taking action is amplified. The archaeological evidence for such amplified conceptual and technological modularization implies a range of cognitive and behavioural complexity and flexibility that is basic to human behaviour today.*

There is an intensified effort to detect the early use of bows and/or spearthrowers in the archaeological record of sub-Saharan Africa (Backwell *et al*. 2008; Lombard 2008; 2011; Lombard & Pargeter 2008; Shea 2006; Sisk & Shea 2009; Wadley & Mohapi 2008), where humans evolved into anatomical, behavioural and cognitive modernity. This trend hinges on research agendas that aim to trace back in time complex technologies and behaviours (Brooks *et al*. 2006; Lombard & Parsons 2011; Lombard & Phillipson 2010; Wadley *et al*. 2009), or highlight differences and/or similarities between Neanderthals and early anatomically modern humans (Shea & Sisk 2010; Villa & Soriano 2010). Despite this emphasis, little or no attempt has been made to explain the potential cognitive implications of mechanically-projected weaponry. This article is a step towards such discussion.

Our aim here is to explore the thinking processes involved in the production and use of bows and arrows, and to investigate potential cognitive differences between bow-and-arrow technology (there is presently no reliable evidence for the use of spearthrowers in sub-Saharan Africa), and hand-delivered spear technology. It is therefore necessary to clarify our choice of terminology. Many archaeologists outside the debate indiscriminately use the term ‘projectile points’ for most pointed stone artefacts, regardless of ultimate use or mode of delivery. Some use ‘projectile’ for weapons either thrown by hand or launched with devices (Knecht 1997), whereas others prefer to use the term exclusively for weapons launched with intermediate tools such as bows or spearthrowers (Brooks *et al*. 2006; Lombard & Phillipson 2010). As research focus changes it is increasingly

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important to be clear about the chosen terms and their potential inferences. Here we use:

a) *Mechanically-projected weaponry* to refer to weapons launched with an intermediary technology such as a bow or a spearthrower, using exosomatically-stored energy to propel the weapon (Lombard & Phillipson 2010); but, whereas bows launch *arrows*, spearthrowers would launch *darts*. The term 'mechanically-projected' is equivalent to Shea and Sisk's (2010) 'complex projectile technology'. Yet, it excludes ambiguity regarding what is perceived as 'complex', especially considering the intricate processes involved in manufacturing stone-tipped thrusting or throwing spears with variable hafting arrangements and/or compound adhesive recipes (Ambrose 2010; Haidle 2010; Lombard 2008; 2009; Wadley 2010).

b) *Hand-delivered weaponry*, for weapons thrust or thrown without the aid of intermediate technology.

The invention of bow-and-arrow technology used to be closely linked to the Late Upper Palaeolithic in Europe (Cattelain 1997), and was thought to be a recent invention in Eurasia and the Americas (Shea 2009). Since sub-Saharan Africa became a focus region for studying various aspects of the evolution of *Homo sapiens*, its archaeological record has been vigorously debated. Opinions regarding the inception of mechanically-projected weaponry also vary considerably. Some maintain that the bone points and hafted microliths of the early Later Stone Age at Border Cave, South Africa, *c.* 40–35 kya, suggest the advent of bow-and-arrow technology (Villa *et al*. 2010), others claim that dart-and-spearthrower technology could have existed by *c.* 100 kya elsewhere in the region (Brooks *et al*. 2006). As research resolution and methods are refined, some researchers are shifting their predictions for the early appearance of mechanically-projected weaponry. For example, Shea (2006) initially did not find support for the widespread use of mechanically-projected weaponry before *c.* 50 kya, but more recently suggested that bow-and-arrow technology developed in sub-Saharan Africa between *c.* 100–50 kya (Shea 2009; Shea & Sisk 2010).

Providing unambiguous evidence for the use of mechanically-projected weapon systems remains challenging (Lombard & Phillipson 2010). There are several ways to explore potential or hypothetical use (Brooks *et al*. 2006; Sisk & Shea 2009; Wadley & Mohapi 2008), but few that can be considered dependable records of application and mode of delivery (Hutchings 2011; Lombard & Phillipson 2010). Recently, Lombard has provided multi-stranded, direct and circumstantial evidence that indicates the use of stone-tipped arrows and, by implication, bows at Sibudu Cave in KwaZulu-Natal, South Africa, between 61 kya and 64 kya, during the Howiesons Poort phase (Lombard 2011; Lombard & Phillipson 2010). The results support previous suggestions that a bone point from the same context at Sibudu signifies bow-and-arrow hunting at the time (Backwell *et al*. 2008; Bradfield & Lombard 2011). Although we do not claim that the small quartz segments from Sibudu denote the oldest use of stone-tipped arrows, we are confident that they currently embody the most direct and convincing evidence for mechanically-projected weaponry during the Middle Stone Age. If we, and others (Backwell *et al*. 2008; Shea & Sisk 2010; Wadley & Mohapi 2008), are correct in our assessment that bow-and-arrow technology emerged in sub-Saharan Africa during the Middle Stone Age it may have significance regarding studies that aim to trace human cognitive and behavioural evolution over time and space.

Bow-and-arrow technology and human evolution

Using ancient stone-tool technology to gauge levels of cognitive or behavioural complexity is not straightforward (e.g. Coolidge & Wynn 2009). Yet, Ambrose (2010) argues that composite tool manufacture — involving the hafting of knapped stone tools in handles of wood or bone with gums, cords and sinews — marks a considerable increase in technological complexity compared with single-component tools. It places greater demands on integrating working memory with prospective memory, and ultimately constructive memory. These faculties are associated with the anterior frontal lobe and Broca's area that also facilitate processes involved with grammatical language and manual hierarchical assembly (Ambrose 2010). Barham (2010) also puts forward that hierarchical thought is integral to composite tool technology, language and imagination. In addition, he emphasizes the broader argument that technology is deeply embedded in human social life (Barham 2010). These insights suggest that, depending on approach and context, the stone-tool archaeological record can provide a means of assessing and/or reassessing hypotheses regarding some aspects of human cognitive evolution.

Composite tool manufacture seems to appear at the transition from the Acheulean to the Middle Palaeolithic and Middle Stone Age (Ambrose 2010). In sub-Saharan Africa the Sangoan industrial complex spans the transition from Acheulean to the Middle Stone Age by *c.* 300 kya (McBrearty & Tryon 2005), and microwear evidence from the Sangoan core axe quarry on Sai Island, Sudan, indicates that some stone artefacts were hafted (Rots & Van Peer 2006). Of approximately the same age are the four wooden, split-base tools from Schöningen 12. These, probably dating to marine isotope stage (MIS) 9 at *c.* 334–301 kya (Urban *et al.* 2011), are interpreted as clamp shafts (Thieme 1997; 1999). Assemblages from the Mousterian site of Campitello, Italy, associated with Neanderthals, contain evidence of pitch production for hafting dating to MIS-6, *c.* 195–130 kya (Mazza *et al*. 2006). Finds such as these imply that the cognitive ability and complex planning associated with the manufacture of composite tools are not exclusive to *Homo sapiens*. We suggest, however, that bow-and-arrow technology — where one composite tool is employed to effectively use another composite tool — may represent a further major increase in technological complexity compared with hand-delivered weaponry. Hence, finding ways to test this hypothesis can be beneficial for the study of human cognitive evolution.

Thus far, regardless of disagreement on the place and timing of the origins of bow-and-arrow technology, there seems to be consensus that it was used exclusively by *Homo sapiens* (Shea & Sisk 2010; Villa & Soriano 2010). Shea and Sisk (2010) argue that mechanically-projected weaponry was a key strategic innovation, driving Late Pleistocene human dispersal into western Eurasia after *c.* 50 kya. They see mechanically-projected weaponry as an ecological niche-broadening strategy, and argue that such weapon systems, similar to those used by ethnographic hunter-gatherers, enabled *Homo sapiens* to overcome obstacles that constrained previous human dispersal from Africa to temperate western Eurasia. Rather than suggesting variability in cognitive complexity as an explanation for the lack of mechanically-projected weaponry associated with Neanderthal subsistence behaviour, they suggest it may reflect energetic constraints and time-budgeting factors associated with complex technologies. We do not want to imply that Neanderthals and/or ‘pre-modern’ humans lacked the cognitive ability to manufacture mechanically-projected weaponry — evidence to the contrary may still be discovered. Yet, we propose that the potential of such technical systems to inform on cognitive evolution should be thoroughly explored, before rejecting it out-of-hand.

Cognigrams and effective chains as investigative method

Haidle recently developed a means to analyse and code tool behaviour in cognitive terms (Haidle 2009; 2010; 2012). The conceptual basis of this technique is the problem-solution distance approach introduced by Köhler (1925), who recognized tool behaviour as an extension of the process of indirect thinking. If tool use is considered to solve a problem, then the main focus, i.e. the immediate desire — getting the kernel of a nut, for example — must be set aside, or inhibited, and replaced by other foci, i.e. one or several intermediate objectives, such as finding or producing an appropriate tool. Thus, at least in the short term, thinking must depart from the immediate problem and shift to abstract conceptualizations of potential solutions. This process results in sequences of physical actions with objects appropriate to achieve a solution in the near future. In different object behaviours the distance between the initial problem and the final solution can vary markedly by the number of actions necessary to reach an aim, by the number and type of involved foci of attention, and by the number and type of effects that those foci can have on each other. The problem-solution distance is not a summary measure which can be expressed in one number: the differences of the problem-solution distance of two behaviours have to be described in detail regarding all elements (number of actions, number and type of foci, number and type of effects). Although structured in a specific way, the description of the problem-solution distance is an open system. For example, in the following description of the problem-solution distance of bow-and-arrow production and use, a type of effect (complementation/symbiosis) will be introduced which has not been necessary to describe tool behaviour studied so far (Haidle 2009; 2010; 2012).

To identify and visualize the differences in the problem-solution distance of distinct behaviours an extension of the *chaînes opératoires* (e.g. Boëda *et al.* 1990; Schlanger 1996; Sellet 1993) method is used. In the resulting cognigrams not only are actions and phases of actions systematically coded as in the *chaînes opératoires*, but also the different involved agents and objects (the foci), the underlying perceptions of need, as well as the effects which the foci have on each other (Figs. 3–9). To give an overview of complex behavioural patterns the foci and the effects are summarized in effective chains (Figs. 10–12). This approach describes properties of behaviours on the basis of archaeological finds. Considering uniformitarianism and mandatory necessities, it is possible to infer past behaviour from archaeologically recorded and analysed technologies, from modern analogies, and from replication experiments. Cognigrams allow the comparison of all kinds of animal (including hominin) tool-use behaviour. Importantly, the approach does not discriminate against other species’ behaviour and cognitive capacity by evaluating them from a ‘modern’ human perspective, but describes similarities and differences in an unbiased way (Haidle 2009; 2012). Thus, it opens the broadest possible material data base for the comparative study of cognitive and behavioural evolution; yet it does not attempt to provide a link to any theory about the structure of mind or neurological structure.

The method for coding tool behaviour using cognigrams, how to read them, and its application is fully described and illustrated elsewhere (Haidle 2009; 2010; 2012). In short it comprises five steps (Fig. 1):

1. Identification of the foci of attention of the individual in the specific action series. Here it is important to distinguish between active agents (A-focus) or passive elements (P-focus). An A-focus is either acting like the subject itself, or it is acting as an extension of the subject like a tool. A P-focus is a passive element, not actively controlled, but taken into consideration and acted upon like an object or a location. To distinguish between tools (A-foci) and objects (P-foci) the definition of tool behaviour made by Benjamin Beck (1980, 10) is used:

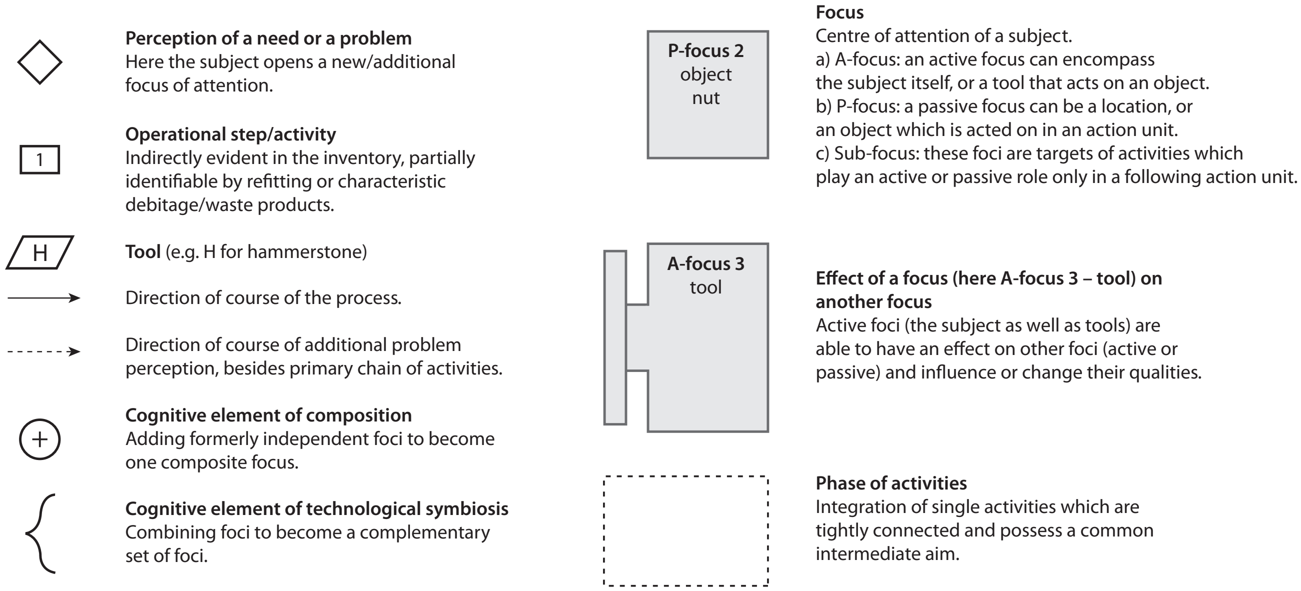
   > Thus tool use is the external employment of an unattached environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself when the user holds or carries the tool during or just prior to use and is responsible for the proper and effective orientation of the tool.

   For a more extended discussion of the differentiation between tools, proto-tools, and other objects see Haidle (2012).
2. Identification of the probable perceptions of needs and problems that initiate the different foci and start the actions.
3. Identification of the smallest action units, i.e. the single action steps that must be taken to solve the different sub-problems and satisfy the basic need.
4. Identification of actively controlled effects of one focus on the elements of another focus.
5. Structuring the thought-and-action processes by identifying the sequences of tightly linked actions that constitute their phases.

In comparing different tool behaviours, it is essential to consider a comparable section of the continuous behaviour of a subject. At best, this is the complete distance between an underlying problem and its final solution: a problem-solution process should always start with a basic need and end in positive or negative satisfaction of the need (Haidle 2009; 2012). This is a rather simple task in the examination of animal tool behaviour with a limited number of elements involved and only limited complexity. In hominin tool behaviour with numerous different subunits or modules, however, it can be difficult to place the boundaries of a problem-solution process. If it is not possible to identify the basic need to the final satisfaction, or if it is not desirable to describe the whole behavioural unit, it is mandatory to choose comparable sections with similar starting and end points. Therefore, comparing nut-cracking in chimpanzees (feeding behaviour with incorporated tool use) with the manufacture of Oldowan tools (tool-production behaviour) (e.g. Joulian 1996), is comparing apples with pears. For a valid comparison the production of Oldowan tools has to be embedded into the feeding behaviour with the use of the tools. The manufacture and use of a simple wooden spear, a spear with a stone tip, and a bow-and-arrow set can be compared without considering the way the prey is processed to become a convenient meal. The mere technical parts of manufacture and use of the weapons can be extracted from the broader behavioural environment as long as similar sections are compared.

The coding of behavioural units in cognigrams yields information about the level of cognitive complexity and cognitive flexibility within and between species. Comparative analyses of animal tool behaviour and Lower Palaeolithic stone and organic tools show a wide range of problem-solution distances (Haidle 2010; 2012). However, the studies also indicate that problem solving in animals is restricted to problem complexes for which a solution can be found in the spatial and temporal vicinity. In human evolution, the complexity of tool behaviour increases regarding the number of active foci managed at a time in an action sequence, the number and diversity of operational steps in a problem-solution complex, and the spatial and temporal frame in which solutions are sought. These results suggest a gradual development of the different aspects of complex cognitive capacity instead of a late introduction of a closed phenomenon with different facets (Haidle 2010; 2012).

A marked difference between animal tool behaviour observed so far and hominin tool behaviour, is the application of a tool to produce a tool to reach an aim. Even in sophisticated tool sets with several active and passive foci (e.g. Boesch *et al*. 2009; Sanz *et al*. 2009), animals apply their tools — be it several — only to the target object. The effective chain is limited to the production and use of one tool, although several of them are used in sequence. In hominin tool behaviour a stone nodule, for example, is a first target on which a hammer-stone (tool 1) is applied, and the resulting flake tool (tool 2) is then applied to the prey as the main target. Even the simplest stone-tool production is based on such an extension of the operational sequence, and the possible extension grows in the course of human evolution. The operational sequence of a single-component wooden spear from Schöningen, Germany, for example, comprises an effective chain



Perception of a need or a problem
Here the subject opens a new/additional focus of attention.

Operational step/activity
Indirectly evident in the inventory, partially identifiable by refitting or characteristic debitage/waste products.

Tool (e.g. H for hammerstone)

Direction of course of the process.

Direction of course of additional problem perception, besides primary chain of activities.

Cognitive element of composition
Adding formerly independent foci to become one composite focus.

Cognitive element of technological symbiosis
Combining foci to become a complementary set of foci.

Focus
Centre of attention of a subject.
a) A-focus: an active focus can encompass the subject itself, or a tool that acts on an object.
b) P-focus: a passive focus can be a location, or an object which is acted on in an action unit.
c) Sub-focus: these foci are targets of activities which play an active or passive role only in a following action unit.

Effect of a focus (here A-focus 3 – tool) on another focus
Active foci (the subject as well as tools) are able to have an effect on other foci (active or passive) and influence or change their qualities.

Phase of activities
Integration of single activities which are tightly connected and possess a common intermediate aim.

Figure 1. *Explanation of graphic elements used in cognigrams.*

of three to five tools needed to produce the weapon and use it to kill prey. The operational sequence of the Schöningen spears is extended in both duration and complexity. In comparing cognigrams of the most sophisticated Lower Palaeolithic stone tools with those of simple wooden spears, a considerable increase is thus detected in the problem-solution distance (Haidle 2009).

The high level of complexity in hominin tool behaviour is possible only by an increased decoupling of satisfaction and basic need in a way that the manufacture and curation of tools can become aims and satisfactions in and of themselves, independent of immediate basic needs. The resulting small operational units (search for, production of, maintenance of material or a tool) are each autonomous with its own intermediate aim (availability of material or a tool to be used in other units). The operational units or modules can be assembled within different operational sequences. A modular way of handling tools and solving problems enables the unlimited combination of operational units side-by-side or in an effective chain without thinking through the whole process of a complex task, such as hunting prey with a wooden spear from the original desire to eat meat to the final satisfaction in all details of raw-material acquisition and tool manufacture. It allows a level of behavioural complexity — for example, in the manufacture and use of composite tools, such as stone-tipped weapons — barely conceivable without modular simplification (Haidle 2010). The modularity described here refers only to modular behaviour in conceptualization, perceptions, planning and resulting actions. It is not connected to the concept of a modular structure of the mind (e.g. Gardner 1985; Mithen 1996).

The cognitive evolution towards a full modular organization of object behaviour proceeded gradually. Several animal species and archaeological artefacts show extensions of different aspects in object behaviour. Such expansions include problem-solution distance concerning, for example:

- the modification of the objects used;
- the number of attention foci;
- the management of parallel needs;
- the subsequent use of different tools on one target object;
- the anticipation of the necessity of several tools;
- the number of elements in an effective chain;
- the simultaneous handling of two objects;
- the perception and pursuit of sub-acute needs, and even;
- the bridging of interruptions to the operational process by competing problems.

These extensions offer an increase in flexibility in different solutions to one problem, in the diverse needs met with one solution, in the exact application of specific action steps/phases, and in the entire course of the operational sequence. The latter includes concepts in which problems are perceived, the combination of separate tools into one process, the combination of raw materials, manufacturing techniques, tool types and tool use. The more tools and their manufacture can be dissociated from immediate subsistence aims, the more problems become soluble. The ways in which modular organization of thought-and-action processes — and the potential flexibility and decoupling of subsistence constraints, problems, and solutions — are expressed in the material culture of a modern human population depend very much on cultural tradition and social factors (Haidle 2010; see also Lombard & Parsons 2011).

Cognigrams of bow-and-arrow manufacture and use

If we accept that a high level of complexity in tool behaviour is possible only by conceptual and technological modularization — where each module has its own intermediate aim — we have to present the modules in separate cognigrams in order to assess their individual complexity. Not doing so will result in skewed levels of complexity; as in reality, all modules are probably seldom or never thought through in terms of a single process. It also avoids repetition of some modules within a thought-and-action sequence, for example, fire-making, which may be required several times during the manufacture and use-life of a bow-and-arrow set. The coding of processes is not based on exact and fully detailed *chaînes opératoires*, but on reconstructions of the processes including the necessary foci/elements and the main action steps and phases. Our cognigrams are therefore parsimonious. They code thought-and-action processes of tool production and use, based on a summary of evidence gathered from archaeological remains, replication experiments and ethnographic analogies. This evidence is completed by realistic assumptions about phases of raw material procurement, transport of different elements, and repeated interruptions of the process by other urgent needs. Minor variability in the sequence of actions is included. We emphasize that cognigrams of past technologies can only be hypothetical. If not specifically noted, cognigrams represent the preferably simplest way of coding a thought-and-action process.

For the simple bow and stone-tipped arrow described here, we used the lines of evidence and data from sources presented below, but draw attention to the fact that other variants of the thought-and-action sequences are possible. Thus, the cognigrams do not represent the ultimate production sequence of bow-and-arrow technology, because this does not exist. They embody one reconstructed variant of a simple Bushman bow and unfletched stone-tipped arrow with fore-shaft and main shaft (Fig. 2). We based this reconstruction on ethnographic observations of Bushman bow-and-arrow manufacture, archaeological and use-trace evidence, and archaeological replication and experimentation.

Data sources used for the hypothetical reconstruction of a bow-and-arrow set

The list below summarizes the data used to code the production and use of a bow-and-arrow set in cognigrams and an effective chain. The specific references for the relevance and details of each operational unit/module are given in the descriptions of the single cognigrams.

1. Micro-residue evidence of meat-procurement strategies on stone tools: Howiesons Poort Industry, *c.* 64–61 kya, Sibudu Cave, South Africa (Lombard 2008; 2011).
2. Micro-residue evidence of ochre-loaded compound adhesives on stone tools: Howiesons Poort Industry, *c.* 64–59 kya, Sibudu Cave, Umhlatuzana Rockshelter, Rose Cottage Cave, South Africa (Gibson *et al*. 2004; Lombard 2006a; 2007a).
3. Macrofracture evidence of impact/weapon use: Howiesons Poort Industry, *c.* 64–59 kya, Sibudu Cave, Klasies River Cave 2 and Umhlatuzana Rockshelter, South Africa (Lombard 2007b; 2011; Wurz & Lombard 2007).
4. Multi-stranded use-trace evidence of transverse hafting as arrowhead: Howiesons Poort Industry, *c.* 64–61 kya, Sibudu Cave, South Africa (Lombard & Phillipson 2010; Lombard 2011).
5. Morphometric results that indicate the hypothetical presence of arrowheads: Howiesons Poort Industry, *c.* 64–61 kya, Sibudu Cave, South Africa (Wadley & Mohapi 2008).
6. Circumstantial evidence for the use of bow-and-arrow technology: Howiesons Poort, *c.* 64 kya, Sibudu Cave, South Africa (Lombard & Phillipson 2010).
7. Experimental observations and results regarding backed stone tools hafted as arrowheads (Pargeter 2007; Lombard & Pargeter 2008; Yaroshevich *et al*. 2010).
8. Analysis of an archaeological, transversely hafted arrowhead; Later Stone Age, *c.* 2 kya, Adamskranz South Africa (Binneman 1994; Lombard & Parsons 2008) (Fig. 2b).
9. Detailed descriptions of Bushman bows and arrows curated in the Iziko, Albany and Natal museums, South Africa (Schapera 1927; Vinnicombe 1971) (Fig. 2a).
10. Meticulous ethnographic observations regarding Bushman bows and arrows, southern Africa (Theal 1922; Maingard 1936; Goodwin 1945; Dornan 1975; Valiente-Noailles 1993).

Basic tools (Fig. 3a–g)

As a result of the modularization of the production processes, the thought-and-action process of bow-and-arrow manufacture must not be seen as a whole.

Instead, it can be dissected into small units consisting of the production of basic tools, the production of unspecific semi-finished products, and process units specific to bow or arrow production. Basic tools are implemented as active foci (A-foci) at several points during the process of manufacturing a bow-and-arrow set. Their use is neither bound to the production of a single bow or arrow, nor to the manufacture of bow-and-arrow technology as such. Rather, these tools can be used and reused for a variety of tasks as part of a generally available tool kit. Basic tools involved in bow-and-arrow production would include hammer-stones, grinding-stones and stirring tools, and their acquisition, as well as flake tools, heavy-duty tools, smoothing tools, straightening tools and fire, and their respective production processes. Cognigrams of the basic tools represent behaviour relating to tools in their simplest form, i.e. with minimal retouch and no hafting (Fig. 3a–g). They show rather simple thought-and-action processes with one to two active foci in a maximum bipartite effective chain. At its most complex, seven operational steps are represented in five phases. Phase activities are narrowly linked, but the tools can be curated and used repetitively for a variety of tasks. Acquiring or producing each of these basic tools is therefore cognitively no more taxing than the production of an Oldowan tool. Exceptions to the simplicity of basic tools, however, are represented in the case of water acquisition and the production of fire.

Basic tool: water (Fig. 4a–c)

Water may be needed several times throughout the production of a bow-and-arrow set. For example, it may be used to moisten binding materials and/or bow strings, and in the process of straightening the bow stave. There are two possible ways of acquiring water:

a) by placing all activities for which water is needed near the water source, so that the only action in this process unit is finding a place to access water (Fig. 4a); or
b) by taking up a small amount of water in a prepared container that can be transported to where the water is needed (Fig. 4b).

Whereas the first way of acquiring water is cognitively rather simple, its use is limited by constraints of the organization of other process units at the location of the water source. The second way of water acquisition is independent from these limitations, but is cognitively more demanding as it requires a container as tool for water storage and transport (Fig. 4c). The acquisition of water using a container is a combination of two short process units with five operational steps in three to four phases. Each process unit comprises two active foci in a bipartite effective chain.

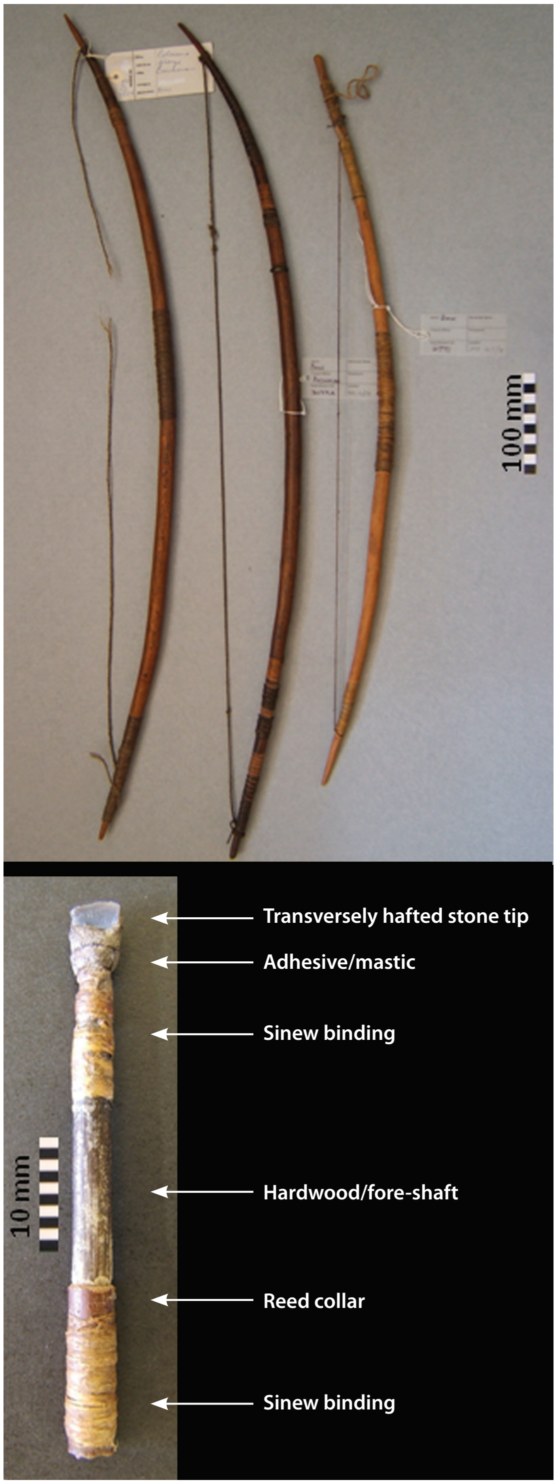
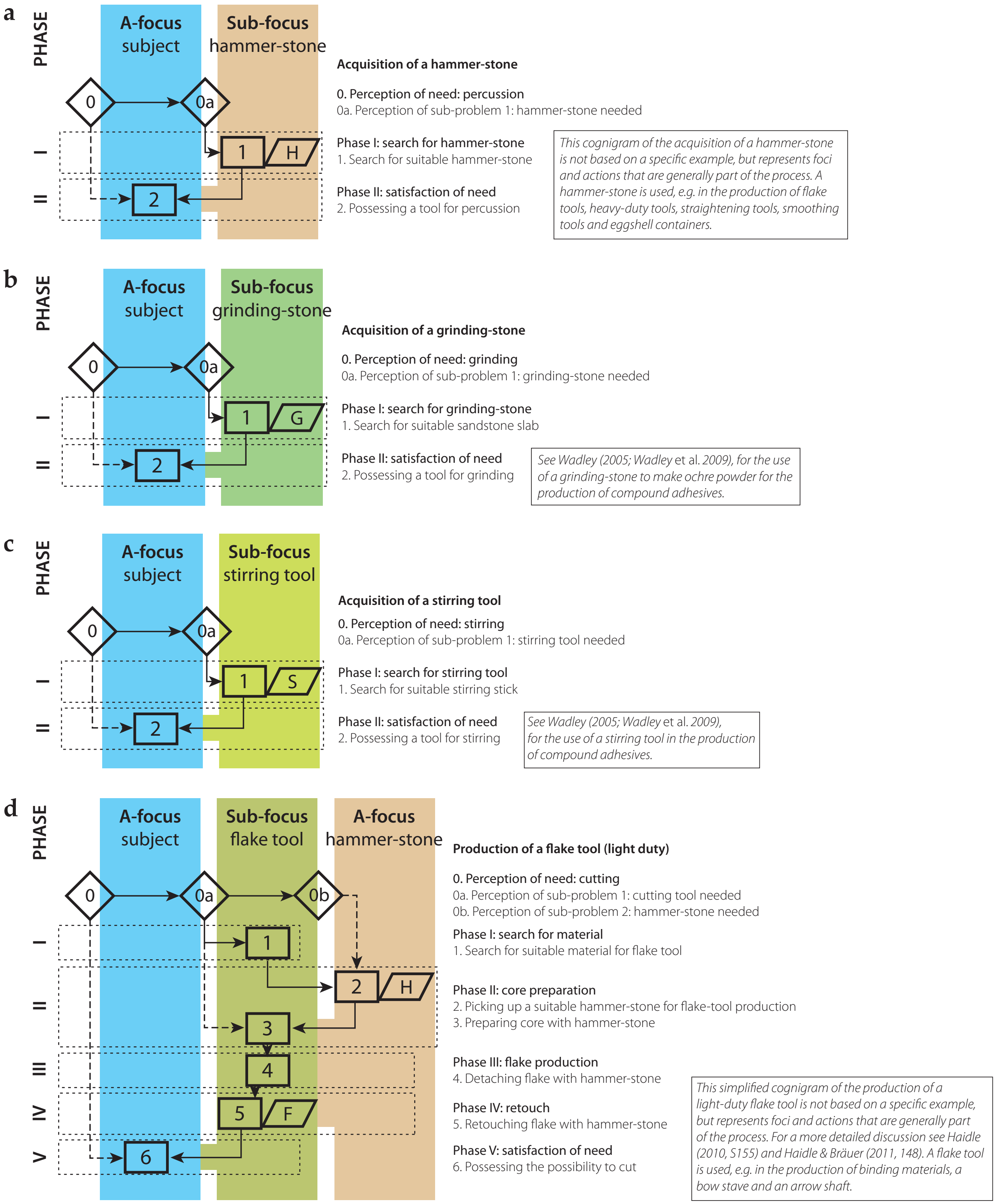


Figure 2. *a) Three examples of ethnographical/historical Bushman bows from Botswana housed at the Natal Museum, South Africa. b) Archaeological arrow with transversely hafted stone tip, excavated by Johan Binneman at Adamskranz, South Africa, from a layer with a radiocarbon date of 1760±50 BP (Pta-6418) (see Binneman 1994).*



Acquisition of a hammer-stone

0. Perception of need: percussion
0a. Perception of sub-problem 1: hammer-stone needed

Phase I: search for hammer-stone
1. Search for suitable hammer-stone

Phase II: satisfaction of need
2. Possessing a tool for percussion

This cognigram of the acquisition of a hammer-stone is not based on a specific example, but represents foci and actions that are generally part of the process. A hammer-stone is used, e.g. in the production of flake tools, heavy-duty tools, straightening tools, smoothing tools and eggshell containers.

Acquisition of a grinding-stone

0. Perception of need: grinding
0a. Perception of sub-problem 1: grinding-stone needed

Phase I: search for grinding-stone
1. Search for suitable sandstone slab

Phase II: satisfaction of need
2. Possessing a tool for grinding

See Wadley (2005; Wadley et al. *2009), for the use of a grinding-stone to make ochre powder for the production of compound adhesives.*

Acquisition of a stirring tool

0. Perception of need: stirring
0a. Perception of sub-problem 1: stirring tool needed

Phase I: search for stirring tool
1. Search for suitable stirring stick

Phase II: satisfaction of need
2. Possessing a tool for stirring

See Wadley (2005; Wadley et al. *2009), for the use of a stirring tool in the production of compound adhesives.*

Production of a flake tool (light duty)

0. Perception of need: cutting
0a. Perception of sub-problem 1: cutting tool needed
0b. Perception of sub-problem 2: hammer-stone needed

Phase I: search for material
1. Search for suitable material for flake tool

Phase II: core preparation
2. Picking up a suitable hammer-stone for flake-tool production
3. Preparing core with hammer-stone

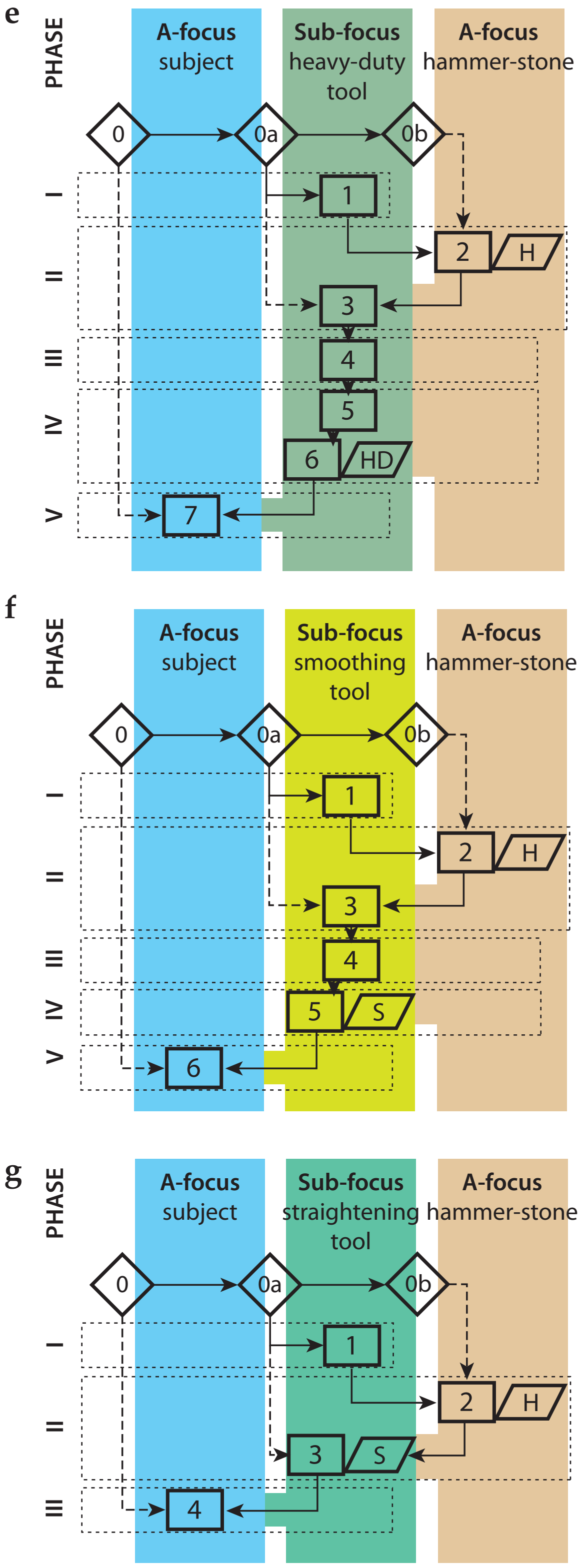
Phase III: flake production
4. Detaching flake with hammer-stone

Phase IV: retouch
5. Retouching flake with hammer-stone

Phase V: satisfaction of need
6. Possessing the possibility to cut

This simplified cognigram of the production of a light-duty flake tool is not based on a specific example, but represents foci and actions that are generally part of the process. For a more detailed discussion see Haidle (2010, S155) and Haidle & Bräuer (2011, 148). A flake tool is used, e.g. in the production of binding materials, a bow stave and an arrow shaft.

Figure 3. *Cognigrams for the acquisition and production of some basic tool types.*



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Production of a heavy-duty tool

0. Perception of need: heavy-duty cutting
0a. Perception of sub-problem 1: cutting tool needed
0b. Perception of sub-problem 2: hammer-stone needed

Phase I: search for raw material
1. Search for suitable raw material for heavy-duty tool

Phase II: core preparation
2. Picking up a suitable hammer-stone for production of heavy-duty tool
3. Preparing core with hammer-stone

Phase III: blank production
4. Detaching large flake with hammer-stone

Phase IV: retouch
5. Retouching blank with hammer-stone roughly
6. Retouching roughout with hammer-stone

Phase V: satisfaction of need
7. Possessing the possibility to cut down branches

The cognigram of the production of a heavy-duty tool is not based on a specific example, but represents foci and actions that are generally part of the process. This simplified version closely follows the production process of a light-duty flake tool. A heavy-duty tool is used, e.g. in the production of a bow stave (Dornan 1975, 94–5).

f

Production of a smoothing tool (scraper)

0. Perception of need: smoothing wooden artefacts
0a. Perception of sub-problem 1: smoothing tool needed
0b. Perception of sub-problem 2: hammer-stone needed

Phase I: search for material
1. Search for suitable material for smoothing tool

Phase II: core preparation
2. Picking up a suitable hammer-stone for production of smoothing tool
3. Preparing core with hammer-stone

Phase III: blank production
4. Detaching flake with hammer-stone

Phase IV: retouch
5. Retouching blank with hammer-stone

Phase V: satisfaction of need
6. Possessing the possibility to smooth wooden artefacts

See Dornan (1975, 95), for type and use of tool to smooth bow stave. Alternatives: grooved pebble instead of scraper (Dornan 1975, 95).

g

Production of a straightening tool

0. Perception of need: straightening arrow shafts
0a. Perception of sub-problem 1: straightening tool needed
0b. Perception of sub-problem 2: hammer-stone needed

Phase I: search for material
1. Search for suitable material for straightening tool

Phase II: production of straightening tool
2. Picking up a suitable hammer-stone for production of straightening tool
3. Picking shallow groove into blank

Phase III: satisfaction of need
4. Possessing the possibility to straighten arrow shafts

See Maingard (1936, 278), for type, production, and use of tool to straighten arrow shaft.

Figure 3. *(cont.).*

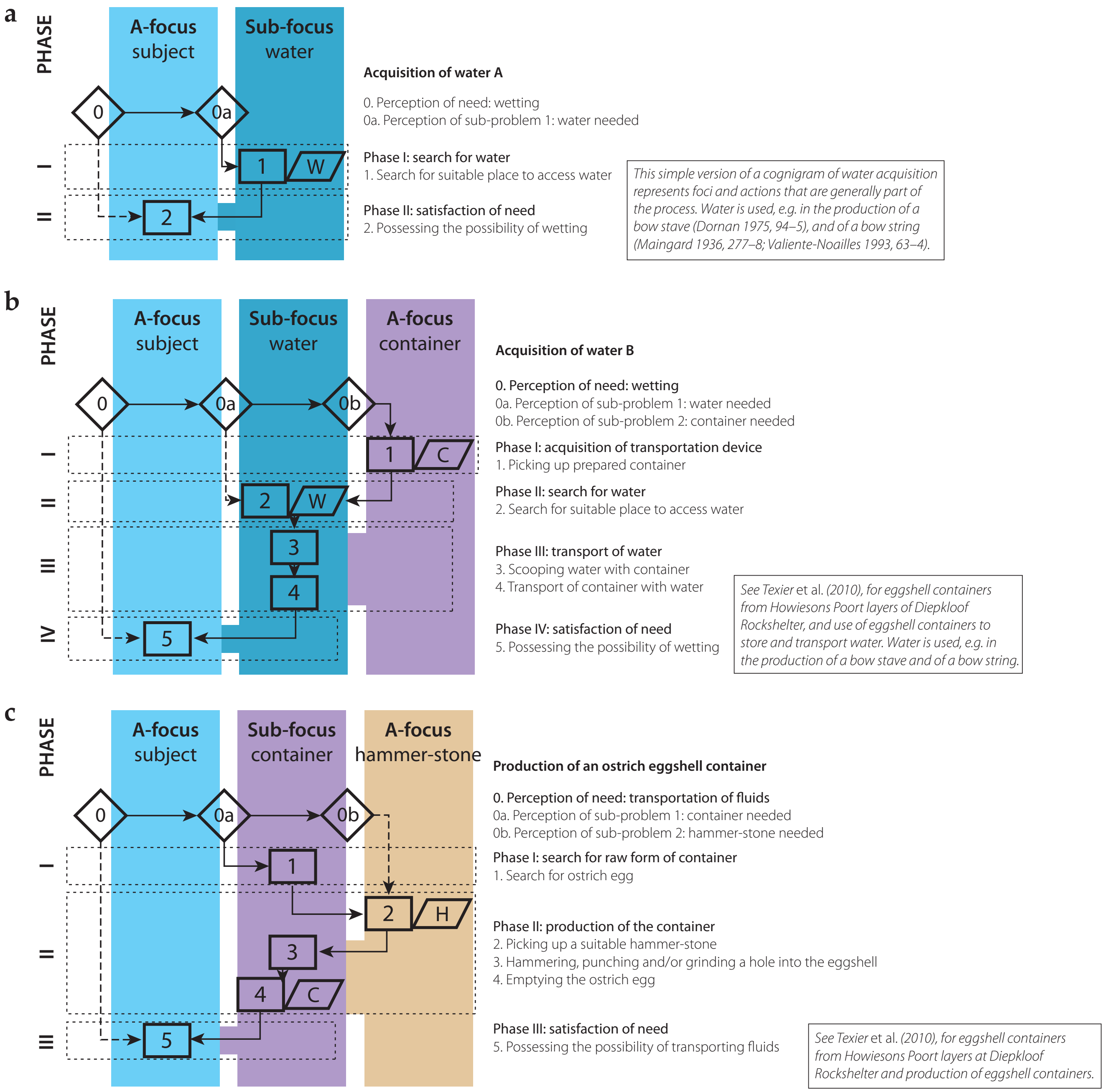
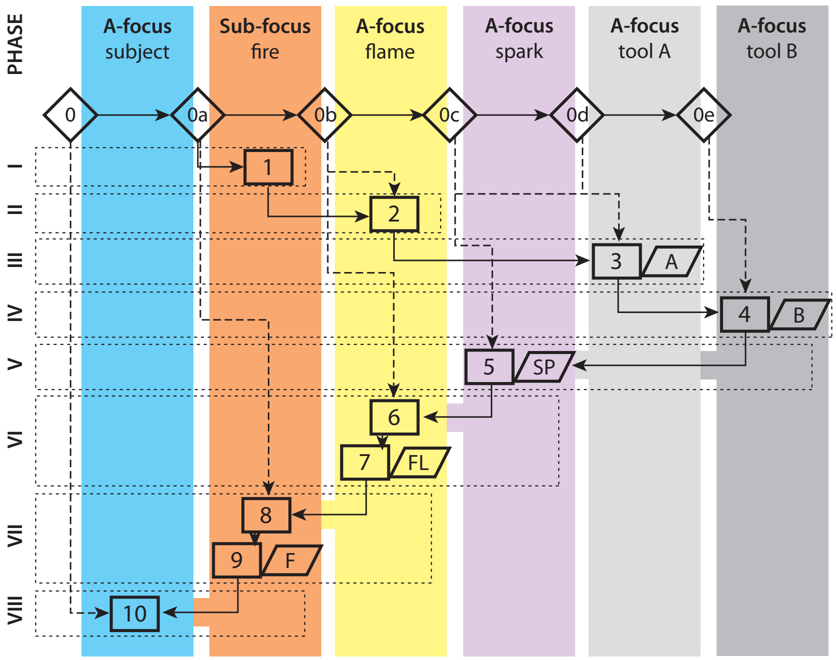


Figure 4. *Cognigrams for the acquisition of water and its transportation.*

Basic tool: fire (Fig. 5)

Fire may be needed several times throughout the production of a bow-and-arrow set, mostly in order to shape the bow stave, straighten arrow shafts and to produce and set adhesives. The deliberate production of fire suggests relatively complex object behaviour (Fig. 5). We show here the thought-and-action processes associated with a fire lighted by producing a spark from two stones. Other methods of starting a fire, such as the traditional Bushman way of rotating a stick between the palms causing friction and a spark on a piece of base-wood, are at least cognitively similar or more complex. The cognigram (Fig. 5) shows that in order to satisfy the basic need for heat, five sub-problems must be addressed. It shows a chain of five tools affecting one another in order to obtain fire as a tool itself, and ten operational steps contained in eight phases. The effective chain associated with fire-making is thus markedly longer in comparison to the cracking of nuts by chimpanzees (one tool effective),



Production of fire

0. Perception of need: heat
0a. Perception of sub-problem 1: fire needed
0b. Perception of sub-problem 2: flame needed
0c. Perception of sub-problem 3: spark needed
0d. Perception of sub-problem 4: tool A needed
0e. Perception of sub-problem 5: tool B needed

Phase I: search for long-burning raw material
1. Search for suitable material for fire

Phase II: search for easily inflammable material
2. Search for suitable material for flame

Phase III: search for tool A (e.g. pyrite) to produce spark
3. Search for suitable piece

Phase IV: search for tool B (e.g. chert) to produce spark
4. Search for suitable piece

Phase V: producing a spark
5. Applying tool B on tool A close to easily inflammable material

Phase VI: producing a flame
6. Supplying spark with easily inflammable material
7. Adding air to support flame

Phase VII: producing a fire
8. Supplying flame with long-burning material
9. Adding air to enhance burning process

Phase VIII: satisfaction of need
10. Possessing a source of heat

This cognigram of fire production is not based on a specific example, but represents foci and actions that are generally part of the process. The simplified version fits different versions of fire production regardless of the chosen types of tools or fuels. Fire is used, e.g. in the production of a bow stave (Dornan 1975, 94–5), the straightening of arrow shafts (Maingard 1936, 278–9), and the processing of compound adhesives (Wadley et al. *2009).*

Figure 5. *Cognigram for the production of fire.*

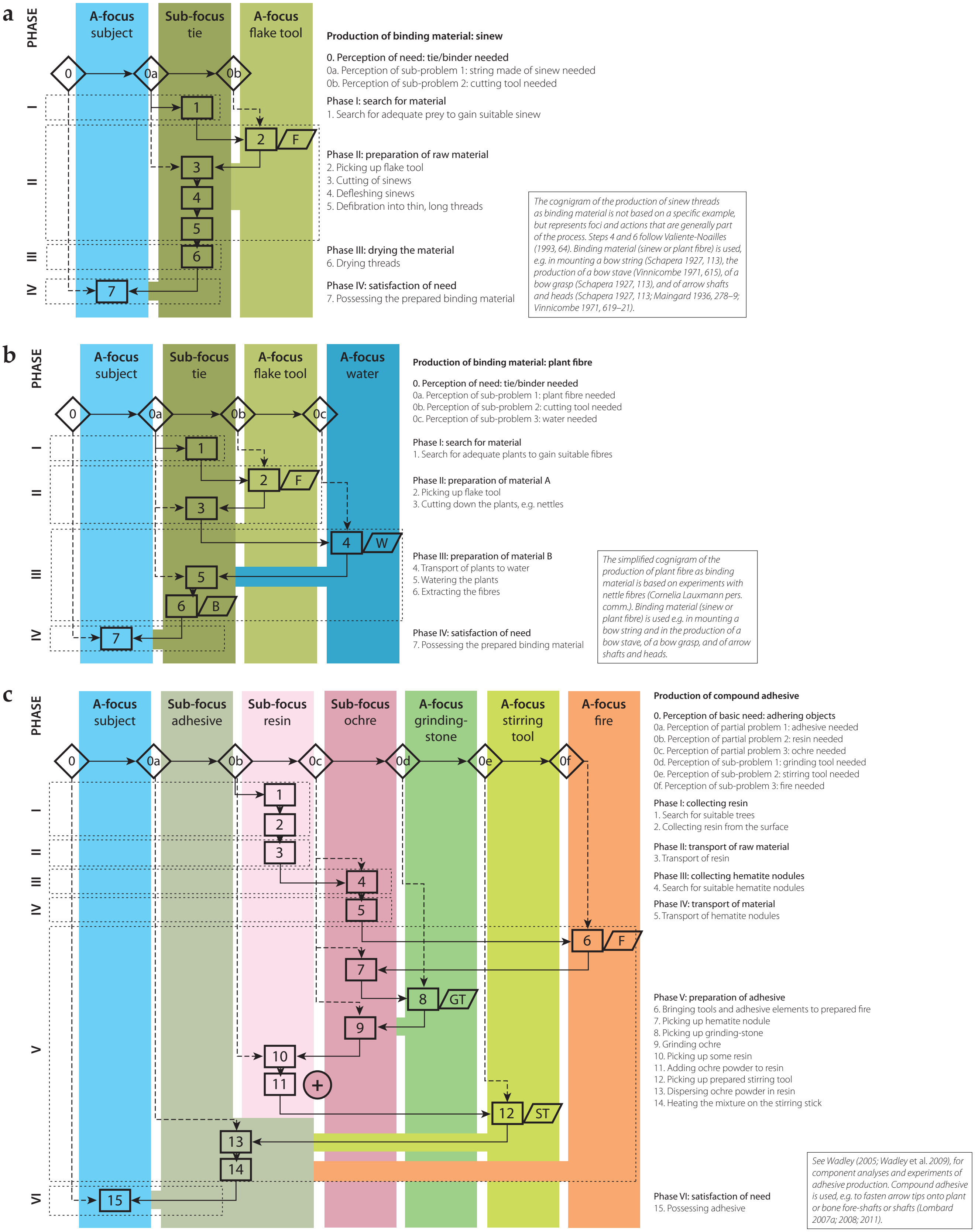
or the use of Oldowan stone tools to cut meat by early *Homo* species (two tools effective) (Haidle 2009; 2010). Direct evidence for deliberate fire production may provide enticing information regarding human cognitive evolution by documenting an extended effective chain in a problem-solution sequence. Additionally, fire is a very special tool as its production process summarizes short activities that may not be interrupted in the main phase from spark to fire.

Unspecific semi-finished products (Fig. 6a–c)

Unspecific semi-finished products can be implemented as passive foci (P-foci) at one or several points during the process of manufacturing a bow-and-arrow set. Their use is neither bound to the production of only a single bow or arrow, nor to the manufacture of bows and arrows as such. Rather, these products can be used in a variety of tasks as part of a generally available set of materials for further processing. Unspecific semi-finished products involved in bow-and-arrow manufacture comprise binding materials from sinew and/or plant fibres, and adhesives.

Units such as the production of binding materials are relatively uncomplicated in cognitive terms (Fig. 6a–b). During the production of sinew binding materials, only one basic tool is directly involved — a flake tool produced with a second tool, i.e. a hammer-stone. The production of plant fibre binding materials, however, includes the consecutive use of two tools — a flake tool and water (see above) — but, they do not affect each other. The procedure shows simple thought-and-action processes with one or two active foci in a principally bipartite, yet in reality (due to modularization) monomial, effective chain. We can therefore deduce that the production of binding materials is a cognitive skill that could have been performed early on in human evolution. However, its use to produce composite tools, where a range of materials is combined to form a single functional unit, potentially represented a cognitive leap forward (e.g. Ambrose 2010; Haidle 2010).

The process of producing compound adhesives comprises at least two materials as passive foci (resin or tree gum and ochre), which have to be treated with the help of three basic tools as active foci, i.e. a grinding-stone, a stirring tool and fire (see Wadley *et al.* 2009). Fifteen operational steps are contained within six phases (Fig. 6c). Within phase V, the most complex of this process, a special feature can be observed that sets the thought-and-action process of the production of compound adhesives apart from all other processes mentioned so far; the cognitive component of *composition* (represented by the encircled + in the cognigram: Fig. 6c). Composition refers to the idea that several separate components can be added together to form a new unit or composite tool to solve a problem. Here,



Production of binding material: sinew

0. Perception of need: tie/binder needed
0a. Perception of sub-problem 1: string made of sinew needed
0b. Perception of sub-problem 2: cutting tool needed

Phase I: search for material
1. Search for adequate prey to gain suitable sinew

Phase II: preparation of raw material
2. Picking up flake tool
3. Cutting of sinews
4. Defleshing sinews
5. Defibration into thin, long threads

Phase III: drying the material
6. Drying threads

Phase IV: satisfaction of need
7. Possessing the prepared binding material

The cognigram of the production of sinew threads as binding material is not based on a specific example, but represents foci and actions that are generally part of the process. Steps 4 and 6 follow Valiente-Noailles (1993, 64). Binding material (sinew or plant fibre) is used, e.g. in mounting a bow string (Schapera 1927, 113), the production of a bow stave (Vinnicombe 1971, 615), of a bow grasp (Schapera 1927, 113), and of arrow shafts and heads (Schapera 1927, 113; Maingard 1936, 278–9; Vinnicombe 1971, 619–21).

Production of binding material: plant fibre

0. Perception of need: tie/binder needed
0a. Perception of sub-problem 1: plant fibre needed
0b. Perception of sub-problem 2: cutting tool needed
0c. Perception of sub-problem 3: water needed

Phase I: search for material
1. Search for adequate plants to gain suitable fibres

Phase II: preparation of material A
2. Picking up flake tool
3. Cutting down the plants, e.g. nettles

Phase III: preparation of material B
4. Transport of plants to water
5. Watering the plants
6. Extracting the fibres

Phase IV: satisfaction of need
7. Possessing the prepared binding material

The simplified cognigram of the production of plant fibre as binding material is based on experiments with nettle fibres (Cornelia Lauxmann pers. comm.). Binding material (sinew or plant fibre) is used e.g. in mounting a bow string and in the production of a bow stave, of a bow grasp, and of arrow shafts and heads.

Production of compound adhesive

0. Perception of basic need: adhering objects
0a. Perception of partial problem 1: adhesive needed
0b. Perception of partial problem 2: resin needed
0c. Perception of partial problem 3: ochre needed
0d. Perception of sub-problem 1: grinding tool needed
0e. Perception of sub-problem 2: stirring tool needed
0f. Perception of sub-problem 3: fire needed

Phase I: collecting resin
1. Search for suitable trees
2. Collecting resin from the surface

Phase II: transport of raw material
3. Transport of resin

Phase III: collecting hematite nodules
4. Search for suitable hematite nodules

Phase IV: transport of material
5. Transport of hematite nodules

Phase V: preparation of adhesive
6. Bringing tools and adhesive elements to prepared fire
7. Picking up hematite nodule
8. Picking up grinding-stone
9. Grinding ochre
10. Picking up some resin
11. Adding ochre powder to resin
12. Picking up prepared stirring tool
13. Dispersing ochre powder in resin
14. Heating the mixture on the stirring stick

Phase VI: satisfaction of need
15. Possessing adhesive

See Wadley (2005; Wadley et al. *2009), for component analyses and experiments of adhesive production. Compound adhesive is used, e.g. to fasten arrow tips onto plant or bone fore-shafts or shafts (Lombard 2007a; 2008; 2011).*

Figure 6. *Cognigrams for the production of binding material and compound adhesives.*

two materials with different qualities are combined to form a new synthetic material with qualities that go beyond those of the original materials (see Wadley *et al*. 2009 for properties of individual elements and ochre-loaded adhesives). Composition is an innovative concept in the problem-solution distance. It introduces a new effect which tools can have on each other. Thereby, composition opens a whole new category of tools with new qualities that cannot be attained by merely increasing the number of actions, foci or simple effects. Composition consequently represents a major development towards increased cognitive and behavioural modularization and flexibility compared to that of single-component tools such as Oldowan and Acheulean stone artefacts, or simple wooden spears (also see Ambrose 2010). During the production of binding materials the cognitive element of composition is implied, but the deliberate production of compound adhesives directly documents this thought process. Notwithstanding its complexity, it is a cognitive trait shared by *Homo sapiens* with several other *Homo* species, including *Homo neanderthalensis* and *Homo heidelbergensis* in Eurasia, and archaic modern *Homo* in Africa.

Process units specific to bow production (Fig. 7a–e)

Process units specific to the manufacture of a bow are generally bound to its production. They can only be applied in other processes with some adaptation. Process units specific to bow production comprise production of a string made of sinews, production of a bow stave, mounting of a grasp as part of a bow, mounting of the string as part of the bow, and applying fat to the bow stave to prevent splitting/cracking. Of these processes the most complex is the production of the bow stave (Fig. 7a). In order to satisfy the basic need of nutrition, a further eleven sub-problems or partial problems must be solved. During this unit six active foci (tools) are applied to a sapling or branch as raw material for the bow stave. Additionally, a passive focus needs to be opened to solve this sub-problem. Altogether twenty-one operational steps are contained in seven phases. Phase IV is particularly interesting (Fig. 7a), with four different ways to continue, based on the chosen method(s) for bending the bow stave. Depending on the material, recursions may be mandatory or shortcuts can be possible. The character of phase IV is furthermore exceptional because, while the blank of the bow stave is continuously affected throughout the phase, the phase itself can be interrupted for the subject without consequences for the blank. This is due to the transfer of the action of bending from the human to a pole and binding material. In sum, the production of a bow stave parallels approximately the production of a Lower Palaeolithic wooden spear by *Homo heidelbergensis* more than 300,000 years ago (Haidle 2009). Depending on the materials and the demands made on the final product, however, the production of a wooden spear may be cognitively less complex than the production of a bow stave.

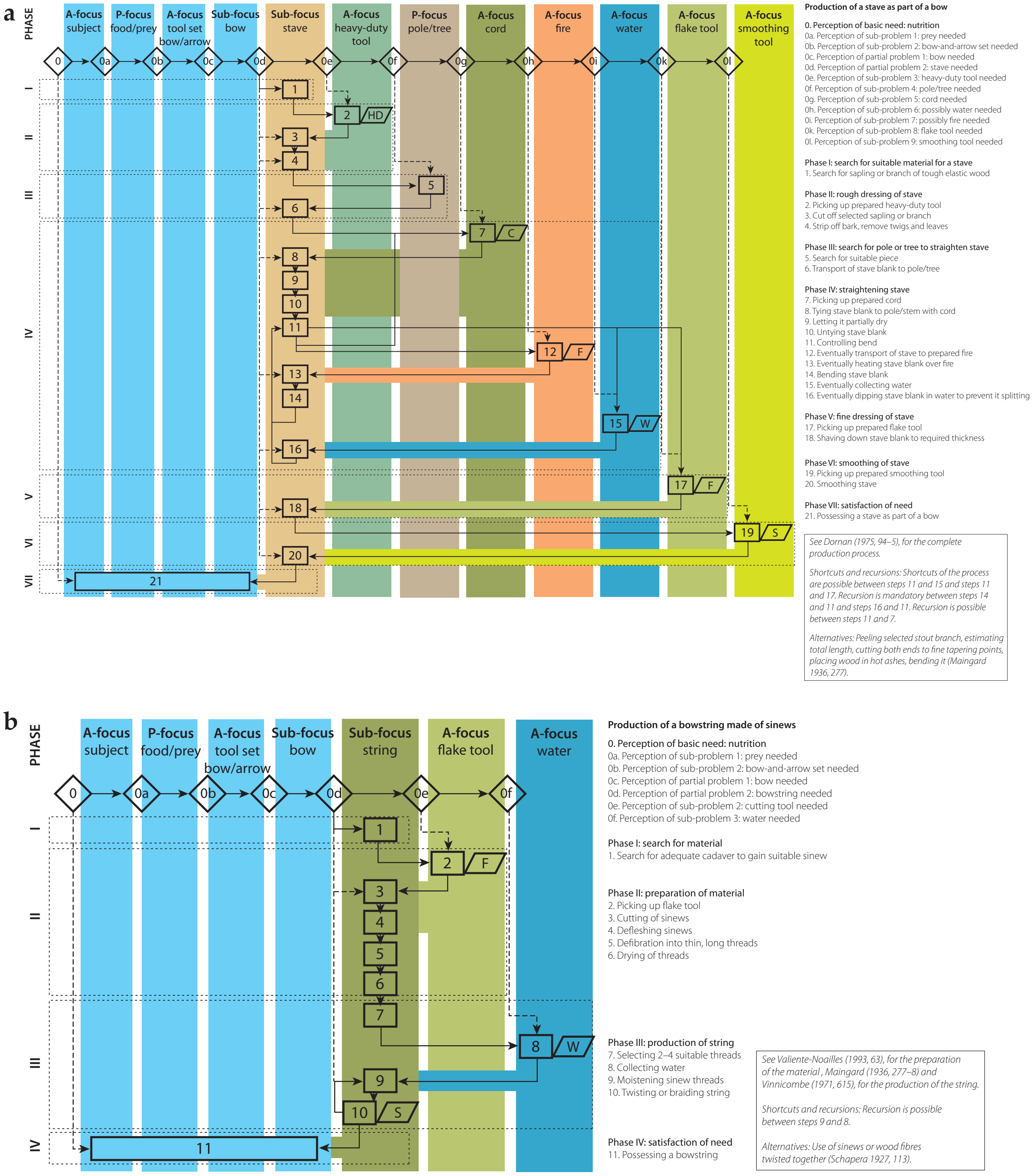
The production of making a bowstring, in contrast, is relatively uncomplicated in cognitive terms (Fig. 7b). Two active foci have to be applied to a cadaver in order to extract the sinews to obtain and use the necessary material to solve the sub-problem, i.e. a flake tool and water (the latter to soften the sinew before string production). Ten operational steps are contained in four phases. The production of a bowstring has to be set apart as a process unit specific to bow production from the manufacture of other sinew binding materials that represent unspecific semi-finished products. The effective chain does not differ between the two sinew products, but the thought-and-action process of the bowstring is extended: a) by considering it as a part of a specific bow-and-arrow set; and b) by additional actions needed to twist the string, providing tensile strength.

Assembling and maintaining bows, by mounting grasps and bowstrings, and by applying fat to the staves in order to prevent splitting and cracking (Fig. 7c–e), represent individual process units that — based on the number of sub-problems, open active foci and operational steps — seem less complex than the production of the bow stave. Mounting a grasp and applying fat use only one active focus and one passive focus within six operative steps in three phases. Mounting a bowstring needs at least two active and two passive foci within twelve operative steps in three phases. However, it is during all three of these units that the presence of the innovative cognitive component of composition can be documented (cf. production of compound adhesive: Fig. 6c). During the mounting of a grasp or applying fat to the bow stave, two components are combined to form a new element with different qualities, and in mounting the bow string three components are effectively assembled.

Process units specific to arrow production (Fig. 8a–e)

Process units specific to the manufacture of an arrow are generally bound to its production. They can only be applied in other processes with some adaptation. Process units specific to the production of a stone-tipped arrow comprise the production of a stone tip, a fore-shaft and a shaft, the mounting of an arrowhead and the mounting of an arrow.

Making the stone tips and hardwood fore-shafts is the least cognitively challenging in the arrow-production process (Fig. 8a–b). Making a retouched stone



Production of a stave as part of a bow

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: stave needed
0e. Perception of sub-problem 3: heavy-duty tool needed
0f. Perception of sub-problem 4: pole/tree needed
0g. Perception of sub-problem 5: cord needed
0h. Perception of sub-problem 6: possibly water needed
0i. Perception of sub-problem 7: possibly fire needed
0k. Perception of sub-problem 8: flake tool needed
0l. Perception of sub-problem 9: smoothing tool needed

Phase I: search for suitable material for a stave
1. Search for sapling or branch of tough elastic wood

Phase II: rough dressing of stave
2. Picking up prepared heavy-duty tool
3. Cut off selected sapling or branch
4. Strip off bark, remove twigs and leaves

Phase III: search for pole or tree to straighten stave
5. Search for suitable piece
6. Transport of stave blank to pole/tree

Phase IV: straightening stave
7. Picking up prepared cord
8. Tying stave blank to pole/stem with cord
9. Letting it partially dry
10. Untying stave blank
11. Controlling bend
12. Eventually transport of stave to prepared fire
13. Eventually heating stave blank over fire
14. Bending stave blank
15. Eventually collecting water
16. Eventually dipping stave blank in water to prevent it splitting

Phase V: fine dressing of stave
17. Picking up prepared flake tool
18. Shaving down stave blank to required thickness

Phase VI: smoothing of stave
19. Picking up prepared smoothing tool
20. Smoothing stave

Phase VII: satisfaction of need
21. Possessing a stave as part of a bow

See Dornan (1975, 94–5), for the complete production process.

Shortcuts and recursions: Shortcuts of the process are possible between steps 11 and 15 and steps 11 and 17. Recursion is mandatory between steps 14 and 11 and steps 16 and 11. Recursion is possible between steps 11 and 7.

Alternatives: Peeling selected stout branch, estimating total length, cutting both ends to fine tapering points, placing wood in hot ashes, bending it (Maingard 1936, 277).

Production of a bowstring made of sinews

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: bowstring needed
0e. Perception of sub-problem 2: cutting tool needed
0f. Perception of sub-problem 3: water needed

Phase I: search for material
1. Search for adequate cadaver to gain suitable sinew

Phase II: preparation of material
2. Picking up flake tool
3. Cutting of sinews
4. Defleshing sinews
5. Defibration into thin, long threads
6. Drying of threads

Phase III: production of string
7. Selecting 2–4 suitable threads
8. Collecting water
9. Moistening sinew threads
10. Twisting or braiding string

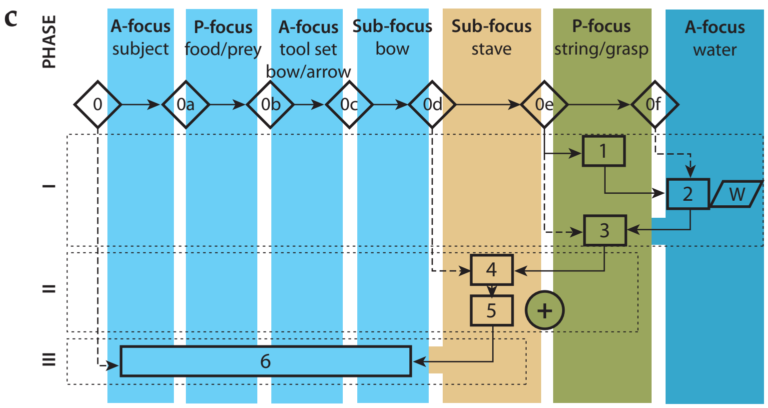
Phase IV: satisfaction of need
11. Possessing a bowstring

See Valiente-Noailles (1993, 63), for the preparation of the material , Maingard (1936, 277–8) and Vinnicombe (1971, 615), for the production of the string.

Shortcuts and recursions: Recursion is possible between steps 9 and 8.

Alternatives: Use of sinews or wood fibres twisted together (Schapera 1927, 113).

Figure 7. *Cognigrams for processes specific to bow production.*



Mounting of a grasp as part of a bow

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: stave needed
0e. Perception of partial problem 3: grasp, strengthening needed
0f. Perception of sub-problem 3: water needed

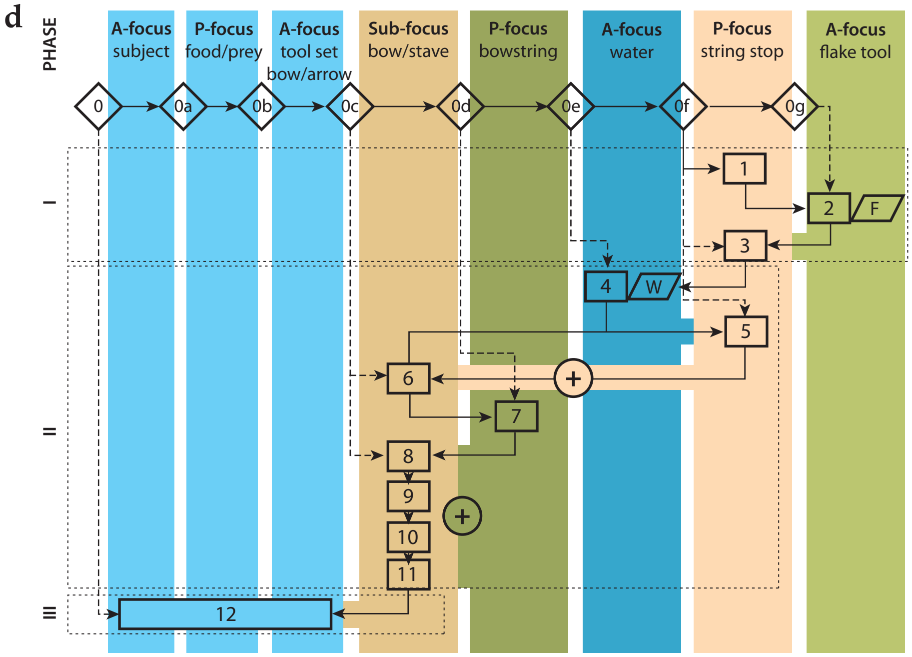
Phase I: preparation of material for grasp
1. Selecting suitable prepared sinew threads
2. Collecting water
3. Moistening sinew threads

See Dornan (1975, 95), Schapera (1927, 113) and Valiente-Noailles (1993, 63), for the mounting of a grasp as part of the bow.

Shortcuts and recursions: A shortcut is possible between steps 1 and 4, if prepared sinew is still fresh and not dried.

Phase II: binding grasp
4. Picking up prepared stave
5. Wrapping sinew around the middle of the stave

Phase III: satisfaction of need
6. Possessing a stave with grasp as part of a bow, strengthening the stave



Mounting of a bowstring as part of a bow

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: bowstring needed
0e. Perception of sub-problem 3: water needed
0f. Perception of partial problem 3: string stop needed
0g. Perception of sub-problem 3: flake tool needed

Phase I: preparation of string stop
1. Selecting suitable sinew threads, leather or gut
2. Picking up prepared flake tool
3. Cutting sinew/leather/gut to suitable dimension

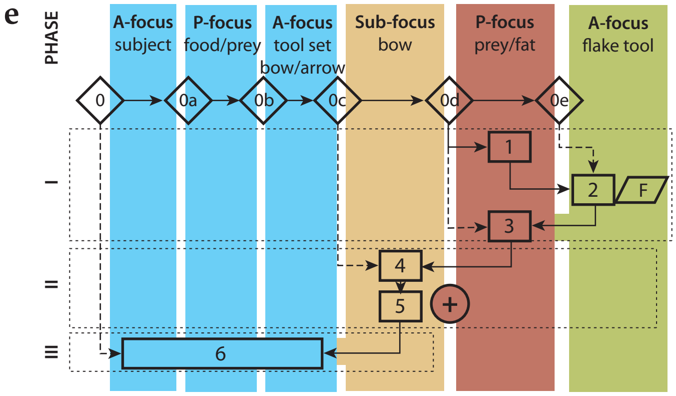
Phase II: mounting bowstring
4. Collecting water
5. Moistening prepared sinew/leather/gut for string stops
6. Fixing string stops at basal/upper end of bow stave
7. Picking up prepared bowstring
8. Attaching string with a simple slipknot at the basal end of stave
9. Winding string tightly, several times round the basal end
10. Bending stave
11. Knotting string to upper end of bow stave

Phase III: satisfaction of need
12. Possessing a stave with string as part of a bow

See Schapera (1927, 113) and Maingard (1936: 278), for the process of mounting a bowstring.

Shortcuts and recursions: Recursion is mandatory between steps 10 and 9.

Alternatives: At one end string attached by a simple knot, at the other twisted twelve to thirty-three times round the bow and fastened with a knot to a small leather knob tied to the wood. To adjust the tension, the twisted part of the bowstring is rotated (Valiente-Noailles 1993, 64).



Applying fat to the bow stave to prevent splitting/cracking/shrinking

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: fat needed
0e. Perception of sub-problem 3: flake tool needed

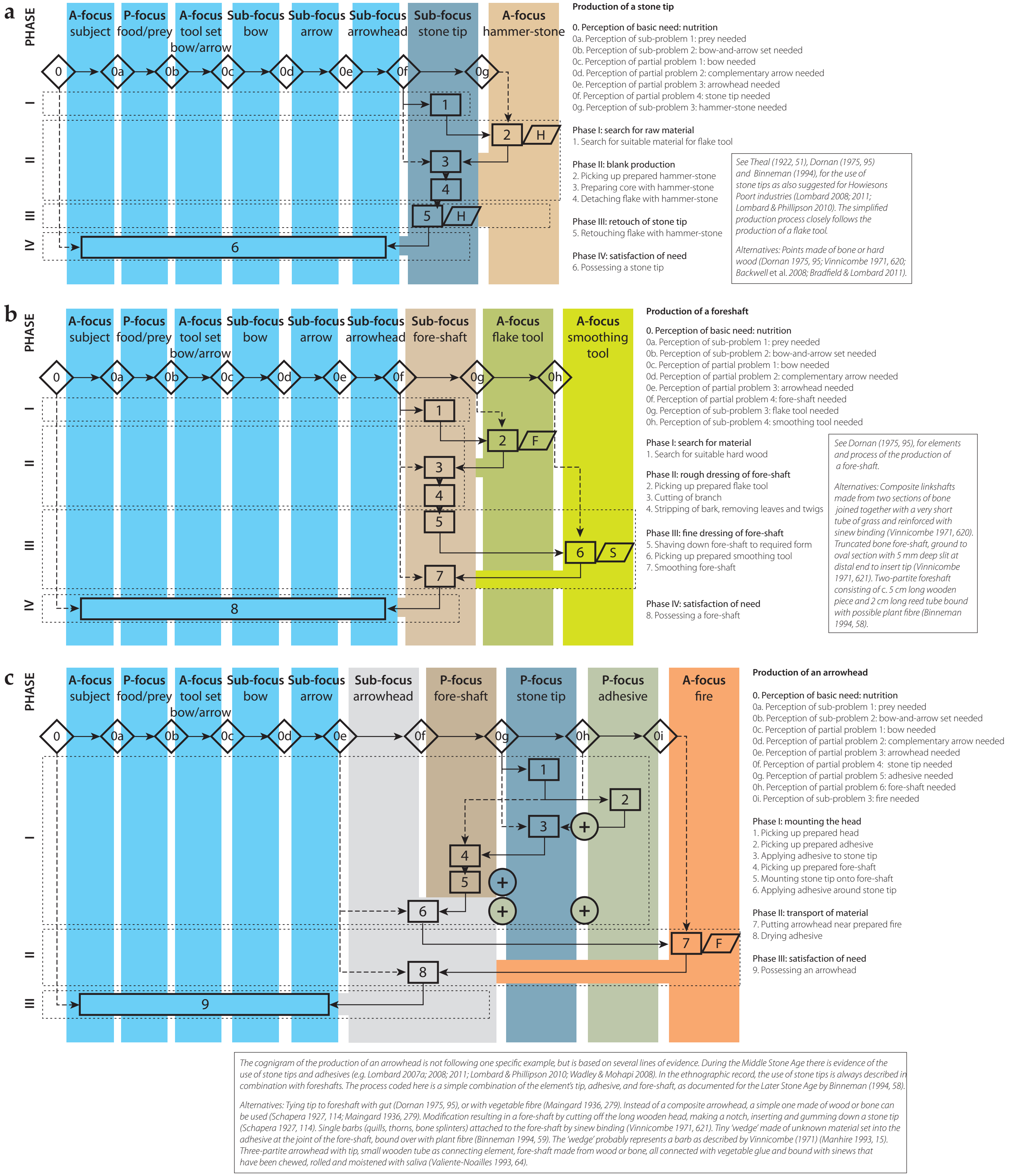
Phase I: preparation of fat for greasing
1. Selecting suitable part of prey
2. Getting prepared flake tool
3. Cutting off piece of fat

Phase II: greasing stave
4. Picking up prepared stave
5. Greasing stave

See Dornan (1975, 95) and Valiente-Noailles (1993, 63) for the application of fat to the bow stave.

Phase III: satisfaction of need
6. Possessing a stave with prevention of cracking/splitting

Figure 7. *(cont.)*



Production of a stone tip

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: complementary arrow needed
0e. Perception of partial problem 3: arrowhead needed
0f. Perception of partial problem 4: stone tip needed
0g. Perception of sub-problem 3: hammer-stone needed

Phase I: search for raw material
1. Search for suitable material for flake tool

Phase II: blank production
2. Picking up prepared hammer-stone
3. Preparing core with hammer-stone
4. Detaching flake with hammer-stone

Phase III: retouch of stone tip
5. Retouching flake with hammer-stone

Phase IV: satisfaction of need
6. Possessing a stone tip

See Theal (1922, 51), Dornan (1975, 95) and Binneman (1994), for the use of stone tips as also suggested for Howiesons Poort industries (Lombard 2008; 2011; Lombard & Phillipson 2010). The simplified production process closely follows the production of a flake tool.

Alternatives: Points made of bone or hard wood (Dornan 1975, 95; Vinnicombe 1971, 620; Backwell et al. *2008; Bradfield & Lombard 2011).*

Production of a foreshaft

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: complementary arrow needed
0e. Perception of partial problem 3: arrowhead needed
0f. Perception of partial problem 4: fore-shaft needed
0g. Perception of sub-problem 3: flake tool needed
0h. Perception of sub-problem 4: smoothing tool needed

Phase I: search for material
1. Search for suitable hard wood

Phase II: rough dressing of fore-shaft
2. Picking up prepared flake tool
3. Cutting of branch
4. Stripping of bark, removing leaves and twigs

Phase III: fine dressing of fore-shaft
5. Shaving down fore-shaft to required form
6. Picking up prepared smoothing tool
7. Smoothing fore-shaft

Phase IV: satisfaction of need
8. Possessing a fore-shaft

See Dornan (1975, 95), for elements and process of the production of a fore-shaft.

Alternatives: Composite linkshafts made from two sections of bone joined together with a very short tube of grass and reinforced with sinew binding (Vinnicombe 1971, 620). Truncated bone fore-shaft, ground to oval section with 5 mm deep slit at distal end to insert tip (Vinnicombe 1971, 621). Two-partite foreshaft consisting of c. 5 cm long wooden piece and 2 cm long reed tube bound with possible plant fibre (Binneman 1994, 58).

Production of an arrowhead

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: complementary arrow needed
0e. Perception of partial problem 3: arrowhead needed
0f. Perception of partial problem 4: stone tip needed
0g. Perception of partial problem 5: adhesive needed
0h. Perception of partial problem 6: fore-shaft needed
0i. Perception of sub-problem 3: fire needed

Phase I: mounting the head
1. Picking up prepared head
2. Picking up prepared adhesive
3. Applying adhesive to stone tip
4. Picking up prepared fore-shaft
5. Mounting stone tip onto fore-shaft
6. Applying adhesive around stone tip

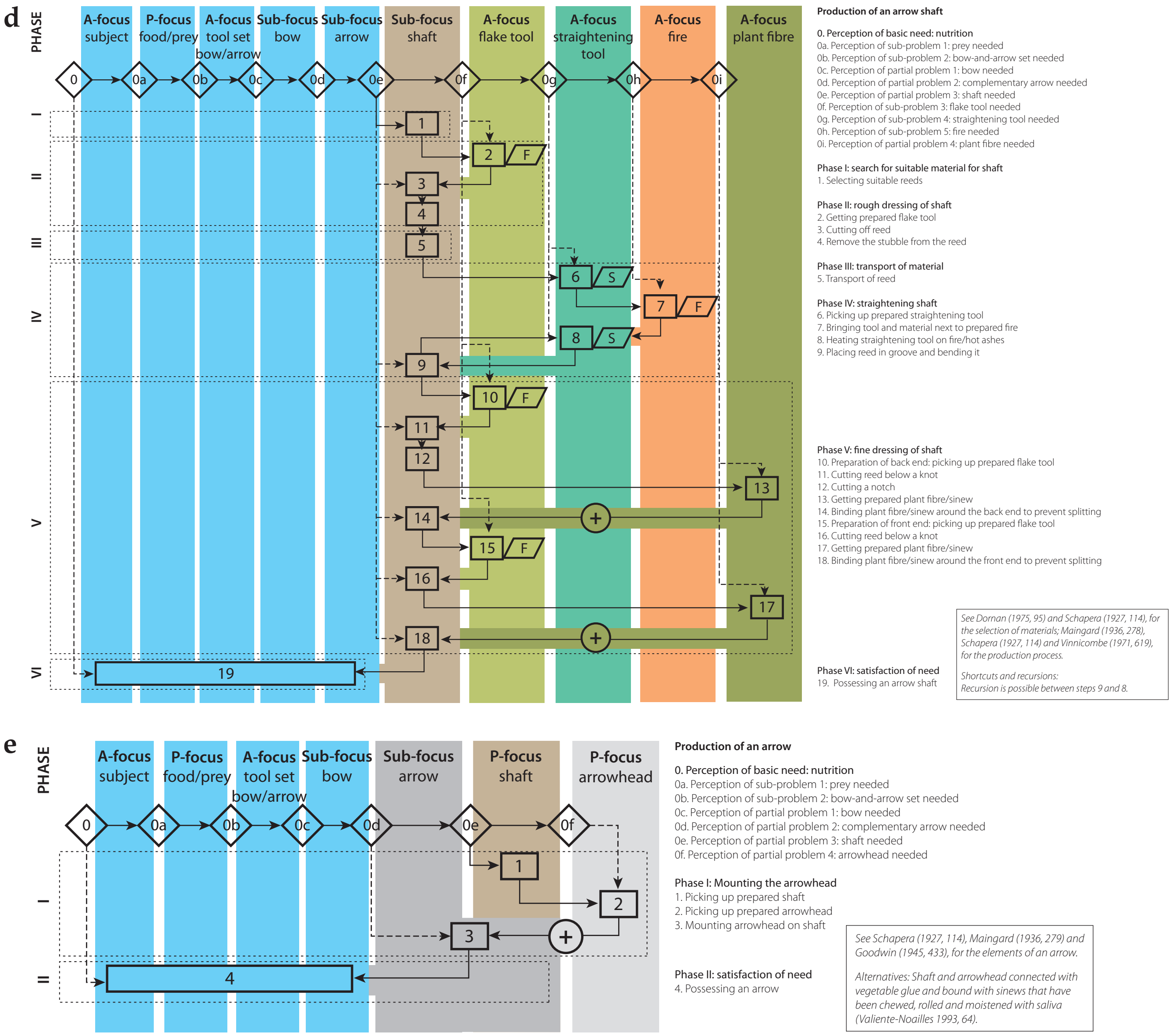
Phase II: transport of material
7. Putting arrowhead near prepared fire
8. Drying adhesive

Phase III: satisfaction of need
9. Possessing an arrowhead

The cognigram of the production of an arrowhead is not following one specific example, but is based on several lines of evidence. During the Middle Stone Age there is evidence of the use of stone tips and adhesives (e.g. Lombard 2007a; 2008; 2011; Lombard & Phillipson 2010; Wadley & Mohapi 2008). In the ethnographic record, the use of stone tips is always described in combination with foreshafts. The process coded here is a simple combination of the element's tip, adhesive, and fore-shaft, as documented for the Later Stone Age by Binneman (1994, 58).

Alternatives: Tying tip to foreshaft with gut (Dornan 1975, 95), or with vegetable fibre (Maingard 1936, 279). Instead of a composite arrowhead, a simple one made of wood or bone can be used (Schapera 1927, 114; Maingard 1936, 279). Modification resulting in a fore-shaft by cutting off the long wooden head, making a notch, inserting and gumming down a stone tip (Schapera 1927, 114). Single barbs (quills, thorns, bone splinters) attached to the fore-shaft by sinew binding (Vinnicombe 1971, 621). Tiny 'wedge' made of unknown material set into the adhesive at the joint of the fore-shaft, bound over with plant fibre (Binneman 1994, 59). The 'wedge' probably represents a barb as described by Vinnicombe (1971) (Manhire 1993, 15). Three-partite arrowhead with tip, small wooden tube as connecting element, fore-shaft made from wood or bone, all connected with vegetable glue and bound with sinews that have been chewed, rolled and moistened with saliva (Valiente-Noailles 1993, 64).

Figure 8. *Cognigrams for processes specific to arrow production.*



Production of an arrow shaft

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: complementary arrow needed
0e. Perception of partial problem 3: shaft needed
0f. Perception of sub-problem 3: flake tool needed
0g. Perception of sub-problem 4: straightening tool needed
0h. Perception of sub-problem 5: fire needed
0i. Perception of partial problem 4: plant fibre needed

Phase I: search for suitable material for shaft
1. Selecting suitable reeds

Phase II: rough dressing of shaft
2. Getting prepared flake tool
3. Cutting off reed
4. Remove the stubble from the reed

Phase III: transport of material
5. Transport of reed

Phase IV: straightening shaft
6. Picking up prepared straightening tool
7. Bringing tool and material next to prepared fire
8. Heating straightening tool on fire/hot ashes
9. Placing reed in groove and bending it

Phase V: fine dressing of shaft
10. Preparation of back end: picking up prepared flake tool
11. Cutting reed below a knot
12. Cutting a notch
13. Getting prepared plant fibre/sinew
14. Binding plant fibre/sinew around the back end to prevent splitting
15. Preparation of front end: picking up prepared flake tool
16. Cutting reed below a knot
17. Getting prepared plant fibre/sinew
18. Binding plant fibre/sinew around the front end to prevent splitting

Phase VI: satisfaction of need
19. Possessing an arrow shaft

See Dornan (1975, 95) and Schapera (1927, 114), for the selection of materials; Maingard (1936, 278), Schapera (1927, 114) and Vinnicombe (1971, 619), for the production process.

Shortcuts and recursions:
Recursion is possible between steps 9 and 8.

Production of an arrow

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of partial problem 1: bow needed
0d. Perception of partial problem 2: complementary arrow needed
0e. Perception of partial problem 3: shaft needed
0f. Perception of partial problem 4: arrowhead needed

Phase I: Mounting the arrowhead
1. Picking up prepared shaft
2. Picking up prepared arrowhead
3. Mounting arrowhead on shaft

Phase II: satisfaction of need
4. Possessing an arrow

See Schapera (1927, 114), Maingard (1936, 279) and Goodwin (1945, 433), for the elements of an arrow.

Alternatives: Shaft and arrowhead connected with vegetable glue and bound with sinews that have been chewed, rolled and moistened with saliva (Valiente-Noailles 1993, 64).

Figure 8. *(cont.)*

tip requires seven sub-problems or partial problems to be addressed. Yet, no more than one active focus is open; six operational steps are represented in four phases (Fig. 8a). Manufacturing of the fore-shaft is only slightly more extended with eight sub-problems, two active foci open, and eight operational steps in four phases (Fig. 8b). During the production of a retouched stone tip only one basic tool is directly involved (a hammer-stone), whereas the production of a fore-shaft includes the consecutive use of two tools, but these do not affect each other (a flake tool and a smoothing tool both produced with a second tool, i.e. a hammer-stone). Thus, the production of a stone arrow tip shows simple thought-and-action processes with one to two active foci in a monomial effective chain. Although being principally bipartite, due to modularization, the effective chain of the fore-shaft can also be regarded as monomial.

The production of the arrowhead (stone tip + fore-shaft + adhesive) is a typical example of the cognitive component of composition (Fig. 8c). This operational unit requires of its maker to consider nine sub-problems or partial problems prior to addressing the basic need of nutrition. Yet, because of the modularity of production units, it only requires one active focus open to work with three passive foci, and nine operational steps within three phases; with phase I, the mounting of the arrow tip to the fore-shaft using adhesive the most complex. Here, three separate elements are brought together in several steps of addition to form a new element, the arrowhead. This reconstruction can also be seen as loosely applicable to the cognitive challenges of making stone-tipped thrusting or throwing spears. It clearly illustrates how simplification, contained in cognitive modularization, facilitates the composition of a composite tool.

Beside the production of the arrowhead, making a seemingly simple reed arrow shaft is the most cognitively complex production unit in the arrow-making process (Fig. 8d). We suggest a suite of nine sub-problems or partial problems to be tackled in its production in order to satisfy the basic need of nutrition. This requires three active and two passive foci to be open during the effective chain. Nineteen operational steps have to be completed within six production or activity phases. Two additions of formerly independent foci, the reed and plant fibres, may take place to become a single composite focus, the shaft, during phase V — the fine dressing of the reed shaft.

Once again, as a result of conceptual, technological and behavioural modularization, assembling the final arrow before use is a relatively simple procedure, requiring the solving of six sub-problems or partial problems during four operational steps in only two phases (Fig. 8e). Thus, similar to bow production, the production of arrows cannot be considered cognitively more advanced than other composite tools manufactured before the inception of bow-and-arrow technology.

Summary of the operational sequences of bow-and-arrow manufacture and use

The production of a bow is a sum of processes aimed at gaining intermediate objectives such as a string, a bow stave, a grasp, a final surface treatment of the bow, and the assembly of these intermediate objectives with the help of basic tools and using some unspecific semi-finished products. The production of an arrow is also a sum of processes in order to gain intermediate objectives. Multiple components can be produced (e.g. stone tips, fore-shafts, shafts), assembled and re-assembled in a variety of sequences, all with independent intermediate objectives, in order to produce the final complete arrow. All the intermediate processes depend on the application of various basic tools, and using some unspecific semi-finished products. Conceptual, technological and behavioural modularization helps to keep the process units small and cognitively manageable. A by-product of such modularization is the increasing number of sub-problems or partial problems to be considered in sub-foci within a single process unit. Although the sub-foci play neither an active, nor a passive role within the process units, attention should be paid to them in order to place the specific thought-and-action process into the right context, and to conceptualize the intermediate objective as an adequate part of a broader aim.

In our hypothetical reconstruction of the production of a simple bow-and-arrow set, we identified 24 decoupled operational units, comprising: a) ten units of acquisition or production of basic tools; b) three units of production of semi-finished products; c) and d) five units each of the production of a bow and an arrow respectively; and finally e) the use of the complete bow-and-arrow set. Each of these units can be autonomous with their own intermediate aims, independent of immediate basic needs. They can be assembled successfully in a variety of configurations for potentially different functions. The 24 units identified for bow-and-arrow production and use are:

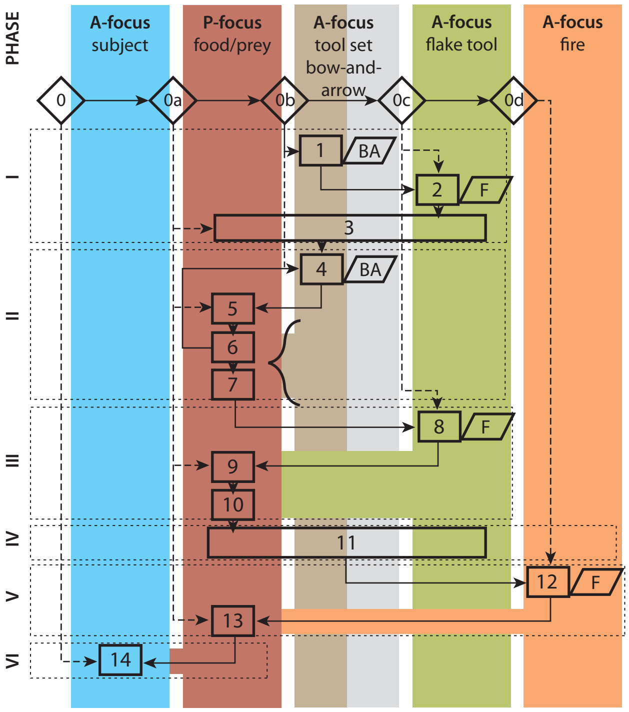
a. Acquisition or production of basic tools
1. Acquisition of hammer-stone
2. Acquisition of grinding tool
3. Acquisition of stirring tool
4. Production of a flake stone tool
5. Production of a heavy-duty stone tool
6. Production of a smoothing stone tool
7. Production of a straightening stone tool
8. Acquisition of water
9. Production of a container
10. Production of fire

b. Production of unspecific semi-finished products
11. Production of binding material (sinew)
12. Production of binding material (plant fibre)
13. Production of compound adhesive

c. Process units specific to bow production
14. Production of a string/cord made of sinews
15. Production of the bow-stave
16. Mounting of a grasp as part of a bow
17. Mounting of a string as part of a bow
18. Applying fat to the bow-stave to prevent splitting/cracking

d. Process units specific to arrow production
18. Production of the stone tip
20. Production of a fore-shaft
21. Production of the arrowhead (tip + fore-shaft)
22. Production of an arrow-shaft
23. Production of an arrow

e. Process unit of bow-and-arrow use
24. Use of bow-and-arrow



Hunting with a bow-and-arrow set

0. Perception of basic need: nutrition
0a. Perception of sub-problem 1: prey needed
0b. Perception of sub-problem 2: bow-and-arrow set needed
0c. Perception of sub-problem 3: flake tool needed
0d. Perception of sub-problem 4: fire needed

Phase I: tracking down prey
1. Picking up prepared bow-and-arrow set
2. Picking up prepared flake tools
3. Tracking down prey, transport of tools

Phase II: hunting prey
4. Selecting suitable arrow
5. Approaching selected animal
6. Shooting arrow with bow on prey
7. Killing prey

Phase III: dismembering prey
8. Selecting suitable cutting tool
9. Breaking open the corpse
10. Dismembering the prey

Phase IV: transport of meat
11. Transport of parts of prey, transport of tools

Phase V: preparing a meal
12. Bringing parts of prey to prepared fire
13. Roasting meat

Phase VI: satisfaction of need
14. Consumption of meal

The simplified cognigram of hunting with a bow-and-arrow set is not based on a specific example, but represents foci and actions that are generally part of the process.

Shortcuts and recursions:
Recursion is possible between steps 6 and 4.

Figure 9. *Cognigram for hunting with a bow-and-arrow set.*

Although it is possible to imagine a different, simpler, bow-and-arrow set that might include fewer modules and produce a simpler effective chain with fewer elements, the cognigrams presented above (Figs. 3–8), show that neither the production of a simple bow (Fig. 2a), nor that of a stone-tipped arrow, even with fore-shaft and shaft (Fig. 2b), can be reasonably interpreted to indicate tool behaviour that is cognitively more complex than composite artefacts produced by Neanderthals or archaic modern *Homo*. As soon as a bow-and-arrow set is used as an effective unit, however — even in the simplest possible form of such a tool set — a novel cognitive component becomes apparent.

This new component represents the conceptualization of complementary tool sets or technological symbiosis (represented by { in the cognigram: Fig. 9). Such tool sets have two different elements: a) enhancing elements with stable capacities; and b) multiple consumable elements with changing, flexible capacities. The application of consumable elements are actively augmented by the enhancing element; handled and controlled by the user in a way that reveals the full potential of the consumable elements only when used jointly in a complementary tool set. Complementation or symbiosis, similar to composition, is an innovative concept in the problem-solution distance. Yet, it introduces an additional effect tools can have on each other and, once again, facilitates an entire new category of tools with new qualities. These new qualities can not be attained by simply increasing the number of actions, the number of foci, the number of simple effects, or the number of composite effects; they can only be reached by actively and simultaneously using a set of symbiotic tools (also see Table 1). Complementation or symbiosis thus represents still another major cognitive increase, which enables a level of technological complexity and flexibility that is not possible with non-symbiotic, simple or composite technologies.

Technological symbiosis and its potential cognitive implication

In the following section we extrapolate on the interpretation of technological symbiosis. Analysing the complete chains of operation, that include all the operational units contained in the cognigrams, provides further insight. It enables us to compare tool behaviour associated with hand-delivered weaponry with that associated with mechanically-projected weaponry. We reconstruct the effective chains for simple wooden spears (Fig. 10a), composite stone-tipped spears (Fig. 10b), and a bow-and-arrow set (Fig. 10c). The diagrams provide an overview of the elements actively involved in the processes (tools; in rectangular frames) and the materials necessary to complete the processes. In the case of the wooden spear (Fig. 10a), the effective chain draws on Veil's (1991) experiments, supported by detailed analysis of the Schöningen spears from Germany (Thieme 1997; 1999), supplemented with commonsense assumptions (Haidle 2009). By studying the operational chain of a seemingly simple, hand-delivered wooden spear, such as those recorded in Germany, *c.* 300,000 years ago, it can be extrapolated that thinking through, and following the operational sequence from the perception of the basic need (hunger for meat), to its final satisfaction would be difficult and demanding.

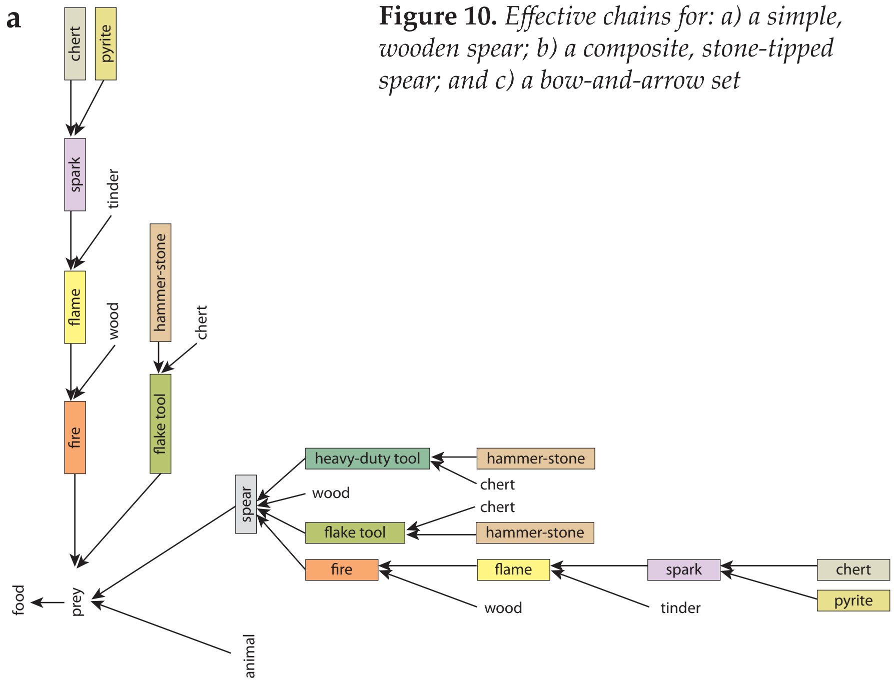


Figure 10. *Effective chains for: a) a simple, wooden spear; b) a composite, stone-tipped spear; and c) a bow-and-arrow set*

These spears already represent an advanced decoupling of satisfaction and basic need, where small operational units, each with its own intermediate aims, can be put together in a modular way in different operational sequences (Haidle 2009). For example, the same material (chert) can be sourced to function as firelighter, hammer-stone, heavy-duty stone tool and flake tool. Also, hard hammer-stones need not be repeatedly sourced, but can be kept, so that they are instantly available for use when required. Through decoupling and modular conceptual and technological behaviour the handling of complex thought-and-action sequences becomes possible. Thus, the manageable complexity in tool behaviour increases.

Our effective chain of the manufacture and use of a stone-tipped spear shows the further cognitive component of composition (the encircled +) (Fig. 10c); an innovative concept in the problem-solution distance that introduces new effects which tools can have on each other. As such, it represents a key development towards advanced cognitive and behavioural modularization and flexibility. The concept of composite tools probably developed gradually over the past 300,000 years (Haidle 2010). Stone-tipped, hand-delivered spears could have been used from *c.* 285 kya in sub-Saharan Africa (McBrearty & Tryon 2005), *c.* 270 kya in the Near East (Mercier & Valladas 2003), and *c.* 200 kya in Europe (Villa & Soriano 2010). Few early assemblages have been analysed for direct evidence of hunting and hafting, but, unambiguous evidence for hunting with stone-tipped weaponry comes, for example, from Klasies River, South Africa at *c.* 100 kya (Milo 1998), and Umm-el-Tlel, Israel at 40–70 kya (Boëda *et al.* 1999), where stone point fragments were found embedded in the vertebrae of large prey animals. From Umm-el-Tlel, in the same context, there is also evidence of bitumen being used to haft such points (Boëda *et al.* 2008).

We are not aware of direct evidence for the use of binding materials such as plant twine or sinew cords during the Middle Palaeolithic of Eurasia to reinforce the hafting of stone points to spear shafts, but the hafting method has been documented in northeast Africa possibly from *c.* 150 kya (Rots *et al.* 2011), and recorded for stone-tipped spears used in South Africa from *c.* 70–35 kya (Lombard 2005; 2006b). In the latter region, and of similar age, are records of the manufacture and use of compound adhesives that included ochre as an ingredient (Wadley *et al.* 2004; Lombard 2006a; 2007a; 2009). Replication of, and experimentation with, stone-tipped spears further inform our effective chain (Lombard *et al.* 2004), and shows that careful recipe and heat control was required for the manufacture of successful compound adhesives (Wadley 2005; 2006; 2010; Wadley *et al.* 2009) (Fig. 6c).

Stone points, for which a hunting function has been established and that contain direct evidence of hafting, thus carry information beyond their mode of manufacture and function. They can be viewed as part of a complex set of operational units that form a spear to hunt for prey that is needed to satisfy a feeling of hunger (Haidle 2010). Such artefacts are consistent with cognitive development based on the modular combination of several operational units that consti-

Figure 10. *(cont.)*

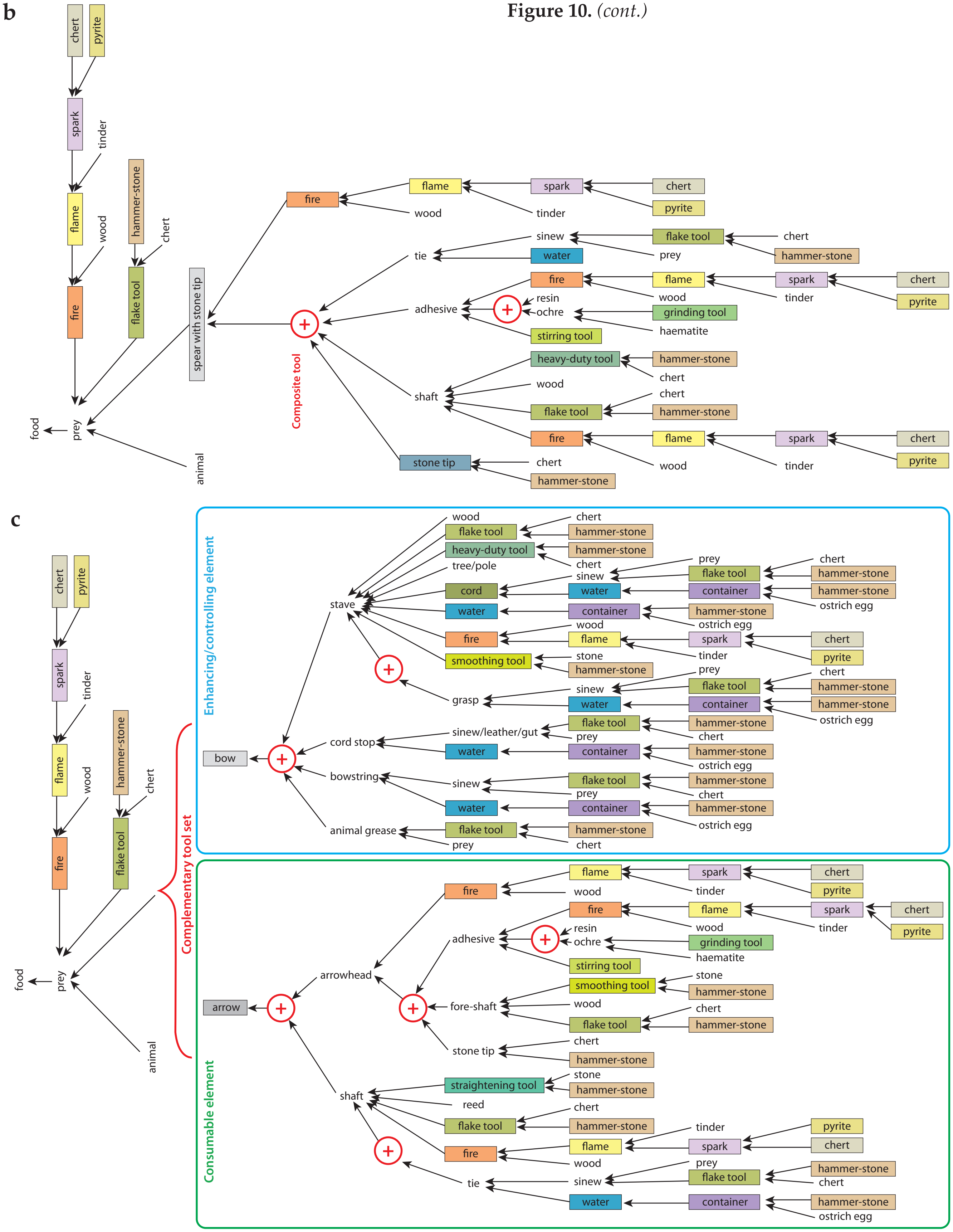


Table 1. *Comparison of cognitive requirements and evolutionary advantages between simple tools, composite tools and complementary tool sets.*

Weapon	**Cognitive requirements**	**Evolutionary advantages**
Wooden (simple) spear	• Decoupling of tool and satisfaction of basic need. • Modularization of action units.	• The handling of complex thought and action sequences is facilitated. • The manageable complexity in tool behaviour increases — modularization.
Stone-tipped (composite) spear	• Decoupling of tool and satisfaction of basic need. • Modularization of action units. • Ability to combine several fully separate elements to create a new concept — composition.	• Combination of different elements made of the same or different raw materials with different properties/ functions. • Properties of the composite tool reach beyond those of its single components • Properties may be enhanced, provide a new combination or provide completely new properties — advanced modularization.
Bow-and-arrow set (complementary tool set)	• Decoupling of tool and satisfaction of basic need. • Modularization of action units. • Ability to combine several fully separate elements to create a new concept. • Ability to conceptualize a set of separate, yet inter-dependent tools — technological symbiosis.	• New properties of a tool. • Augmentation of modular flexibility — amplified modularization.

tutes the idea of composition. Such combinations go beyond a simple addition in sequence. By combining different elements made of the same or different materials, with different properties and/or functions, the properties of the composite tool or compound adhesive reach beyond those of its single components. These properties might represent an enhancement of the original properties of the components, a new combination of their properties, or a completely new set of properties.

The effective chain reconstructed for a bow-and-arrow set (Fig. 10c), shows a cognitive development expressed in technological symbiosis, i.e. the ability to conceptualize a set of separate, yet inter-dependent tools. It further increases the problem-solution distance, enabling the conceptualization of new technological categories representing yet another major increase in levels of behavioural and cognitive complexity and flexibility. Such complementary tool sets are able to unleash new properties of a tool, inconceivable without the active, simultaneous manipulation of another tool. Single elements are adapted to each other, only reaching their full potential when used in a symbiotic set. Complementary tool sets may possess stable parts that are effective on the flexible parts and, depending on how the elements are used, the properties of a tool set can change instantly. For example, a bow can be used with an arrow for hunting, with a drill bit as bow-drill, or with a fire stick as fire-drill. Another change of properties is possible by using different flexible elements in the same set. For example, including an arrow with a stone tip, an arrow with a blunt tip (possibly to hunt birds), or an arrow with a poisoned tip, etc. In addition, the effects of the complementary tool set can be enhanced flexibly by the number of variable elements in use. The repeated hand-delivered use of a non-composite or stone-tipped spear by an individual in a single hunting event is time consuming and often dangerous. In contrast, several and/or differently constructed arrows can be shot by a single hunter from a bow into the same target within a short time frame. We therefore suggest, that the main evolutionary advantage regarding the ability to manage technological symbiosis, by actively focusing on, and manipulating complementary tool sets, is the augmentation of modular flexibility (amplified conceptual, technological and behavioural modularization) (Table 1).

Discussion

The question now arises as to whether a hammer-stone and anvil used by a chimpanzee to crack nuts can be considered technological symbiosis or amplified modularization? The simple answer is no. A reconstructed cognigram of this activity with fixed anvil (e.g. a rock, or a root of a tree) illustrates that there is only one tool, the hammer-stone, which is actively manipulated. There is no effective chain: the hammer-stone effects the nut actively, and the anvil has only a passive effect on the same object (Fig. 11a). If a movable anvil is used in the nut-cracking process (Fig. 11b), another phase 'position control of anvil' is amended with additional actions. The number and type of foci, however, is the same (Fig. 11a–b). Nut cracking with a hammer-stone and anvil involves three foci beside the subject but it is important to note that only one active focus (other than the subject itself) is open and actively effective. An effective chain is not existent because there is no effect of the anvil (which is not a tool, but a specific location if it is fixed, or a proto-tool if it is movable) on the hammer-stone, or *vice versa*. The cognigram

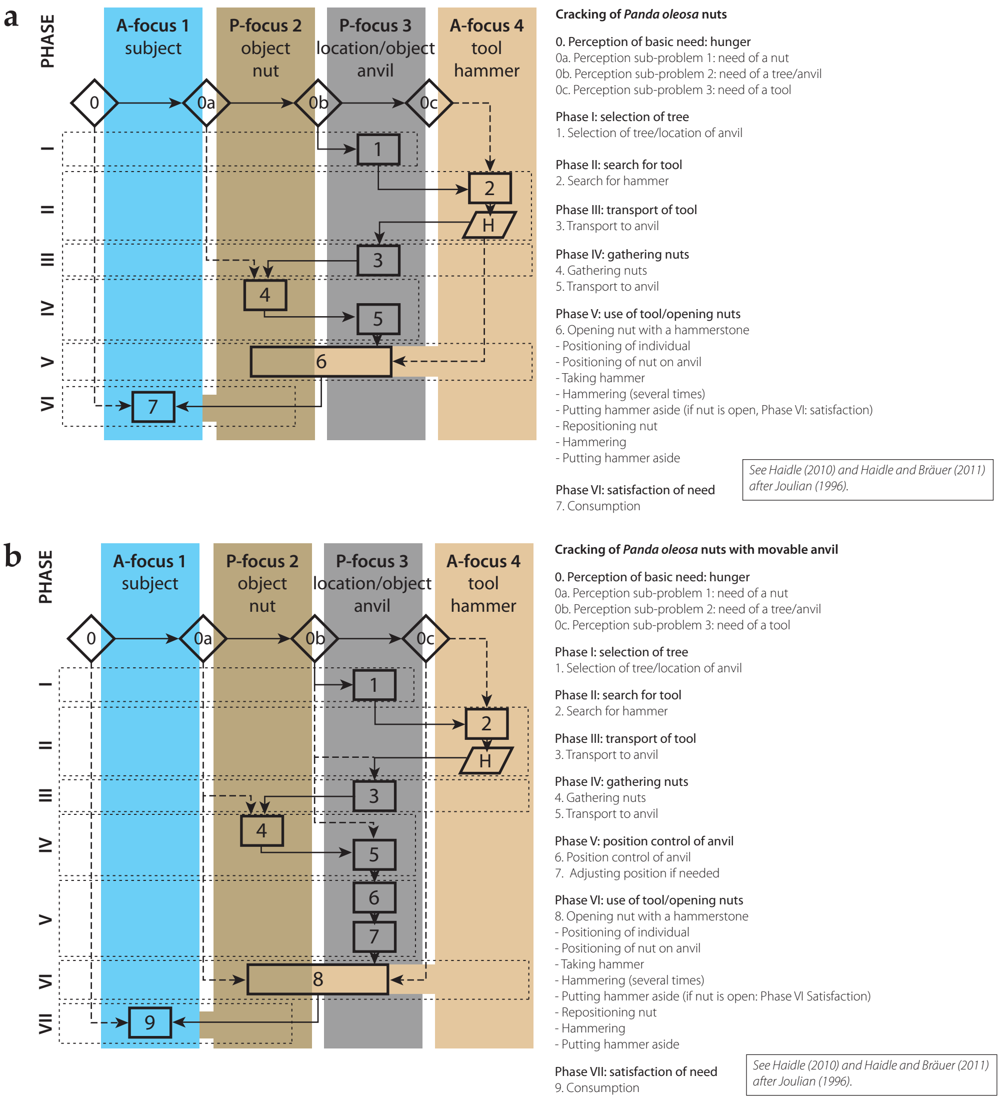


Figure 11. *Cognigrams for the cracking of* Panda oleosa *nuts by chimpanzees.*

shows some distance in problem-solution (Fig. 11a–b), but, the properties of neither tool (hammer-stone) nor location or proto-tool (anvil) are changed as a result of using them for a single purpose.

Chimpanzees have also been recorded to use different tool types in sequence to solve distinct sub-problems within one process. For example, they were observed to apply two different two-tool sets in tasks to extract termites, or to use up to three different tools in accessing honey (Sanz *et al*. 2004; Sanz & Morgan 2007). Using our definition, these tool sets cannot be considered complementary. Yet, the associated behaviours already show a realization of the need for two different tools to solve a problem sequence. Different foci have to be open and managed in the correct sequence to achieve the goal. Different components of the problem-solution process are perceived in advance, indicating planning. Chimpanzees, therefore, show a distinct flexibility in all aspects of cognitive behaviour, including contexts and problem-solution distances (Haidle 2010). Notwithstanding such flexibility, in all recorded tool behaviours associated with chimpanzees, both or all the tools are applied to the same object (the termite nest, honeycomb or nut). This is opposed to secondary tool use (Kitahara-Frisch 1993), where one tool is used to produce another tool, which is then applied to the basic need. Thus, even the most complex chimpanzee tool behaviour fails to demonstrate the basic ability to apply tools in an effective chain which is the prerequisite of composite and complementary tool use.

We maintain that the same principle applies to the human archaeological record; not all tools used consecutively or simultaneously can be considered complementary tool sets or examples of technological symbiosis in a cognitive sense. Only those demonstrated to represent amplified modularization — i.e. all four cognitive requirements for such tool sets including: a) the decoupling of tool and satisfaction of basic need; b) the modularization of action units; c) the ability to combine several fully separate elements to create a new concept; and d) the ability to conceptualize a set of separate, yet inter-dependent tools — can be interpreted as such (see Table 1). The principle of tracing complementary tool sets in the archaeological record is therefore not a quick fix for extrapolating complex cognition from every Middle Palaeolithic or Middle Stone Age grinding- or hammer-stone. Rather, it is an approach that requires careful consideration of the thought-and-action processes involved, and how the elements and activities relate to each other. Viewed separately, much information about cognitive aspects such as goal-oriented decision-making, sequencing of actions, or flexibility in problem solution is lost. Cognigrams provide an integrated approach where action steps are pooled in phases of action assigned to different attention foci. The method incorporates all separate, discrete elements of attention that form part of the sequence including the acting subject, objects to be treated, locations and actively handled tools (Haidle 2010).

The full decoupling of tool and satisfaction of basic need, and the increased modularization of action units can already be postulated for simple wooden spears at >300 kya (Haidle 2009; 2010). We have previously mentioned that the more tools and their manufacture can be dissociated from immediate subsistence aims, the more problems become soluble. The full set of consequences of this decoupling and modularization, however, unfolds only in more progressive cognitive expressions. In composite tools, the modularization does not only make the initial production process easier, it also facilitates the maintenance of the system. Single elements such as a spear tip can easily be renewed without thinking through the complete processes of producing and using a stone-tipped spear. Additional elements, such as binding materials and tips, can be made in advance and curated as stock or spare parts. The decoupling of tool production from basic need provides the tool with independent existence. Such tools have the potential to provide solutions for problems yet to be identified, for example, the same stone point can be hafted as either spear tip or knife blade depending on the situation. Thus, problems are no longer perceived or solved solely in the immediate or extended present. With modularization and composition, cognitive time depth is growing (Haidle 2010).

Advanced modularization and composition represent the modification of cognitive tool behaviour that opens the way towards a vast expansion of problem solutions (Haidle 2009). The modular organization of thought-and-action processes constitutes an important simplification of complex multifaceted operations facilitating solutions that would otherwise hardly be considered (also see Beaman 2010). The cognitive evolution towards modular organization of object behaviour was gradual with several species showing extension of object behaviour and expansions of problem-solution distances. These extensions and expansions offer increased flexibility in different solutions for one problem, diverse needs met with one solution, the application and sequencing of action steps, the contexts in which problems are perceived, and combinations of tools, materials, uses and technologies associated with a single process. However, so far, only hominins seem to have developed the basis of more complex tool behaviour by secondary tool use: the use of tools to produce other tools to satisfy a need.

With complementary tool sets, or technological symbiosis, the advantages of modularization increase exponentially into what we refer to as amplified modularization. The production and maintenance processes are facilitated in a similar way as suggested for composite tools. Yet, additional elements can be stocked, not only as spare parts (a second bowstring, in case the original snaps during the hunt), but also as variants (arrows with different heads for different prey types), or as copies (a set of arrows with the same heads for several shots on the same/similar prey). In the case of bow-and-arrow technology, different projectile types (which are also easy to carry in numbers) can be instantly selected or changed depending on situation or encountered prey type. It also has the advantage of easily facilitating multiple shots fired by the same hunter in quick succession, without being in reaching distance of the prey. Consequently, flexibility regarding decision-making and taking action is amplified with the option of using complementary tool sets. The modular, hierarchical organization of operational processes is a consequence of extensions and expansions regarding object behaviour and problem-solution distances. It allows a range of cognitive and behavioural complexity and flexibility that is basic to modern (current) human behaviour.

The statement above returns us to the debates about tracing early expressions of complex technologies and behaviours and differences and/or similarities between Neanderthals and early modern humans.

In this article we used the recent evidence of bow-and-arrow technology in southern Africa at 64 kya as an example of amplified conceptual, technological and behavioural modularization. Previously we alluded to the fact that it was proposed that such weapons enabled *Homo sapiens* to overcome obstacles allowing them to disperse from Africa into Eurasia after *c.* 50 kya (Shea & Sisk 2010). The technology probably spread to western Eurasia along with dispersing *Homo sapiens* populations but, according to Shea and Sisk (2010), neither insufficient intelligence nor inadequate biomechanics are plausible explanations for the absence of evidence for mechanically-projected weaponry amongst the Neanderthals. Rather, they argue that the situation may reflect energetic constraints and time-budgeting factors associated with such complex technologies.

Conversely, based on the work presented here that explicitly set out to assess levels of complexity in tool behaviour in cognitive terms, we suggest that it is premature to dismiss a cognitive explanation for the conceptualization and use of mechanically-projected weaponry or other examples of technological symbiosis in the form of complementary tool sets (as defined in this article: see Table 1). A cognitive explanation does not rule out the possibility that species other than our own may have produced such technologies — even though unambiguous evidence remains elusive. It also does not imply that Neanderthals were not weighed down by their higher daily calorie requirements (compared to *Homo sapiens*), leaving them with insufficient time to develop mechanically-projected weaponry, and impacting on how they integrated technology with their subsistence and land-use strategies (e.g. Shea & Sisk 2010). Perhaps, as is so often the case in human history, it was a permutation of factors including subsistence requirements, the environment, and the tempo and direction of cognitive evolution that caused Neanderthals not to develop mechanically-projected weaponry (also see Kuhn 2006; Lombard & Parsons 2011).

On the other hand, the cognitive explanation robustly supports the hypothesis that mechanically-projected weaponry – as an example of a complementary tool set signalling the development of technological symbiosis, and as such, amplified conceptual, technological and behavioural modularization — enabled *Homo sapiens* to overcome obstacles and played a role in our successful dispersal across the globe. Similar to our permutation argument regarding its seeming absence amongst the Neanderthals, we agree with Shea and Sisk (2010) that this scenario does not necessarily refute the potential synergetic roles of symbol use and demographic change in explanations for this dispersal. We also agree that the significance of mechanically-projected weapon technology has been underestimated in models for the global dispersal of *Homo sapiens*. Our reasons for agreeing on this latter point, however, may differ.

For us, contemplating the concepts of technological symbiosis and amplified modularization (expressed in the production and use of a bow-and-arrow set), the ecological niche-broadening strategy reaches further than subsistence behaviour. Yet, once such complex technologies became an option, there is no rule that dictates their becoming or remaining the only solution to a problem (Lombard 2011; Lombard & Parsons 2011; Parsons & Lombard 2011). As modern humans we are known for our boundless flexibility; within a matter of seconds we may choose to use anything from the simplest to the most sophisticated of technologies, depending on need and context. Amplified conceptual, technological and behavioural modularization was a significant step towards opening up almost limitless options to actively and effectively engage with our needs and our environments, be they natural, cultural or socio-economical.

Conclusion

The increase in cognitive, and consequently behavioural, flexibility is the main evolutionary advantage of complementary tool sets or symbiotic technologies — one that can hardly be overestimated. We suggest that once humans were able to fully decouple tools and satisfaction of basic needs, assemble objects and actions in an amplified modular way, combine several fully unrelated elements to create a new concept, and conceptualize a set of separate yet inter-dependent tools, the range of innovative and/or creative problem-solving became almost limitless. It is therefore our current hypothesis that evidence of the adaptation towards using complementary tool sets, that demonstrates technological symbiosis and amplified modularization, signifies a major cognitive step forward as it offers instantaneous and spontaneous flexibility to effectively handle any one possibility or situation out of a suite of diverse foreseen (and unforeseen) scenarios.

It is not finding the artefacts, or providing evidence for the presence of early mechanically-projected weaponry that is most important. Key is the fact that, when unambiguous evidence for their mode of delivery can be established, they are a clear indication of the cognitive concept of technological symbiosis, and therefore the capacity for extended and enhanced (amplified) conceptual, technological and behavioural modularization. Not all complementary tool sets have to be as complex as the bow-and-arrow set described in this article. Other examples of such tool sets or technological symbiosis can be found in the production and use of a spearthrower and dart, a hammer and chisel, or a fishing rod with line and hook. It is therefore not the artefacts themselves, nor their apparent complexity, but the cognitive components or concepts which they represent that may contribute to current debate.

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Marlize Lombard
Department of Anthropology and Development Studies
University of Johannesburg
PO Box 524
Auckland Park
Johannesburg 2006
South Africa
Email: mlombard@uj.ac.za

Miriam Noël Haidle
Heidelberg Academy of Sciences and Humanities
Senckenberg Research Institute
Senckenberganlage 25, D-60325
Frankfurt am Main
Germany
Email: miriam.haidle@uni-tuebingen.de

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Author biographies

Marlize Lombard is associate professor in Archaeology, Department of Anthropology and Development Studies at the University of Johannesburg. Her current research focus is on development, change and variability in Middle and Later Stone Age hunting and hafting technologies over the last 300,000 years in southern Africa and their role in recent human evolution and cognitive and behavioural complexity.

Miriam Noël Haidle is an archaeologist and palaeoanthropologist specialized on cognitive and cultural evolution. Her work focuses on comparative studies of object behaviour of animals and hominins. Currently, Haidle coordinates the research center 'The Role of Culture in Early Expansions of Humans' of the Heidelberg Academy of Sciences and Humanities at the Senckenberg Research Institute and the University of Tübingen.