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Stone knapping

the necessary conditions for a uniquely hominin behaviour

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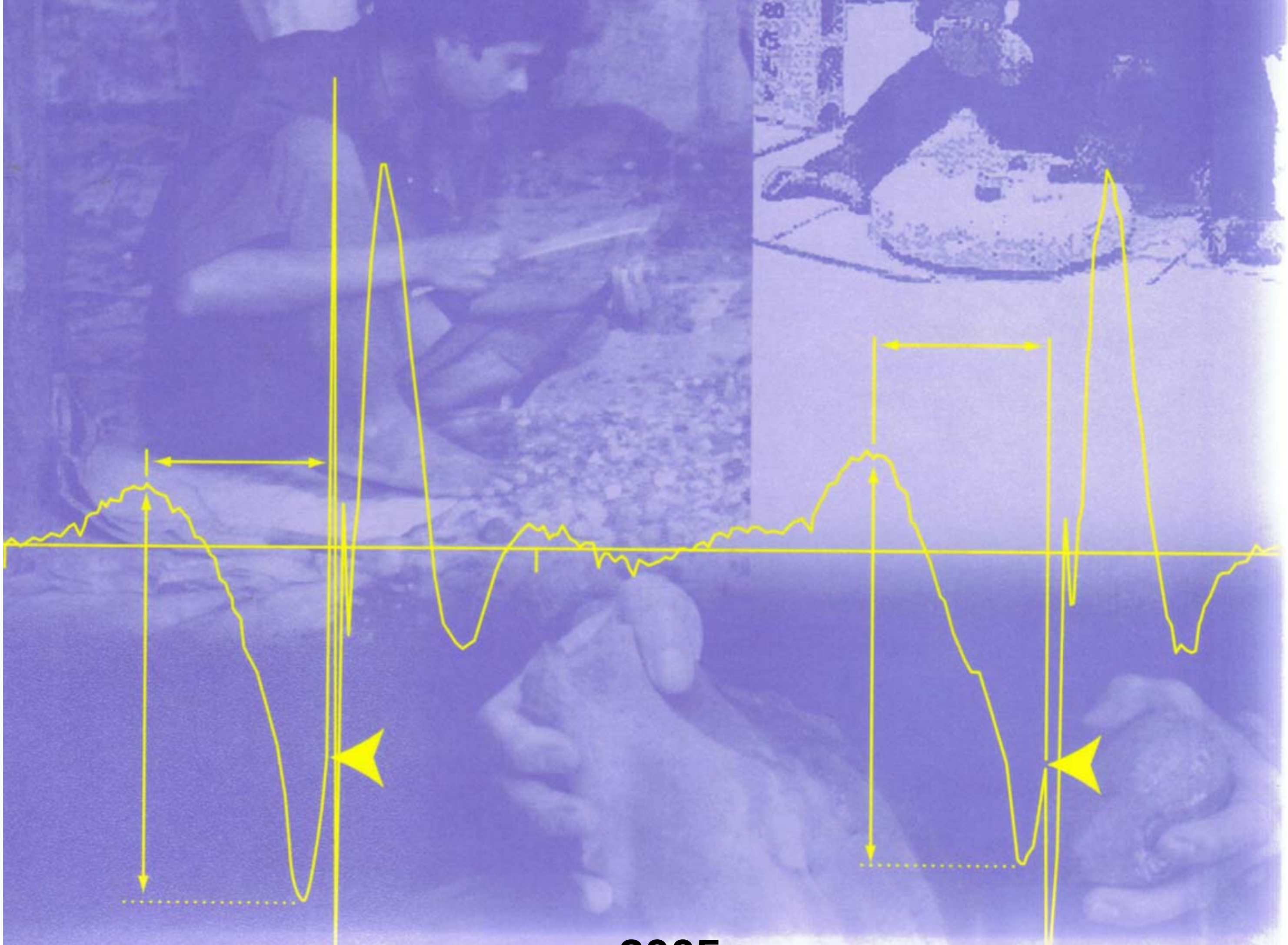

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Chapter 1

General Introduction: a Dynamic Systems Framework for Studying a Uniquely Hominin Innovation

Valentine Roux & Blandine Bril

> The Oldowan lithic culture differs from anything known for free-ranging apes, but all of the capacities needed to make it are manifested in the non-lithic tools of chimpanzees (Wynn & McGrew 1989). The challenge is to find anything uniquely hominid in the capacities needed to make these artefacts (McGrew 1993, 165).

Evidence of stone knapping first occurs in East Africa during the late Pliocene, *c.* 2.6 million years ago (Myr). This is the beginning of a long technological story during which different genera (*Australopithecus* and *Homo*) and species coexisted and evolved. The technological story describes the development of more and more elaborate knapping processes, as reported by Jacques Pelegrin. Hélène Roche's recent research in Turkana, northern Kenya, however, reveals that Oldowan lithic assemblages (between 2.6 and 2.2 Myr) are not as homogeneous as previously supposed. They represent the legacy of both awkward opportunistic knappers and, on the contrary, skilled knappers who controlled the flaking process through careful core monitoring. Oldowan lithic variability raises the question not only of the genus and species assumed to be the tool-makers, but also of the reasons that might explain why some groups performed better than others. Could it be a question of differences in competence and/or performance? Might these differences in competence act as adaptive values in the selective process that underpin hominin evolution?

The tentative purpose of this book is to characterize the capacities involved in stone knapping. The question of their specificity remains a highly-controversial issue. Considered essential for a better understanding of what distinguishes early hominins from non-human primates, the specificity of stone knapping has been tentatively explored in numerous studies. The issue has been addressed either by assessing the non-human primate capacities involved in tool use and tool-making (e.g. Boesch & Boesch 1990; 1992; 2000; McGrew 1992; 1993; Wynn & McGrew 1989), or by teaching stone knapping to primates (e.g. Schick *et al*. 1999; Savage-Rumbaugh & Lewin 1994; Toth *et al*. 1993; Wright 1972), or by interpreting lithic industries in terms of motor and cognitive skills in reference to neuropsychological concepts (e.g. Pelegrin this volume; 1993; Wynn 1985; 1991; 2002a; Roche & Texier 1996; Roche *et al*. 1999; Schlanger 1996). Primatologists contend that compared with non-human primates, Oldowan toolmakers do not display distinct motor or cognitive capacities (e.g. Joulian 1996; Wynn & McGrew 1989), even though they admit that it is problematic for chimpanzees to learn how to knap stone. In this respect, the experiments conducted with Kanzi (Savage-Rumbaugh & Lewin 1994) are very telling (Schick *et al*. 1999). Kanzi understands that producing flakes is a means of obtaining cutting edges. In addition, he understands that flakes can be obtained by breaking stones. Yet, after a few years of apprenticeship, Kanzi only manages to produce splinters, with accidental conchoidal pieces looking like 'flakes' (Pelegrin this volume). In other words, Kanzi has not succeeded in learning how to knap stone. He is definitely unable to control the conchoidal fracture. Savage-Rumbaugh suggested that: '... if Kanzi is limited in the quality of flaking through hard-hammer percussion, it is the result of biomechanical, not cognitive, constraints' (Savage-Rumbaugh & Lewin 1994, 219). The hypothesis that the specificity of stone knapping could pertain to motor skill has been taken up by a few archaeologists (e.g. Ambrose 2001). Few studies, however, have focused on this skill-related behavioural aspect of tool-making. Most of them focus on the cognitive capacities that one might infer from lithic industries (e.g. Gowlett 1992; Pelegrin 1993; Toth 1993; Wynn 2002a).

In order to renew the approach to the question of this uniquely hominin invention, the knapping

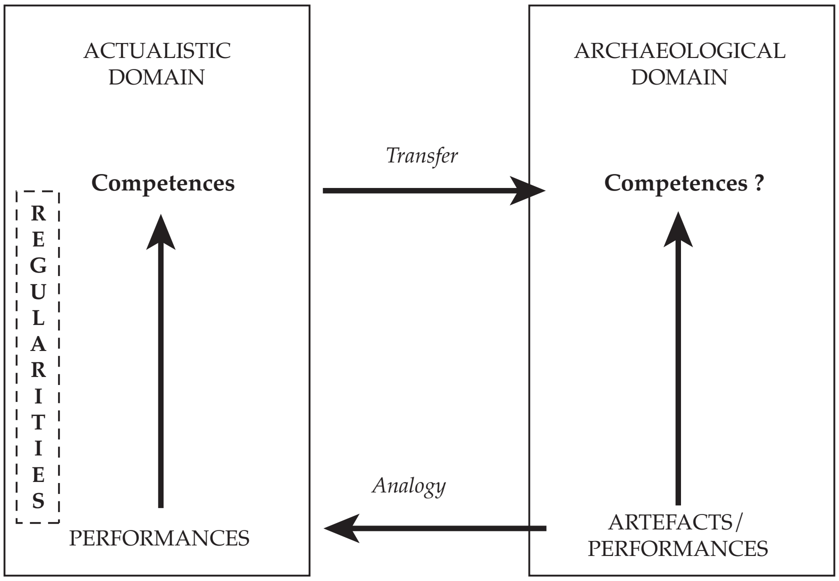

Figure 1.1. *Analogical process according to which archaeological data are interpreted in reference to actualistic regularities (after J.C. Gardin 1979).*

task is studied here in the light of other skilled activities and various disciplinary perspectives. As stated by Thomas Wynn (2002b, 718), 'all studies of skilled activity can provide potential analogues and ... more general accounts of human and non-human cognition can provide important insights'. These studies are mainly actualistic: they are psychological, biomechanical, anatomical, neurological, primatological and ethnoarchaeological. Indeed, the interpretation of artefacts requires that knowledge external to archaeology should be drawn upon (Gallay 1986). Prehistoric artefacts are interpreted following a reasoning by analogy and by transfer of attributes (Gardin 1979). In the case of lithic industries, performances are indicated by the objects themselves. They are deciphered through technological analyses, which enable prehistorians to reconstruct the entire evolution of lithic technology. On the contrary, the competences that underpin observable performances, as well as the conditions for the effectuation of these competences, are not 'given' by the artefacts themselves. They are necessarily interpreted in reference to actualistic data, which associate performances with competences. In other words, given that regularities between performance and competence are established in actualistic domains, prehistoric artefacts can be interpreted in terms of competence (Fig. 1.1). The regularities studied here refer to the competences that underpin skilled tool-related behaviour, to the bio-behavioural, anatomical and neuronal conditions needed for their development, and to the socio-cognitive conditions required for their actualization. They are highlighted through comparative studies of human and non-human primate tool-related skills, in order to apply them to stone tools made by the early hominins for whom no analogues exist.

Following the principles of the analysis of technological change (Roux 2003), this volume is organized into three sections. The first section includes such papers as contribute to characterize stone knapping in terms of techniques and skills. The second section includes papers which contribute to the study of the mechanisms that underpin the effectuation of the skills involved in stone knapping. The study of these mechanisms should bring to light the essential prerequisites of stone knapping and help assess the extent to which the skills involved in stone knapping are specific to human primates, as compared to non-human primates. Finally, the third section presents the papers pertaining to the definition of the socio-cognitive conditions needed for the actualization of stone knapping, the focus shifting at this point from invention to innovation.

Invention and innovation are here clearly distinguished from one another. Invention is what happens locally, on an individual scale. It affects the evolution of the system when it becomes an innovation through being widely accepted (van der Leeuw & Torrence 1989). Innovation is a complex social and anthropological process characterized, like any complex system, by interactions between numerous non-hierarchically-ordered components which, in the present case, operate in and across the technological and the social domains (Roux 2003). The main components are the technical task, the subject and the environment. Innovation stems from interactions between the properties of these components (Fig. 1.2). An analysis of innovation thus requires the analysis, not only of the technical task, but also of the subject's intention(s), which are rooted in the socio-cultural arena and its collective representations, and of the environment. As a historical process, innovation corresponds to a local scenario (Gallay 1986), which has to be reconstructed on the basis of the archaeological data liable to provide information on the cultural specifics as expressed in the subject's intention(s), and on the basis of environmental data (the evidence of remains and theoretical modelling). The study of local scenarios and their related metaphoric explanations is beyond the scope of this book, which focuses mainly

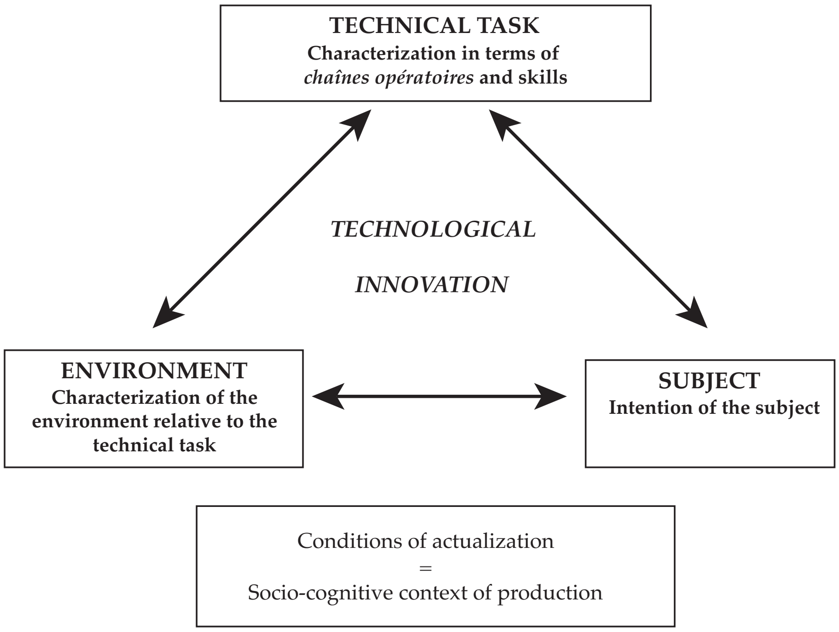

Figure 1.2. *The dynamic process of technological change (after Roux 2003).*

on the invention of stone knapping, a process that operates at the level of the technical task. It also, however, includes papers on the conditions required for the actualization of stone knapping as an innovation.

Stone knapping: characterizing a tool-related task

To begin with, it should be specified that the technical task, as one of the three components of the innovation process, refers on the one hand to the technique that allows the transformation of raw materials into objects, and on the other hand to the motor and cognitive skills that convert technique into action. It can be described independently of the cultural context within which it takes place. It is a subsystem that possesses its own dynamics and is supposed to become an emergent property of the technological system, but whose actualization proper depends on the dynamics of the technological system (the innovation process). Skills are at the heart of the mechanisms that underlie changes in technical tasks, since a new technical task necessarily requires new skills (Bril & Roux 2002). The skills that make a technological invention possible can be characterized as either continuous or discontinuous, depending on whether the individual has to acquire new capabilities or can build on pre-existing ones.

Because the study of a technical task requires that it be characterized in terms of techniques and skills, this first section comprises introductory studies presenting the techniques of stone knapping, followed by studies on the skills involved in tool-related tasks.

Stone knapping: a technical characterization

A technique is defined as the physical modality according to which raw material is transformed (Tixier 1967). As shown throughout prehistory, a technical task can be achieved using different techniques. Studying the invention of stone knapping implies a fine understanding of the physical modalities according to which the first lithic tools were made in order to characterize this task compared to other percussion tasks such as nut cracking. Indeed, nut cracking, as a percussive technique, has been often considered as the technical action from which stone technology (e.g. de Beaune 2004; Sugiyama & Koman 1979) or the intention to flake (e.g. Marchant & McGrew this volume) developed. As we shall see, however, nut cracking and stone knapping call for different physical modalities by which nuts or stone are transformed. As underlined by Pelegrin, who summarizes the characteristics of stone knapping, these are not comparable techniques.

Stone knapping responds to the mechanism of conchoidal fracture. It must be distinguished from split breaking. Conchoidal fracture alone ensures that the transformation of the stone is controlled. Split breaking is caused by a forceful stroke, with no control over the fracture of the stone, which then breaks in unexpected ways. A conchoidal fracture refers to the Hertzian cone phenomenon. Detaching flakes by conchoidal fracturing implies the control of numerous parameters and requires, in particular, much more precision than split breaking, which allows for a large precision tolerance. In conchoidal fracturing, the stroke has to be applied near the edge and at no less than a 90° angle; precision of the stroke determines the geometric characteristics of the detached flake. Pelegrin's contribution is essential for understanding that the lithic production made by Kanzi is not obtained by controlled conchoidal fracturing and that, in this respect, Kanzi's technique for making splinters is comparable to the nut-cracking technique alone, that is, split breaking. Controlled conchoidal fracturing can be achieved according to different techniques. Techniques must be distinguished from methods. Methods relate to the organized reduction processes. Pelegrin recounts how stone-knapping methods became more and more elaborate during prehistory, testifying to what could be specifically human cognitive capacities.

Now, as reported by Roche, the earliest-known lithic industries provide clear evidence of conchoidal fracturing. These industries belong to late Pliocene archaeological sites (2.6 Myr to 2.2 Myr) from East Africa, where no fewer than five species grouped into two genera (*Australopithecus* and *Homo*) are present at the time. These industries may be characterized as heterogeneous. On the one hand, there is a type of flaking that can be qualified both as simple, given the limited succession of removals achieved, and as poorly skilled, as shown by percussive strokes whose points of impact sometimes lack precision (as at Gona and Lokalalei 1). On the other hand, there is a surprisingly well-organized debitage of flakes that testifies to a high degree of control over the percussion gestures, as specifically shown by the total absence of 'hammering' on the cores. This is the case at Lokalelei 2c. Refittings on 13 cobbles demonstrate a genuine monitoring of the cores. In one case, up to 73 flakes were detached from a single cobble. Evidence of such an organized debitage is not even attested in the Early Pleistocene. Roche emphasizes the fact that the Lokalelei 2c lithic assemblage testifies to an exceptional command of elementary gestures associated with a well-controlled unfolding of series of removals. Still, several hundreds of thousands of years will have to pass before prehistoric stone knappers are able to free themselves from the initial geometric characteristics of the raw material and give the stone the desired morphology. Roche also recounts this later part of the history of lithic technology, up to the moment when the genus *Homo* becomes predominant.

Stone knapping: characterizing the skills involved

Acting in everyday life presupposes the capacity to perform goal-directed actions, that is, the faculty to produce conclusive behavioural sequences that bring the agent nearer the objective. Tool use and tool making are complex actions that involve compound sequences of movements to carry out the task at hand. Tool use entails interacting — most often manually — with objects in the environment. This places significant challenges on the cognitivo-motor system. To address the issue of the nature of the skills involved in tool use it is common nowadays to contrast two different approaches to action.[1] One approach, referred to as the computational or cognitive approach, postulates that action depends upon an internal representation; action is guided by a pre-existing representation. This approach has been more concerned with the nature of the processes that precede action rather than with the way the action itself is carried out. This 'motor system approach' emphasizes an information-processing perspective, the existence of some kind of 'central representation', 'internal models', or 'motor commands'. Along this theoretical position, the agent activity is directly caused by some kind of planning that controls the production of behavioural sequences.

The second theoretical approach, referred to as the ecological approach, stresses the reciprocal role of the organism and the environment acting as a set of constraints from which behaviour emerges. This approach considers the agent as participating in the world, not as controlling it, and insists on the action as being the result of the functional coupling between the organism and the environment. This 'action system approach' considers itself to be more appropriate to the study of everyday life skills (Reed 1988).

Goal-oriented action: the 'motor system approach'

'Knowing how' and 'knowing that' are often considered when everyday life technical or tool-use skills are referred to. This distinction echoes two different types of knowledge, procedural and declarative knowledge (Anderson 1980), each implying two distinct encodings or representations (Annett 1996). Knowledge associated with motor actions is usually considered as procedural, which is implicit, hence unconscious. By contrast, 'knowing that' qualifies declarative knowledge, available to consciousness. As a result, it can be expressed verbally. A clear definition is given by Parker & Milbrath (1993), who consider that:

> knowing how 'to make a tool' is an example of procedural knowledge which also constitutes procedural planning. While preceded by intention, procedural plans are represented primarily in action schemes, which if interrupted can be modified on the spot. In contrast, planning based in declarative knowledge involves representation which in turn allows for anticipation of consequences and modification of planning sequences before plan execution. Declarative knowledge is more flexible . . . (Parker & Milbrath 1993, 315)

Miller *et al*.'s (1960) seminal definition of planning is often referred to:

> A plan is any hierarchical process in the organism that can control the order in which a sequence of operations is to be performed (Miller *et al.* 1960, 16)

Here emphasis is placed on the ability to structure the serial order of the organism's behaviour. This traditional view considers that the notion of plans addresses the question of structure. In other words, an action has the structure it does, because it arises through the execution of entities called plans, which have the same structure.

The problem becomes more difficult when simultaneously considering both a sequence of actions and the elementary actions that are called upon to carry out the global action. In both cases planning is called upon. Jeannerod (1997), among others, considers that simple actions are embedded in more complex actions; that is, elementary actions are sustained by higher-order factors, which refer to the final goal of the action. Here the main function of planning is to select, from a stock of available 'motor schemas', those

> which will have to be performed, relate them to the proper internal and external cues, and organize them into an appropriate sequence (Jeannerod 1997, 127).

Along this line, planning consists essentially in selecting stored elements — schemas, scripts — that will best satisfy the goal, and regulates their modality and time of expression. It is acknowledged, however, that the whole course of action need not require a complete representation of the detailed succession of elementary actions, and that part of the process may be carried out on-line. If difficulties arise, changes in planning will be made and search for other and more appropriate schema will be accessed and selected and accordingly more suitable action performed.

This view grants 'plan' as program a causal role. Plan as program determines the agent activity. Yet this theory does not offer a convincing account of how actions are adapted to their circumstances, how uncertainty is faced up to. As real life is characterized by the unfolding of continuous unpredictable events, behaviour must denote flexibility and adaptability. In this classical view, the 'homunculus' is asked to make an overwhelming number of decisions, which requires an overwhelming amount of information besides a huge repertoire of action schemas or action representations. In addition, the origin of these representations there remains a difficult question to deal with. The other puzzling issue difficult to meet concerns the processes that 'bridge the gap between ideas (or representation) and behaviour, a "miracle"', to use Kunde's (2001) words, often taken for granted. How can an abstract action plan be translated into a concrete motor behaviour? How is a single one chosen among the infinite number of equi-functional action/motor representations? One view developed by artificial intelligence is to give planning a smaller role. Agre & Chapman (1990) consider planning as a resource among others. The agent participates in the world, but does not control it. The 'plan as communication' as opposed to the 'plan as program' does not directly determine the agent's actions. A plan is a resource, i.e. a plan guides activity but does not give solution to problems (Agre & Chapman 1990). Here again, however, while this view does not ascribe behaviour to one main cause and emphasizes the multi-causal origin of action, it does not really elucidate the guiding function of such a plan. In addition it works at the level of the sequence of actions, not at the level of the elementary action.

Goal-oriented action: the 'ecological' framework

To overcome these difficulties the ecological framework proposes a thoroughly different approach — one that has been adopted, to a certain extent by most of the contributors to this volume who are studying skills as a complex phenomenon (Bril *et al.*; Bushnell; Corbetta; Cummins-Sebree & Fragaszi; Jacobs *et al.*; Lockman; Roux & David; Smitsman; Stout). Originating in the association of Bernstein's (1967) view of motor control, which leaves 'as little as possible residing in the homunculus', and Gibson's (1977) perception/action overtures, the ecological framework offers new foundations for action apprehension. As the focus of this volume is not to give an exhaustive presentation of the ecological framework, we shall present the main features that we think are fundamental to understanding why this approach is presented here as an alternative to more cognitive views.

The main trait of the ecological perspective is to consider the organism (human or animal) as part of a larger system. More specifically it is the mutual relationship between the organism and the environment that is central to the analysis. The environment is described not in physical but in ecological terms, and behaviour is viewed as a solution a person engaged in a goal-oriented action has been able to perform, owing to the environmental constraints. Behaviour is then considered as an emergent phenomenon. Stable action modes emerge from the dynamics of the organism–environment system, which is in turn guided by the information produced by the ongoing action, and therefore specific to these dynamics (Warren 1990). Gibson (1986) expressed it in what has become a notorious maxim: 'We must perceive in order to move, but we must move in order to perceive' (Gibson 1986, 223).

Shaw & Wagman (2001) recently rephrased this idea that perception and action are mutually interacting, through an information field in the following way:

> Any adequate theory for perception and action linkage should satisfy an intentionality condition — that perceiving refers to acting, and acting refers back to perceiving. Similarly, ecological psychologists generally agree that a circular causality holds between perceiving and acting, where agents perceive how to act to reach a goal and then the acting updates the next goal-specific perceiving, which then updates the next goal-relevant acting, and so on until the goal is reached or the effort aborted. Goal-directed activities conform to a perceiving-acting 'cycle' wherein information and control reciprocate under mutually shared intentions (Shaw & Wagman 2001, 905).

Three concepts — constraints to action, degrees of freedom and affordances — are essential for understanding the ecological framework, and more specifically for understanding why this approach may be fruitful when discussing issues relating to stone knapping skills.

Constraints to action: Newell (1986; 1996) considers that three sources of constraints combine to provide the boundary conditions to carry out an action: the organism, the task at hand, and the environment. The organism embraces all the dimensions of a person (or a non-human primate): his/her physiological, biomechanical, neurological, as well as cognitive, and affective facets. The task properties refer to its functional properties, that is, to what the organism must produce to successfully reach the goal. Walking, for example, consists of displacing the body ahead, along the anteroposterio axis, by means of a succession of unipodal and bipodal stances, with the constraint of alternate left and right unipodal stances. To successfully reach the goal, one must produce forces that will 'cause' the intended gait movements. The environment comprises universal constraints experienced by all living organisms, such as gravity or temperature, and more specific and local constraints such as tools. Back to the example of walking, considering walking behaviour as emerging from these three sources of constraints focuses the analysis on the possible range of variation of the action, and more precisely 'on the emerging properties of the co-ordination modes of action, and to the resultant expression of skill' (Newell 1996, 405). The gait movements differ in toddlers and in adults, in visually impaired persons compared with persons with normal vision, or for the same person when walking on a flat surface, uphill or downhill. Exactly the same demonstration can be made for knapping movements.

Degrees of freedom: The degrees of freedom of a system refer to the number of independent dimensions to be controlled. The question of the degrees of freedom in movement has been to a large extent developed by Bernstein (1967; Turvey *et al.* 1982). Usually it is considered that the greater the number of degrees of freedom of a system, the more difficult the control. Depending on the level of analysis the number of degrees of freedom varies greatly. As far as joints are concerned, the upper limb for example has seven degrees of freedom (see Biryukova this volume), the whole body about 10^2, but at the level of muscles the number of degrees of freedom is as high as 10^3, and 10^{14}, if the level of neurons is considered.

Bernstein viewed the degrees of freedom question as central to the understanding of movement co-ordination and skill. Due to the large number of degrees of freedom of the human body there is an infinite number of ways to solve any 'everyday-life motor problem'. As a result it is this great number of possibilities of action that guarantees the flexibility needed to adapt action to local circumstances (Newell 1996; Jordan & Rosenbaum 1989). Depending on the level of analysis, the main question is then: how are these degrees of freedom controlled? How is a system, with an infinite number of possibilities that would be impossible to control, reduced to a controllable system? This question is beyond the scope of this book (for a recent review see Roby-Brami *et al.* 2005), but is of substantial importance to understanding technical skills. For Bernstein, learning a (motor) skill consists of progressively mastering the redundant degrees of freedom of the system, and 'exploiting' these degrees of freedom of the organism–tool system (see Biryukova this volume).

Affordances: The organism–environment mutuality has been expressed by Gibson (1977; 1986) through the concept of affordance, an original word coined by Gibson himself. An affordance is a relation between an organism — human or animal — and its environment, that has consequences for behaviour. In other words, affordances are properties of the environment that have consequences for the organism behaviour (Stoffregen 2000). The properties of the environment constitute affordances only when taken in reference to the action capabilities of the organism. Recent views about affordances insist on the functional utility of the environment (Flash & Smith 2000). In other words what is perceived of the environment is its potential for action, as well as the potential consequence of action. In return, the intention to perform a specific action constrains information detection. This means that the affordances of the environment may be different from one organism to another. Affordances, however, need to be perceived, and therefore learning to perceive the information from the environment constitutes a necessary stage.

In sum, according to this view, the mastering of a technical skill depends on the capacity of an organism to set up the constraints of the system according to the task demand, and to mobilize adaptively the degrees of freedom of the system. At a behavioural level, the unfolding of the action may be viewed as an emergent process, at the interface of information available to the organism (affordances) and the set of constraints associated with the task.

Contrary to what has often been said, the ecological perspective does not deny that some kind of 'representation', or planning could exist. As suggested by Shaw & Wagman (2001), however, the ecological framework stipulates that 'program or symbols should be used sparingly, and then only to set subtle boundaries on dynamical processes'. Along this line Agre & Chapman's (1990) proposal to consider planning as resources that guide the unfolding of the course of action is not incompatible.

Three sub-sections of this volume organize the studies of the skills involved in technical tasks. The first sub-section gathers together papers concerned with stone-knapping case studies, such as stone-bead knapping, a craft still practised in India, and a study of experimental handaxe knapping. In a second sub-section, the motor and cognitive skills involved in tool use and tool making are further considered. These studies allow the characteristics of the competencies underlying tool making to be assessed at a more general level. In a third sub-section, the skilled behaviour developed by non-human primates is examined. The results obtained enable us, by comparison, to characterize the tool-related skills developed by human primates.

Skills involved in stone knapping

The studies by Bril *et al*., Biryukova *et al*., and Roux & David report field experiments conducted at Khambhat (Gujarat, India), one of the very rare places in the world where the stone-knapping technique still adheres to the principles of the conchoidal fracture. The technique practised is indirect percussion by counter-blow and is used for making stone beads. This technique is a recent one in the history of techniques. Assuming, however, that similar skills are required for mastering the parameters of conchoidal fracture, the situation can be considered an appropriate referent for studying the skills involved in stone knapping. In order to characterize these skills, a program of field experiments was developed. A field experiment is a compromise between fieldwork and laboratory experimentation. The craftsmen should operate in a setting departing as little as possible from their usual work context, but the nature of the data obtained should also allow the analysis of parameters usually studied under laboratory conditions.

The first study to be carried out was Bril *et al*.'s. The experiment was designed to uncover the features enabling high-level experts to be distinguished from lower-level experts. The aim was to tentatively disentangle and characterize the different dimensions of expertise. Referring to the distinction between technique and method, the process of knapping a roughout to produce a preform was analyzed along three levels of action:

1. the *course of action*, which refers to the way each craftsman actualizes the method; it corresponds to the 'path' of sub-goals produced to transform a roughout into a preform;
2. the *sub-goals*, that is, the way the different functional operations are actualized; a sub-goal is generally carried out by means of a succession of elementary actions, i.e. of strokes;
3. the *elementary action*, that is the flake removal; it corresponds to the actualization of the technique and is carried out by performing a stroke.

An original technical set-up was developed which made it possible to simultaneously record data on the course of action and on the elementary action. The elementary action was analyzed through its main functional dimensions, that is, the movement of the hammer by means of an accelerometer stuck on its head. The rationale for the experiment was the introduction of glass, a new raw material to be knapped. An experimental paradigm based on the capacity for transfer and generalization was considered. It was assumed that the higher the dexterity of the craftsmen, the greater their capacity to transfer to new situations. The results very strongly suggest that expertise rests on the elementary action rather than on the course of action. High-level experts are more capable than low-level experts of adapting the acceleration of the hammer to the raw material and to the length of the flake they want to remove. They have a more flexible behaviour, better adapted to the task constraints. Rather than from *a priori* planning of the overall task (level of the method), expertise thus appears to stem from a command of the dynamics involved in the task (level of the technique), that is, the dynamic coupling between the craftsman, the stone, the hammer and the anvil. Becoming an expert, argue Bril *et al*., consists of learning how to turn the properties of the system to best account in order to reach a given goal.

In this experiment the functional outcome of the percussive arm movement (i.e. the movement of the hammer) was analyzed. It was shown that high-level experts adapted the acceleration of the hammer in a more tuned manner than low-level experts. Once this tuning capacity was recognized as one dimension of high expertise, the next step was to try to understand how it is produced. For this purpose, a subsequent experiment aimed at qualifying kinematic arm synergies in craftsmen of different levels of expertise was carried out: craftsmen who participated in this experiment were high- and low-level experts, as well as high- and low-level learners. In addition to the accelerometer used in the Bril *et al*.'s experiment, an electromagnetic device was used to record the kinematics of the arm movement. The analysis led by Biryukova *et al.* is based on the fact that the human arm is kinematically redundant, which means that there are many ways to perform the same movement of the hammer using different combinations of rotations in the joints. The hypothesis was then that the peculiarities of the kinematic synergies should reflect the peculiarities of motor-control strategy in relation to the different levels of expertise. The comparative analysis of the kinematic synergies in high-level and low-level experts and in high-level and low-level learners led to the following conclusions. The low-level expert synergies are characterized by stereotyped kinematic patterns of both joint trajectories and hammer trajectories. On the contrary, the high-level expert synergies show flexible behaviours expressed in: 1) rich kinematic content of the synergies, i.e. large number of degrees of freedom, involved in the motion; and 2) a large repertory of motor synergies allowing the successful task completion. The analysis of the arm movement highlights the importance of a high degree of control over the elementary action, that is, over the technique.

In order to develop the relationship between the command of elementary movements and the course of action, Roux & David then studied the courses of action followed by craftsmen of different levels of expertise for transforming chalcedony pebbles into parallelepipedal roughouts. As far as planning is concerned, this knapping stage is supposed to be more informative than the transformation of roughouts into preforms because shapes and raw material are not standardized. The results obtained tend to confirm the previous conclusions, that is, that a knowledge of the methods is not sufficient for making high-quality roughouts. Methods are guidelines along which courses of action unfold. In this respect, they can be considered to represent pre-existing mental schemes. They are not sufficient, however, for the craftsman to act efficiently. Neither are adequate courses of action — which are the actualization of the methods — sufficient for making high-quality roughouts. Expert courses of action are mainly characterized by the use of efficient subgoals (typical removals) for rectifying delicate situations due to previous failed removals. The interesting point is that all the craftsmen know the subgoals required for making a roughout. Given that apprenticeship bears on the subgoals, that is, on the technique itself, rather than on the methods or the courses of action, the authors suggest that the effectuation of what could be called 'efficient' courses of action stem from the command of the technique. This hypothesis is borne out by the variability observed within and between craftsmen of different levels of expertise. Depending on how well the technique is mastered, knapping courses of action present an either flexible or rigid ordering of subgoals. Command of the techniques has implications for the perception of the task, which also affects the variability of the courses of action. Roux & David conclude that expertise in planning is linked to the command of elementary movements, a result that has relevant implications for the study of the evolution of lithic industries.

The results of the Khambhat studies converge with those obtained by Winton in the course of an experimental study conducted with modern-day knappers, both novice and skilled. Her objective is to gain a better understanding not only of the lithic variability observed on prehistoric handaxes, but also of the skills that prehistoric knappers had to develop in order to become skilled practitioners and make well proportioned, serviceable handaxes. For this purpose, she examines the procedure followed by the different modern-day knappers to obtain handaxes, through a fine analysis of their production. She observes mainly that the tools produced by novice knappers tend to be smaller than those made by skilled knappers. These short proportions appear to be due to the inability to detach large flakes during the 'roughing out' stage. These are thinning flakes, which are necessary for defining both faces of the tool as well as proper angles for future thinning and shaping of the handaxe. This problem of controlling different types of flakes is recognized to be the major difficulty met by novice knappers. Winton also notes that the last reducing stage may be the easiest for learners to accomplish, since the morphology of the 'roughout' 'more closely resembles the end product than did the unmodified unit of raw material'. This observation tallies with the observations made in Khambhat, where owing to the difficulty of controlling the detachment of thinning flakes, bead knappers learn to knap preforms before roughouts.

Further considerations on the skills involved in tool use

Stone knapping implies a dexterity whose characterization can be highlighted through the analysis of other types of motor behaviour. The principles of production of efficient strokes, be they stone flaking or tennis strokes, are examined by Ivanova, whereas principles of planning in tool use are discussed by Smitsman. Their studies enable us to assess the extent to which the results obtained for stone knapping can be generalized to other contexts.

In the first place, the importance of the fine control of the moving segments in strokes, as shown by the Khambhat data, is also demonstrated by Ivanova in different complex coordinated strokes. To be successful, a stroke necessitates the consecutive involvement of all moving segments to provide the required final velocity of the working point, which is the racket for tennis stroke, the hand for volleyball stroke, the foot for the football stroke, or the head of the hammer for the hammer stroke. Ivanova analyzes the generation of the working point velocity through the impulse transmission. A comparison between experts and non-experts shows important differences in the way the impulse is transmitted from proximal to distal segments. Impulse transmission is much higher for experts than for non-experts. The dramatic differences in the process of impulse transmission illustrate the very high complexity of body-segment coordination needed to produce the adequate velocity of the working point, be it the tennis racket or the hammer. This example clearly illustrates how expertise in motor behaviour rests on common principles, which can be identified at the level of the elementary action.

Secondly, considering action at a more general level, Smitsman *et al.* similarly outline the importance of the elementary action in the dynamics of the course of action. The authors elaborate on the general capacities involved in tool use and tool making. Because these activities are primarily actions that have an important motor component, Smitsman *et al*. consider that the necessary capacities involved cannot be reduced to the cognitive component alone. They define the capacity to act as 'determined by opportunities and limitation of the body relative to a particular environment task'. Implementation of a tool extends the boundaries of action because it modifies the bodily resources that can be mobilized to perform a task. As a consequence, tool use implies taking advantage of the changes that occur within the scale of the individual's action system (body–task–environment). Taking full advantage of a modified system is a complicated task that may require years of practice. In order to understand how it operates, the authors study the relationship that exists between the constituents of a tool-use situation (tool, target and their surroundings). For this purpose, they develop a 'topological' approach that enables them to describe tool use and tool making in terms of the regulation of a set of relative geometrical and dynamical parameters (relative distance, orientation, size, shape, linear and rotational motion, inertial and material properties). As far as planning is concerned, Smitsman *et al.* conceive

> planning as being time-dependent, and order as emerging out of the complexity of the many mutual influences at the lower level of the activities themselves, and by internal, environmental and task constraints.

They argue that planning cannot be understood without considering its emergence. Study of its emergence highlights that planning is a 'dynamic affair', which consists in regulating a set of parameters, driven by attention, memory and perceptual input, and which leads to ordered sequences of events. Smooth order is a question of constraints on topological parameters, and as a result, planning need not include all the phases of the action. In conclusion, the authors suppose that the evolution of the brain did not lead to mental representations of longer and more complex sequences of events, but to more stability and flexibility in the dynamics of planning, allowing humans to evolve tool use and technology.

Skills involved in object-related tasks in non-human primates

The specificity of the skills developed by the early hominins, as expressed in stone knapping, may be assessed by comparing these skills with the ones developed by non-human primates for tool-making and tool-using skills. In a way, non-human primate tool-related skills have already been the object of numerous studies (e.g. Beck 1980; Boesch *et al.* 1994; Inoue-Nakamura & Matsuzawa 1997; McGrew 1992; McGrew *et al.* 1997; Myowa-Yamakoshi & Matsuzawa 2000; Russon 1999; van Schaik *et al.* 1999; Westergaard & Fragaszy 1987). When it comes to comparing non-human and human primate tool-related skills, however, methodological questions arise relative to captive condition *versus* nature, recording procedures, object-related task *versus* tool-related task, inter-species comparison, intention, environment, etc. The studies presented here address some of these issues by conducting analyses of object-related tasks according to methodologies that echo the ones used for describing the tool-related skills developed by human primates. The apparatus for recording procedures of action is the same as that used with human primates (Foucart *et al.*). The analysis of action distinguishes between elementary movements and plan of action (Byrne; Cummins-Sebree & Fragaszy). The study of tool-related tasks is broadened to object-related tasks in order to have a large comparative body of data (Byrne). Moreover, not only apes, but also monkeys are considered in order to investigate convergent evolution of tool-using abilities (Cummins-Sebree & Fragaszy). As we shall see, the results obtained by the authors highlight that the differences between the skills developed by human and non-human primates are mainly a matter of degree, perceptible at the motor rather than at the cognitive level. In particular, non-human primates arguably lack the precision of human primates for the effectuation of the elementary gestures required for controlling the conchoidal fracture.

Let us first consider the study of nut cracking. This task is considered as the task *par excellence* to be compared with stone knapping, not only because it is a percussive technique but also because it implies a bimanual asymmetrical co-operative activity of the hands. This has led some authors to consider nut cracking as the starting point of human technology (Sugiyama & Koman 1979; Boesch & Boesch 1981). But how close is the connection between nut cracking and stone knapping? From a technical point of view, technologists have shown that these were not comparable techniques (Pelegrin this volume). Now what about the technical gestures involved? Indeed, the history of techniques abundantly shows that inventions may often result from a transfer of technical gestures (Haudricourt 1987). In order to assess whether the nut-cracking and stone-knapping gestures are comparable, Foucart *et al.* propose to analyze the movements performed to crack open a nut as well as the dynamics of the task as expressed by the succession of movements. The authors report an experiment carried out with a captive chimpanzee (Loi) from the Great Ape Research Institute (Okayama, Japan). In order to assess the capacity for flexibility and adaptation of Loi's movements, the task was based on two varieties of nuts and two different anvil-tools. Both sessions were entirely recorded with video cameras. A 3D reconstruction of the upper limb movements was performed. The action was described according to postural parameters, sequences of movements and elementary movements. Preliminary results clearly show that, at the level of the action, that is, the striking strategy and the succession of blows, the chimpanzee Loi shows a flexible behaviour adapted to the specificity of the task. The results are less clear concerning the adaptation of the movement, even though they tend to show that Loi has the capacity to finely adapt his movement to the situation. The authors conclude that the capacity for adaptation and flexibility in chimpanzees appears mainly at the level of the action. Even if more data are needed to assess chimpanzee capacity to adjust their movement to the properties of the hammer, Foucart *et al.* suppose that, in any case, nut cracking and stone knapping are basically different, the conchoidal fracture imposing more precise movements. Moreover, stone knapping requires an asymmetrical use of both hands, characterized by the simultaneous control of at least two variables (reciprocal orientation of the core and of the trajectory of the hammer, which keeps varying during the sequences of blows). That would be far beyond chimpanzee capacities.

Foucart *et al.*'s study focuses on movements, the smallest functional unit of action, and their chaining. Byrne proposes to consider not only the elementary gestures and their chaining, but also the courses of action within which they take place in order gain a better understanding of the specificity of the skills developed by early hominins. He compares the different ways 'hard-to-process' plants are prepared for consumption in living great apes, since this object-directed manual skill is found inter-species and reveals the psychological capacities of apes when coping with complex tasks. A wide range of elementary movements has been recorded among apes. They are achieved in asymmetric bimanual hand action with manual role differentiation. They are characterized by important digit differentiation. They are hierarchically organized and are combined in many different ways, suggesting a quite outstanding feature, that is, generative skills. This latter feature is apparently rare or absent in monkey species. It suggests that apes do have the cognitive capacities to deal with complex manual tasks, which require flexible courses of action. Conversely, apes may not be able to achieve elementary movements that require both power and precision as in stone knapping. Indeed, Byrne argues that if population-level manual laterality is taken as reflecting difficulties in manual tasks, it appears that the more difficult tasks apes can achieve never combine power and precision, which are exerted in alternation. Byrne concludes that apes are not in a position to develop stone knapping, even though the intention were present as well as the required cognitive capacities, because of an inability to produce the requisite elementary movements.

Comparable conclusions are obtained by Cummins-Sebree & Fragaszy, who study the skills developed by capuchins in object-related tasks. The authors examine the extent to which the skills and psychological capacities necessary for stone knapping can be compared with those involved in the manual tasks exerted by capuchins in captive conditions and in nature. From the skill point of view, it appears that capuchins can apply force with one object to another object or a surface, even though this force is limited given their size and weight (capuchins weigh a mere 3 kg); they use a precision grip, including thumb-forefinger opposition; they exhibit differentiated roles for the two hands in bimanual manipulation; and last, they can develop strong manual preferences arising from practice with the task. These skills are fostered by the capuchins' postural stability while seated or standing bipedally, as well as by their terrestrial habits. Concerning their psychological capacities, observation and experimental data show that capuchins use stones as pounding tools and modify stones for making cutting tools. They have the cognitive capacities for exploring and discovering the properties of objects by managing multiple simultaneous dynamic spatial relations and planning actions accordingly. They also have the capacities for selecting appropriate tools according to their properties. Cummins-Sebree & Fragaszy conclude that capuchins display skills and psychological capacities that could, to a certain degree, be compared to those found in stone knapping. However, because difference in degree is determinant, capuchins will probably never knap stone: to begin with, the kinetic force of their blows will never reach that of humans; in addition, although capuchins may possess all the action capability relevant to stone knapping, humans are better at every single step. Lastly, and this is a central point, it is not certain whether capuchins can 'modulate actions of the two hands in an integrated task requiring precise positioning and production of force, as occurs in knapping' (p. 180).

Stone knapping: the necessary conditions for the required skills

Studies on skilled tool-related behaviour demonstrate that there are differences between the skills developed by human and non-human primates, even though it may only be a question of degree. These differences relate mainly to manipulative behaviour, and more precisely to bimanual elementary movements. Hence the following question: what enables human primates to develop such skilled behaviour that non-human primates acquire? In other words, given the importance of the elementary movements for stone knapping practices, what are the necessary conditions required for producing the elementary movements enabling the control of the conchoidal fracture? Defining these conditions should enable us to understand how stone knapping was possibly instantiated among human primates and why this is not the case among non-human primates.

Forty years ago, a novel hypothesis was developed by Leroi-Gourhan (1964) among other scholars. Leroi-Gourhan stressed the probable importance of the dynamics at work in-between the vertical posture, the freeing of the hand and the evolution of the brain. The debate is now well enriched with new empirical data established by researchers from different fields, particularly psychology, anatomy and neural sciences.

The conditions for developing the skills involved in stone knapping are here studied for the organism components at issue when exerting functional bimanual controlled movements, that is the bio-behavioural system, the hand anatomy and the neural substrate.

The bio-behavioural system

Such a favourable bio-behavioural system as the one developed by early hominins may represent the necessary conditions for the emergence of stone knapping. As demonstrated by Corbetta, this favourable bio-behavioural system is characterized by an erect posture, handedness and fine bimanual coordination. She argues that to perform precise two-handed movements, such as stone knapping, stable dynamic interactions between a steady posture, handedness (stable division of labour between hands) and fine bimanual coordination between hands are necessary. As shown by findings with human infants and non-human primates, such stable interactions can be achieved following the emergence and adoption of the erect posture. Findings with human infants show, in particular, strong links between stability of the two-handed coordination and the lateral organization of the upper limbs, which change as infants learn to sit, crawl and walk. In particular, hand preferences and specialization stabilize only following the emergence of upright locomotion. Findings with non-human primates show that, if in an upright position, solving manual tasks leads to greater indexes of hand preference. Together, these data suggest that bipedal forms of locomotion facilitate stable lateralized fine bimanual coordination. From this body of evidence, Corbetta first argues that the emergence of bipedalism may have created bio-behavioural conditions for the development of manual specialization, given that the 'brain continuously changes and reorganizes itself, in particular, following novel sensory-motor experiences and motor skill learning'. In particular, emergence of bipedalism would have contributed to dissociating patterns of muscle activity for the arms from patterns of muscle activity specific to walking. It would have then favoured manual specialization and handedness. Handedness may have been an established behavioural trait when hominins stabilized their erect posture. Secondly, Corbetta argues that stone knapping may have developed only in hominins, because only hominins adopted a fully-erect posture.

The fact that an analogous bio-behavioural system has not been identified among non-human primates would thus explain why they never developed the skills required for stone knapping. More precisely non-human primates present a bio-behavioural system whose components would prevent them from developing stable dynamic interactions comparable to the ones necessary for stone knapping. These interactions may not be comparable because the behavioural components at stake are not developed to the same degree. They do occur, however, when non-human primates show interactions between handedness and asymmetric bimanual coordination, as observed for apes by Byrne, and interactions between postural stability and handedness, as elaborated by Holder and touched upon by Cummins-Sebree & Fragaszy.

More precisely, Holder investigates, according to a cost/benefit/milieu approach, how and why manual specialization is acquired by individual primates, and what is the link between manual specialization and postural stability. Manual specialization is defined as a motor skill acquired over time through repeated practice which 'requires the optimization of biomechanical potential for the task to be successfully performed' (p. 205). Most manual specializations are performed with a consistent manual preference since biomechanical optimization is then needed. Manual tasks, however, that do not require biomechanical optimization may be achieved with a consistent hand preference when routinely performed. In this case, benefits of hand preference derive from task automatization. At last, manual tasks can be performed by ambidexters. In the case of ambidexters who can perform half the manual tasks with one hand, and half with the other hand, strong manual specializations can develop. Manual specializations are acquired when the perceived benefits either balance or outweigh associated costs, within a given context. Describing how five species of wild African primates typically behave in their environment has enabled Holder to identify what factors other than presumed brain specialization might be capable of influencing manual asymmetry. Among these factors, one finds postural stability, development and injury. Directional hand preferences (right or left) have been identified at the individual, but not at the species level.

As shown by primatology, interactions at the bio-behavioural system level enable non-human primates to develop specific task-related skills. But their behavioural components do not present the same characteristics (posture, handedness and coordination) as human ones. Different outcomes in terms of skills ensue. The cornerstone is the erect posture. As demonstrated by Corbetta, bipedalism is determinant in the way both handedness and fine bimanual coordination develop among human primates. Among human primates, handedness occurs at the population level, contrary to non-human primates, even though Byrne reports that gorilla leaf-eating tasks show weak but statistically significant right-handedness. Importance of fine bimanual coordination, and *a fortiori* of stone knapping, for the development of handedness at the population level are reported by Steele & Uomini.

Steele & Uomini discuss the mechanisms liable to explain handedness as a population-level bias. They link handedness and stone knapping. The hypothesis is that there is an advantage for the dominant hand in tool use. This advantage is seen in the greater skill of the dominant hand. It relates to 'an underlying efficiency in information transfer rate in the contralateral hemisphere'. The practice of stone knapping would therefore have contributed to handedness as a behavioural trait. Handedness in tool use can be identified on skeletons, as shown by studies of skeletons from modern times to prehistoric times populations. Predominant right-handedness appears to extend back in time to at least the early members of our own genus *Homo* (*Homo ergaster*). Archaeological evidence from tools and other artefacts can also be used to infer the evolution of human handedness. Steele & Uomini review the material-cultural markers of handedness including tool production (multiple flake analysis, knapping scatters, knapping gesture, lateral retouch, use and use-wear), cut marks on teeth and art (representations of lateral tool use, engravings, profile drawing, handprints and hand stencils). The authors' conclusion insists on the importance of the study of human handedness for addressing the issue of the evolution of human tool making and tool use, while acknowledging that this may only be part of the problem.

Somatic and neural substrate

In a recent paper entitled 'What's so special about human tool use?', Johnson-Frey (2003) emphasizes the growing number of research studies that provide evidence for homologous mechanisms involved in the control of prehension and in sensorimotor abilities among human and non-human primates. This view minimizes differences in the motor capacity of human and non-human primates to use tools. In this section, the different authors explore some aspect of the somatic and neural substrate of tool use in human and non-human primates. Manual dexterity is here considered as a prerequisite to optimal tool use. The data discussed show how both the hand anatomy and the neural system might contribute to the understanding of the precondition for dexterity and tool use. Markze examines the necessary conditions for a hand to be used by a tool maker, while Maier and colleagues address the question of the evolution of the neural structure that controls this apparatus (i.e. the hand). In the last two chapters, Stout and Jacobs and colleagues investigate the cerebral control of tool use.

In order to define the hand anatomical features necessary for stone knapping, Markze conducted a multi-level comparative study aimed at discovering specific tool-making patterns. The first step consisted of examining how modern human-hand morphology relates to the manipulative behaviour required by stone knapping. Systematic biomechanical studies were performed with modern stone knappers, enabling the author to characterize manipulative requirements for stone knapping in terms of forceful precision grips that resist large external forces. These grips are not shared by chimpanzees. The second step consisted of finding skeletal correlates of joint movements, stresses and muscle functions associated with human forceful precision grips and the power squeeze grips. Markze finds clear evidence throughout the human hand for a unique pattern of morphology 'that is both distinctive of humans and consistent with the movement capabilities and stresses associated with the manufacture of stone tools' (p. 249). This pattern is characterized by a set of features (including bone shape and internal structure, joint surface topography, muscle and tendon attachment areas) that is consistent with stone knapping when defined in terms of bimanual percussion using forceful precision grips. Looking at early hominin fossil bones, Markze proposes nut-pounding but not stone-knapping manipulative behaviour for *A. afarensis*. On the contrary, bones from Sterkfontein and Swartkrans are consistent with forceful manipulative behaviour. Drawing on a comparison with gorillas, who exert force in food retrieval and processing, the author suggests that such food activities may have fostered the evolution of features in ancestral hominin hands, predisposing them to subsequently exert forceful precision grips in tool making. Although not central to Markze's issue, the neurological requirements for manipulative behaviour are also touched upon.

The neurological basis of manual dexterity is developed by Maier *et al*. They examine the emergence of dexterity in relation with the phylogenetic development of the corticospinal track among different species. Dexterity is here considered in a more restricted way than Bernstein's definition (1967) as it refers exclusively to its neural basis. While acknowledging that crucial features of hand morphology are needed to provide the mechanical substrate for manual skills, Maier *et al.* underline the possibility that the evolution of hand morphology and of neural control may not have been concomitant. The key issue of their chapter is the assessment of which premotor system is most important for providing a high degree of manual dexterity. Considering that the neural basis of manual dexterity rests mainly on two neural systems, the corticospinal and propriospinal systems, the authors speculate on the relation between the evolution of these two systems, the growth of dexterity and the development of tool use and tool manufacturing. The corticospinal system, a direct pathway, allows for the ability to complete independent finger movements, the mark of dexterity. It may equally control some aspects of reaching needed to support distal grasp and manipulation. The propriospinal system that also contributes to dexterity is an indirect cortical pathway. The authors base their demonstration on an interspecies comparison of the phylogenetic development of manual dexterity and of the two neural systems in four species — cat, squirrel monkey, macaque monkey and *Homo*. After an extensive discussion of what identifies dexterity, the authors develop a very detailed and rigorous analysis of published data, including their own, relating the index of dexterity and the efficacy of motoneurons excitation of corticospinal neurons (CM) and propiospinal (PN) systems. They show a clear qualitative relation between an increase in dexterity and efficacy of the CM system, and a negative relation between dexterity and efficacity of the PN systems. They conclude that phylogenetic development favours direct (corticospinal system) rather than indirect (propriospinal system) cortical control over motoneurons. The existence of direct cortico-motoneuronal connections appears as a necessary and sufficient precondition for a high degree of manual dexterity; they provide the necessary descending output system, but dexterity alone is not a sufficient condition for tool use and tool manufacturing. In this respect this conclusion is akin to Ivanova's view. In order to use manual dexterity for manipulation and consequently for tool use, other modalities are necessary, be it sensory modalities and/or cognitive modalities.

Studies by Stout and Jacobs and colleagues offer an insight into the neuroanatomical structures that are active during tool use and even more specifically during stone knapping.

Adopting a perception-action approach, Stout examines brain activation during simple Oldowan-style stone knapping using Positron Emission Tomography (PET). The theoretical position of Stout is novel in the sense that brain imaging is generally called upon in defence of a representational approach aiming to localize the neural substrata of complex cognitive processes. Stout reports results from an exploratory study and ongoing research with experimental stone knappers. If PET imagery does not explain how neuronal activity contributes to behaviour, it does indicate where this activity takes place. The spatial distribution of activation shows that stone knapping involves activation of a network of structures commonly associated with visuomotor performance (pericentral cortex, superior parietal lobe, occipital lobe and cerebellum) and no activation of the frontal association cortex involved in tasks that demand planning of complex goal-oriented actions, or of the temporal and/or parietal cortex possibly associated with internal models of object's physical properties. Stout's results make it clear that 'the most salient mental demands of [Oldowan-style stone] knapping have to do with execution rather than conceptualization' (p. 282). This conclusion challenges representational perspectives, which have been more concerned with how the individual conceives what he does than with what the individual actually does. It emphasizes the fact that stone knapping, including its earliest manifestation, is an especially demanding perceptual-motor task. Going one step further, Stout suggests the existence of microstructural adaptations relating to stone-knapping ability, for which evidence might be found in a 'uniquely human adaptation in the dorsal stream of cortical visual processing' (p. 283).

The clinical approach espoused by Jacobs, Bennis and Roby-Brami, inverts the rationale of Stout's study. While Stout takes stone knapping as his starting point and then focuses on the underlying brain activity, Jacobs and colleagues open with apraxis and brain damage patients and go on to consider the impairment in tool-use actions. Theirs is a major contribution, all the more since archaeologists sometimes refer to neuropsychology as a conceptual framework (Pelegrin 1993). Their well-articulated review of the neuropsychological theories about the control of complex gestures and actions raised by the study of apraxia echoes and helps to put into perspective the different accounts of motor theories discussed in several previous chapters. In spite of the enormous variety of cases encountered, or maybe because of this variety, the authors underline the fact that 'neuropsychological concepts such as *movement representations* ... remain an abstract "black box"' (p. 291). Commenting on this puzzling point, Jacobs and colleagues address, through the precise biomechanical description of tool-use movement in apraxis and healthy adults, the question of how the motor system concretely controls complex actions such as tool use. The analysis focuses on the working point of the tool (i.e. the head of the hammer in hammering), like that of Biryukova and colleagues. Their results are potentially, if indirectly, very informative for our understanding of stone-knapping skills. They demonstrate that left brain damage affects the capacity to anticipate and adapt the action to the mechanical properties of the task. More eloquent is the inability of patients to capitalize on the tool's mechanical properties to produce the most efficient movement possible. Jacobs and colleagues suggest that this behaviour might reflect a disability to integrate the tool's mechanical properties into the movement (see also Smitsman *et al.* this volume).

'Actualizing' conditions for innovation in stone knapping

Concerning the reasons causing innovation to occur at specific 'moments' in time, the dynamic systems framework suggests that the context in which qualitative innovation takes place should be investigated (Roux 2003). In technology, this context of innovation corresponds to the conditions actualizing the innovation, that is, the context of craft production in the broad sense of the word, and more specifically here the context of stone-tool production (Fig. 1.2). This context encompasses social structure, sociability, apprenticeship, cultural transmission, cognitive capacities and technical traditions. These matters have received particular attention in a wide range of studies pertaining to the domain of tool-use traditions in primates (e.g. Boesch *et al.* 1994; Box & Gibson 1999; Byrne 1999; McGrew *et al.* 1997; McGrew 1992; Matsuzawa 2001; Tomasello 1999; van Schaik & Pradhan 2003; Whiten *et al*. 1999). Three aspects of such studies bearing on 'actualizing' conditions are developed in this third section: the psychological capacities required for discovering new tool actions, the social conditions required for learning and transmitting technical actions, and finally the technological context required for developing stone-knapping technology. The psychological conditions are found at the individual level, as opposed to the social and technological conditions, which are found at the collective level. Indeed, because the actualization of innovation connects real time (invention) and the *longue durée* of historical time (innovation), and because the most elementary components of a system can, over time, constrain its global structure or form (Aslin 1993), conditions for the actualization of innovation deal with both individual and collective conditions. More precisely, invention expresses individual cognitive activity, whereas innovation is expressed by the emergence of a new tradition, whose development and acceptance can be slow or rapid depending on the cultural context. It is the temporal course of these two interacting variables — the individual and the collective — that gives the system its faculty to adapt and bring about widespread technological change. As a result, conditions for the actualization of innovation are to be found at both the individual and the collective levels, which have to be dealt with as a whole.

Concerning the psychological conditions, found at the individual level, they can be considered as part of the supportive context necessary for invention to happen and be transformed into innovation. This supportive context should not be confused with the necessary conditions for exerting an action. It corresponds to individual capacities for producing new actions, which are made manifest through a specific transmission behaviour. Among these psychological conditions, causal understanding and future-oriented thinking are considered as central to making and using tools. To begin with, Bushnell *et al.* note that causal understanding, like future-oriented thinking, increases from monkeys to humans, as well as in the course of early child development. Among infants, however, as well as non-human primates, there are situations where tool action is performed without causal understanding. Bushnell *et al.* propose to study how causal understanding emerges, in order to define the favourable cognitive conditions for the coming into existence of stone knapping. They suggest that imitating the means might be a mechanism that could support early instances of means–ends behaviour without causal understanding. This capacity for imitating the means, rather than emulating the ends, governs motor transfer among infants. Transferring the means appears to be an intermediate step in the development of causal cognition. It would also be at the root of individual invention, the means being transferred to new objects even without full causal understanding. Reverting to prehistory, the authors suggest that the early hominins had the imitative capacities that enabled them to transfer the means, to discover the physical effect of these means, then to invent and, later, refine knapping techniques.

Lockman enlarges on the question of the favourable psychological capacities for developing elementary forms of tool use by focusing on the manipulative capacities of infants for discovering the properties of tools. The hypothesis is that a study of these capacities can lead to new insights into the foundations of tool use. Lockman adopts a Gibsonian perspective in the light of which he reassesses the discontinuous models of tool use according to which advanced representational or symbolic capacities are necessary for the emergence of tool use. Rather than implying that tool use represents a discontinuous cognitive advance, the Gibsonian perspective suggests 'that tool use is rooted in the perception–action routines that infants perform to explore and act on their surroundings' (p. 323) and is not the product of a sudden insight or newly-developed cognitive abilities. Lockman's own researches show that tool use develops from object manipulation and capacities to relate objects to substrates in their surroundings. In this respect, it seems that tool use may be considered to be a perceptuomotor achievement rather than a cognitive one, and that the emergence of tool use may not require sophisticated cognitive abilities.

Concerning the social transmission of knowledge about tools, considered by many as essential for the development of tool use and manual skills with objects, debates bear on the one hand on the mode of transmission at the caregiver level, and on the other hand on the social organization that permits different modes of transmission between caregivers and infants. Bushnell *et al*. and Lockman outline the importance of the learning context at the caregiver level for actualizing the favourable psychological capacities underlying the emergence of tool use. Lockman proposes that object manipulation itself may in part be 'a socially mediated achievement'. Indeed, in a perception-action perspective, caregivers may highlight information available from objects and in so doing may promote mastery of object manipulation and tool use. The resulting rich learning environment is rarely observed in our living primate relatives and would therefore represent a quite unique feature of human primates, something also suggested by Byrne, who emphasizes that active teaching is very rare among apes.

Turning now to the favourable social organization for stone-knapping skill acquisition, Stout examines the role of the social and cultural context for learning stone knapping through a study of the stone adze-makers of Langda village in Indonesian Irian Jaya. He notices that the social and cultural context of adze-making in Langda provides an important scaffold for skill learning. The adze-makers structure the learning process by providing a learning schedule appropriate to the different difficulties that must be successively controlled over the years, and through continual interaction between experts and novices. Reverting to prehistory, Stout suggests that the skills involved in the making of lithic objects such as hand-axes would have been long to acquire and would have similarly required social arrangements for supporting their progressive apprenticeship. As shown by the researches led by van Schaik *et al.* (1999) among modern ape populations, the degree of social tolerance seems to influence the distribution of tool use. This degree is assessed by 'the number of individuals in the social unit with whom the naive individual spends a significant amount of time in close proximity' (van Schaik & Pradhan 2003, 648). Hence, a high degree of social tolerance would have represented favourable conditions for the transmission of technical skills among early hominins. Such a degree of tolerance, however, would not have been sufficient for acquiring expertise, apprenticeship of which extends into the adult age and requires the kind of social support that ape populations do not develop. From this point of view, and according to Stout, comparative actualistic data suggest that the transmission of skills long to acquire, such as stone knapping, would have required meaningful social relationships, 'characterized by Tomasello (1999) as the key adaptation underlying the emergence of modern human cognitive sophistication' (p. 338).

Finally, Marchant & McGrew consider the technological context in which stone knapping could have appeared. They suggest as a favourable technological context one that would already have a complex percussive technology tradition. Following Matsuzawa, the complexity of a percussive technology is defined by the number of objects involved in the task. The authors review the different percussive technologies found in apes and present new data on percussive technology for cracking open baobab fruit found at Mont Assirik, Senegal. The issue concerned the way in which percussive technology was used (anvil only *versus* hammer and anvil). Anvil use only is suggested by both ethno-archaeological and behavioural data sets. The first type of data, involving indirect evidence, points to terrestrial smashing on stones, whereas the second, involving direct evidence, shows smashing on the trunks or branches of baobab trees. These data raise the question of a percussive technology used as an arboreal *versus* a terrestrial activity. On the strength of this, the authors develop an evolutionary scenario with, as a starting point, arboreal apes smashing big fruit on tree trunk; the next stage entailed a shift from arboreality to increasing terrestriality and the use of harder anvils, made from stone; in order to smash small fruit, such as nuts, the items involved in the task changed from two to three, that is, from the anvil alone to the hammer and anvil. All was then set for the transition to stone knapping, that is, the shift from accidental flaking by stone on stone percussion to goal directed percussion.

Concluding remarks

The field of investigation of this volume has been deliberately restricted to the skills involved in tool use and tool making in order to better understand the specificity of stone knapping, when considered as a uniquely hominin invention.

In relation to this goal, quite a few chapters focus specifically on the characteristics of object-related tasks defined in terms of techniques and skills. Studies based on new techniques and methods are reported in several of these chapters. We believe that such recording techniques will give new insights into the question of the nature of skilled behaviour, and consequently lead to relevant comparisons between human and non-human primates.

We are well aware, however, that numerous questions related to such an innovation as stone knapping are not dealt with or even touched upon in this volume. But the reconstruction of the historical process that underpins this innovation necessarily requires, as a preliminary step, the well-controlled analysis of the technical task in terms of techniques and skills, that is, the analysis of the invention of stone knapping itself. In the same way that invention and innovation are here distinguished, the distinction between innovation and the 'actualizing' conditions for innovation enables us to 'isolate' the context in which innovation takes place, and therefore to solve a major methodological problem when considering that technological facts are embedded in socio-cultural systems. Here again, only some aspects of this context are addressed in this volume. But as we shall see in the 'synthesis and speculations' final chapter, the array of papers presented in this volume all excellently contribute to shedding new light on the necessary conditions for a uniquely hominin invention, stone knapping.

Note

1. The controversy among researchers dedicated to complex movement behaviour has been reported very interestingly in a book published in 1988 and entitled *Complex Movement Behaviour: the Motor-action Controversy*. The aim of this book, edited by O.G. Meijer & K. Roth, was to debate the common ground of these theories as well as their points of departure.

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