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Applied Ergonomics ▮ (▮▮▮▮) ▮▮▮–▮▮▮

APPLIED ERGONOMICS

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Cognitive aspects of tool use

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Received 23 June 2004; accepted 6 June 2005

Abstract

Tool use has traditionally been viewed as primarily a physical activity, with little consideration given to the cognitive aspects that might be involved. In this paper, a new approach to considering tool use in terms of Forms of Engagement is presented and discussed. This approach combines notions of schema from cognitive psychology with the idea of task-specific devices to explain psychomotor aspects of using tools. From the perspective of Forms of Engagement, various aspects of craftwork and skilled tool use are considered.

1. Introduction

This paper focuses on the use of tools, specifically hand tools, and the cognitive aspects of this activity. When one thinks of hand-tools, one probably imagines spanners, hammers, knives, etc. and their associated activity, and may well find it difficult to imagine that cognition could play a role. For ergonomics, key issues relating to tool design and use have tended to concentrate on such issues as comfort (Kuijt-Evers et al., 2004), risk of injury (Aghazadeh and Mital, 1987) or general principles of design (e.g., Freivalds, 1987; Greenberg and Chaffin, 1977; Mital, 1991; Eklund and Freivalds, 1990; Kadefors et al., 1993; Sperling et al., 1993). Recent years have seen focus on the possible risks associated with the use of power tools, particularly due to vibration effects (Gerhardsson et al., 2005; Kihlberg et al., 1993, 1994; Freivalds and Eklund, 1993). However, one is hard pressed to find much in the literature on the ergonomics of tools that specifically addresses cognitive factors.

A further point for this review is that one rarely finds mention of tools in cognitive psychology texts (although one rarely finds mention of any aspect of physical activity in such books). Alternatively, one might anticipate that there is a large literature on psychomotor skills and that this would cover the use of tools. However, much of the contemporary literature on psychomotor skills is either focussed on very basic activity or on applications in sports. It strikes me that a significant problem for ergonomics lies in the division between the physical and the cognitive (this division is apparent in many other disciplines that seek to study human performance); with the consequence that research dealing with physical aspects of performance has little room for consideration of cognition, and research on cognitive aspects rarely mentions any physical aspect. Of course, there is often little reason why the research needs to stray into the other domain, but this is precisely the point that I am making. If we set up an artificial boundary between the 'physical' and the 'cognitive', then it is difficult to see a unified theory of ergonomics coming into being. And by implication, without a unified theory of ergonomics, it is difficult to see a coherent discipline as opposed to a diverse collection of activity. The challenge is to find a means of bridging the chasm between physical and cognitive aspects of human performance, and an obvious starting point lies in the study of using hand-tools. Not only does this offer the opportunity to introduce cognitive aspects into what appears to be a predominantly physical activity, but

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0003-6870/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.apergo.2005.06.004

many aspects of using tools seem to be fundamental to other ergonomics research.

In discussing tools, the paper refers to the physical implements and artefacts that we use in everyday life and work. There are two broad definitions of the word 'tool' that are important to this paper. In one definition, a tool is a handheld artefact that serves as an extension of the user and can be used to perform a task. To this end, Samuel Butler (1912) wrote that, "Strictly speaking, nothing is a tool except during use. The essence of a tool, therefore, lies in something outside the tool itself. It is not in the head of the hammer, nor in the handle, nor in the combination of the two that the essence of the mechanical characteristics exists, but in *the recognition of its unity and in the force directed through it in virtue of this recognition*." [Butler, 1912, p. 121, italics added]. For me, the key aspect of this quotation is the implication that a tool that is not being used is merely an object, and that in order to actually be a tool it is necessary for the user to both recognise that properties of the tool and to use the tool to direct force onto the world. In other words, the user of the tool is able to recognise its function through its form. The tool is not merely an object, but acquires meaning and relevance through the function it supports (as Butler points out). Indeed, this relationship between a tool's function and the capability of the person to use it has been at the root of the 'folk norms' of many of the dimensions of hand-tools (Drillis, 1963).

A common assumption is that tools extend human actions, implying that a physical object enhances a physical action, e.g., a hammer allows us to hit something harder than we could just using our hand. As Vygotsky (1928) points out, a defining feature of tool-use in humans lies in our ability to internalise tools. For example, when a child learns to count, it might make use of beads to keep track of the numbers being counted, but as it becomes more proficient so it can, in effect, internalise the beads and count in its head. Counting then becomes a matter of manipulating an internal representation. As the maths becomes more complicated, so we might resort to physical artefacts (such as pencil and paper or a calculator) for support. In this case, we are manipulating external representations in support of our activity. Thus, the artefacts represent some knowledge, and we manipulate both the representations and, through them, the knowledge.

In a second definition of tool, one could refer to *any* form of support that allows us to expand upon the limited repertoire of manual and cognitive skills that we possess. This is what McCullough (1989) refers to as 'applied intelligence', i.e., having solved a particular problem by developing a physical device to help us, we then continue to use this device when we next encounter a similar problem. This notion sets tools apart from other technology in that rather than replacing an action, we are (somehow) supplementing or extending it. From this perspective, a tool embodies our understanding of the world; it represents a 'standardised' solution to a given problem and knowledge of how to affect the world in order to achieve that solution. As Preston (1998) points out, "*a spoon embodies in its very shape aspects of our knowledge of the physical properties of liquids, and therefore is a peculiarly appropriate mediator of the interaction between individual and world in situations where this knowledge comes into play*." (Preston, 1998, p. 514). The implication of this statement, as far as ergonomics is concerned, is that far from being merely physical objects, tools represent both declarative and procedural knowledge about how we ought to interact with the world and the objects it contains.

It is possible, taking the notion of 'applied intelligence', that tool use also involves this manipulation of artefacts and knowledge. In order to appreciate what this idea of tools manipulating knowledge might mean, we turn our attention to the concept of schema.

1.1. Schema

In the view of one pioneer of schema theory, a schema is the organisation of past experience, which can be assumed to underlie any well-adapted response (Bartlett, 1932). The point is that, a response which has the appearance of being well-organised is probably drawing upon a collection of similar responses that have been made in the past. However, it is essential to note that this does not mean the mere repetition of responses. Rather, the responses are based on a mass of knowledge that has accumulated during the person's activity. Thus, when performing an action, such as a tennis shot, the person does not produce something entirely new, nor simply repeat something old (Bartlett, 1932). Rather the person is, as we shall see below, predisposed towards to particular pattern of action based on the accumulation of previous responses and expectations. This accumulation of responses and expectations was, for Bartlett, part of the schema that the person held. Other researchers, notably Bernstein (1967), propose a different point of view, and an aim of this paper is to attempt to reconcile these competing views in the context of using tools.

A significant feature of schema is that they are, by definition, not open to conscious awareness and consist of activated knowledge structures. This means that they are unlikely to be stored as static representations but as series of states in an active network that are combined with current stimuli. An appealing consequence of this view is that actions are not built anew nor simple repetitions of old actions, but are the result of assembling current stimuli with 'chunks' of activated knowledge.

Some 50 years after Bartlett's initial exposition of schema theory, Norman and Shallice (1980) proposed a model of human performance to account for everyday activity in a manner that was essentially schema-driven (this model has been subsequently extended by Cooper and Shallice, 1997). A horizontal structure (the Supervisory Attentional System—SAS) relates features from the current situation to a set of schema. As schema become active, so responses are selected, and the person then performs the response. As the person practices the responses, so a closer coupling of features to schema to response occurs, such that the behaviour becomes 'automatic'. For example, when changing gear in a manual-drive car, the actions of removing one's foot from the accelerator, depressing the clutch, shifting the stick to a new gear, engaging the clutch and the applying the accelerator can be difficult to sequence for the novice driver, but with practice can be performed seamlessly. From this perspective, the use of hand-tools could readily be described in terms of SAS. As the actions become automatic, or habitual, so the level of attention required to perform these actions reduces. A consequence of this is that one's attention can shift from the physical actions to the goal of the task. Often experienced craft-workers will speak of losing sense of the tool that they are using, and focussing only on the goal or outcome of the actions.

Whilst the notion of SAS provides some mechanism for how schema might be used, it does not provide much in the way of structure. Schank (1982, 1999), following a different line of enquiry, has proposed a memory structure based on schema. Memory Organisation Packets (MOPs) are defined as clusters of knowledge called scenes, i.e., high-level components of scripts (where a script is a sequence of action associated with a particular context, e.g., a 'going to a restaurant script'). The premise is that scripts and scenes are hierarchically organised within a network. Above these MOPs sit Thematic Organisation Points (TOPs) which apply a theme to a collection of scripts and scenes. Whereas Schank (1982) implied that access to these MOPs was largely automatic, there is evidence that they require activation within a specific context. In other words, one might say that MOPs defined the region of knowledge within a network that was activated by specific contextual features.

In broad terms, therefore, schema represent bodies of knowledge. If one assumes that this knowledge is represented in the form of a hierarchical network, then a schema could be viewed as the activation of a specific collection of related nodes within this network. From Bartlett's description, the combination of features in the world with activated schema supports recall of actions. From SAS, the selection of action is defined by the activation of specific schema. Before discussing what this means for tool use, I want to consider a view that implies that action does not require schema to fashion it.

1.2. Task specific devices

The Russian physiologist Bernstein (1967) proposed that people adapt to repeated activity through development of co-coordinative structures. A co-coordinative structure is a highly tuned sequence of muscle firings and limb movements that allows a set of actions to be performed seamlessly. The more this set of actions (or routine) is practised, the more the routine will appear effortless and skilled. This is not to say that the routine merely becomes 'hard-wired'. Rather a characteristic of skilled performance is that ability to modify the routine to take account of changes in demand. In this account there is no obvious need for schema (or any form of cognition), and in this respect the approach is similar to the concept of 'affordance' (see below). However, a development of co-coordinative structures can be seen in the notion of task-specific devices (Beek and Bingham, 1991; Bingham, 1988). The focus of task-specific devices is on behaviour that is directed towards a goal and assumes that the person and the environment are temporarily organised into a special-purpose machine, i.e., a task-related device" (Bingham, 1988). For example, when throwing balls of different weight, people typically exhibit different throwing styles. For heavy balls, the thrower might need to lock the wrist (in order to provide support for the weight) which, in turn, constrains the throwing style and leads to movement around the elbow with a straight forearm; for lighter balls, the thrower can adopt a looser posture at the wrist and include movement of the wrist in the throw. In both instances, the co-coordinative structure involves similar muscle and limb collections, but the management of the structure varies.

Tools obviously modify the properties of effector systems, i.e., a hand holding a hammer differs in mass and posture to an unencumbered hand. This, in turn, alters the potential movements and actions that can be performed (Smitsman, 1997). Relating the possible actions to the perceptions of tool in the hand represents a form of perception–action coupling that needs to be learned and modified through continued exposure. Lockman (2000) proposes that perception–action coupling can be used to describe the ways in which very young children acquire and develop psychomotor skills. In particular, he suggests that part of the process of acquiring the skills needed to manipulate objects is the detection and interpretation of the affordances that they offer.

1.3. Affordance

Gibson (1996) proposed that rather than an organism and the environment existing as separate entities, with one acting upon the other, these entities were conjoined into a single dynamic unit. From this perspective, objects in the world do not exist as collections of physical properties so much as collections of features that 'afford' some specific response. In this manner, the response that one performs is the result of a perceptio-n–action coupling in which perception becomes an invitation to act (Gibson, 1996). Recent neurological research suggests that the physical appearance of an object that can be grasped (Chao and Martin, 2000), e.g., a tool, leads to activation in the motor cortex (and such activation does not occur when images of faces, houses or cars are presented). The implication of this research is that, for humans (and monkeys), the physical appearance of a graspable object is sufficient to elicit preparation of a grasp response. Indeed, in some forms of apraxia, the grasp response is performed even when the patient is instructed not to perform the action (Forde and Humphreys, 2000). In other studies, patients with apraxia can show how objects are used even when they are unable to name them, which implies that the representation of the name of an object is separate from the representation of its use (Kempler, 1997). These studies imply that the presence of an object which affords grasping is sufficient to evoke a grasp response, that objects which require a sequence of actions to use are represented both by name and by sequence of action, and that it is the presence of the object which is required to completely elicit the representations sufficient to effectively use the object.

The idea that perception is partly used to encode visual information and partly to guide movement, and that these processes represent separate pathways, has been put forward by Goodale and Milner (1992) and Jeannerod (1997). One source of evidence for this point of view comes from studies into reaching to grasp objects. In reaching for an object in front of the body, the hand moves towards the object, and at the same time the hand is oriented and the thumb and fingers are extended to provide clearance for the object's boundaries with the fingers following a trajectory towards surfaces that afford stable grasp. Jeannerod (1997) observed that differences in object width result in changes in hand aperture but do not affect the speed of the hand toward the object. In addition to making the hand an appropriate shape to grasp the glass, one needs to exert sufficient frictional force on the glass to overcome the load forces that will act when the object is lifted. Johansson and Westling (1984) asked subjects to use a precision grip to lift objects a small distance off a support. The surface slipperiness was systematically varied (in decreasing order of slipperiness—silk, suede, sandpaper). In all cases they noted that grip force started to *rise* before the object was lifted. The suggestion is that people are able to rapidly modify their grip forces to compensate for any changes in the stability of the object. Further, these grip forces can also be shown to be anticipatory, e.g., Turrell et al. (1999) show that grip force adjustments in holding a tool subject to a collision anticipate the impact force which in turn reflects object mass and velocity. The former may be gained from prior knowledge, the latter from vision.

Recent research has been concerned with the manner in which people acquire information about objects, e.g., through exploration of the objects. Work by Lederman and Klatzky (1996) documents ways in which people manipulate objects when asked to recognise or classify them. They noted consistent patterns of finger movement and suggested that people maintain a limited repertoire of such exploratory procedures (EPs) which they tend to use in a relatively fixed sequence when faced with acquiring information from an object. This research suggests that people employ a set of EPs which are used to acquire specific sorts of information concerning specific object properties, e.g., the weight of an object is evaluated by hefting the object in the palm. One implication of this work is that we have stereotypical routines for conducting simple manipulations of objects. This is, of course, similar to the classic ergonomics concept of population stereotypes for the control of devices (Fitts and Seeger, 1953; Chapanis and Lindenbaum, 1959; Warrick, 1947). Indeed, Ellis and Tucker (2000) demonstrate that precision and power grips can be cued by high or low auditory tones (suggesting the objects are encoded in terms of their potential to support action, or affordance, and that this encoding can be accessed using other cues).

1.4. Conclusions

From this discussion, it is proposed that, as with many other everyday activities, people may possess schema covering tool use. These schema would allow actions to be performed automatically, in the presence of specific environmental stimuli in order to achieve specific goals. The notion of SAS shows how such a mechanism could function. The notions of co-coordinative structure and task-specific devices imply that collections of motor response can be chunked into routines, such that a specific routine will automatically recruit its constituent parts. From the notion of affordance, one can say that an object that affords grasping will elicit a specific response, and from the studies into apraxia one can say that the response and associated routine are represented separately from the ability to name the object. This returns us to the point made earlier (in response to the Samuel Butler quotation) that the 'recognition of the unity of the tool' is not simply a matter of knowing the tools name, but of having sufficient representations for routines and schema to affect the appropriate action.

1.4.1. Are tools unique?

Before progressing it is worth asking the question what makes tools any different from the countless objects that we encounter and use in our everyday lives? Surely we encounter many 'manipulable objects' on a day-to-day basis that are not tools in the sense used in this paper. Obvious examples would include keys, door handles, gear-sticks, etc.

It is proposed in this paper that tools occupy a space that is both related to other manipulable objects and quite distinct from them. A tool is designed and used with the purpose of acting upon the world in order to effect a change. Of course, the other objects are also covered by this definition. However, tools provide an opportunity for flexible manipulation by the user in order to control and refine the effects of the changes. In other words, tools are instruments through which goals can be expressed and which are designed to allow the user to modify and alter the manner in which the tool can be used. Thus, a door handle supports pretty much one type of grasp (with minor variation) if it is to be used properly, but a screwdriver supports at least two types of grasp (the precision grasp to place the tip into a screw's head and the power grasp to drive the screw home). A gear-stick needs to operated with a specific degree of force if it is to allow the gears to change, but a hammer can be operated with varying degrees of force, from the gentle taps to get a nail to bite to the firmer hits to drive the nail in. The other manipulable objects considered above all function as specific devices to perform single, specific operations. They are, thus, defined entirely by the immediate context and by the design of their surroundings. Tools function as the means by which sequences of actions can be combined together and performed in a variety of contexts.

As mentioned above, there is growing neuropsychological evidence to suggest that there are specific areas of the cortex that are associated with representing objects that can be manipulated. Much of this work has concentrated on the presentation of images of tools or of physical handles to be grasped. More recently, Imamizu et al. (2000) had participants use a mouse to move a cursor on a screen and analysed brain activity. When the person was presented with a cursor that moved opposite to the mouse, they need to 'learn' a new mapping between movements. The scan revealed increased activity in an area of the cerebellum during the learning of this new activity, which suggested that a model of pairing of movement and consequence was being built. Furthermore, when the participant performs similar tasks using two mice, activation occurs in different areas, suggesting unique models for each activity (Imamizu et al., 2003).

Evidence from apraxia also suggests separate representations of the declarative knowledge about the physical appearance of objects and modes of use, and procedural knowledge relating to how to use them (Johnson-Frey, 2004). Taken together, the neuropsychology evidence suggests a set of representations that support perception–action coupling of objects to manipulations (which could conceivably relate to any manipulable object) and representations of specific action sequences (which can relate to any form of dextrous action sequence). What is unique about tools is that they combine both the properties of manipulable objects and the need to manage dextrous action sequences, often in a manner that requires a degree of flexibility in response.

1.4.2. Representing tool use

From the discussion so far, it is proposed that people hold two representations for tool use: (i) a representation of the form of a tool and the manner in which it is manipulated; (ii) a representation of the sequence of actions that are involved in tool use. The first representation can be related, in part, to notions of affordance, in that people can more or less automatically reach for, and grasp, objects in a manner suitable for activity. This is also supported by evidence from neuropsychology which indicates that activation of areas of motor cortex occur even when people are only shown images of graspable objects. Thus, there is some evidence to suggest a coupling of object appearance with type of grasp required to manipulate it. Further evidence for this comes from the 'pantomiming' of tool using tasks, in which people might affect an appropriate hand-shape and arm movement to indicate how a given tool is used. In both cases, damage to specific regions of the brain impair people's ability to either perceive affordances or to pantomime tool use appropriately. The second representation is related more to the planning and coordination of movement. Much work on this topic has come from the area of sports science and skill acquisition, although (surprisingly) it appears to be a significantly under-researched area for ergonomists.

In order to develop a theory that combines both motor and cognitive dimensions, it is proposed that one can align some aspects of cognitive schema with the notion of task specific devices. From this discussion, my proposal is that tools warrant special treatment. In terms of task specific devices:

(i) We have knowledge of appropriate grasps for manipulable objects. The selection of an appropriate grasp typically occurs as we are approaching the object, i.e., it is not a pre-planned operation but is defined ad hoc. The selection will depend on the object that is to be grasped, e.g., the width of a handle, the material from which the handle is made, etc. The selection will also depend on the use to which the object will be put, i.e., raising a full glass to drink or an empty glass to put in the washing up bowl. The definition of an appropriate grasp is, in all likelihood, part of a learned repertoire of object manipulations that we have acquired over our lives and may well exhibit similar stereotypical tendencies to the 'population stereotypes' that influence the use of controls or the exploratory procedures that influence our testing of materials;

(ii) We have knowledge of appropriate coordination of actions. These have been considered in terms of 'task specific devices' and 'coordinative structures'. The idea is that a rehearsed set of actions begins to reinforce certain grouping of muscle firing and other neurological events. Thus, when faced with a similar situation, one will be able to cue the set and perform it rapidly and efficiently. Of course, there is ample evidence to suggest that people do not simply 'run' a programme, but that the set is open to adjustment, correction and other modifications during its performance;

(iii) We hold appropriate sequencing of actions. Thus, the task of 'making a cup of instant coffee' has a clearly defined group of actions and a sequence of performance. Again the sequence need not be rigidly defined, e.g., does it matter if the step 'get teaspoon' is performed before the step 'get cup'? Having said this, some steps are clearly dependent, e.g., the step 'put a teaspoon of coffee granules in cup' clearly requires that the teaspoon, cup and jar of coffee granules are to hand.

We can predict what happens if some aspect fails, both in terms of neurological damage or in terms of slips. Thus, failing to select an appropriate grasp on approaching an object could lead one to collide with the object, knock the object over or otherwise not grasp the object appropriately. If the object in question is the handle of a power-tool, say, then the failure might also arise from grasping too low on the handle (so that the weight of the tool pulls the wrist forward). Having grasped the object, selection of an appropriate set of actions might fail due to incomplete specification of force, movement etc. If the object is a tack hammer, one might apply too much force and bend the tack when hitting it. Having selected an appropriate set of actions to use the tool, then the process could fail when a step is added or omitted from a sequence of actions. If the procedure relates to a maintenance job in which a collar is tightened and then a retaining screw fitted and screwed in, it is plausible that the 'tighten collar' would serve to signify closure and the 'fit screw' be omitted.

In terms of schema, the following proposals can be put forward:

(i) We hold schema that relate the appearance of objects in the world to specific goals. From this it could be proposed that one holds a hierarchy of 'object appearances' (forms), with different aspects of the appearance linking to functions, and a mechanism through which the form-function representations can be linked to specific goals. Thus, the goal of 'fix a picture hook on the wall' could be related to goals of 'fixing objects' using nails, screws or other media. The selection of path to solving the goal might well depend on prior experience, i.e., might relate the a schema that describes solving a related goal in the past. Thus, to paraphrase an old proverb, 'to a man with a hammer, all problems are nails';

(ii) We hold schema that relate the function of tools to previous experiences of similar tools. Thus, until we know otherwise, we might assume that all hammers are used in the same manner, or that a power-screwdriver is used in a similar manner to a 'manual' screwdriver;

(iii) We hold schema that are shaped by our enculturation and experiences of the specific tool-set of the country in which we live. Thus, using knives and forks, chopsticks or breads to eat are equally 'natural' in different countries, When we move between cultures, then either the schema require modification or we need to develop new schema.

The notion of SAS provides a means of explaining how our actions can fail, when considering cognitive schema. If the wrong schema is selected, then the action might fail. For instance, we might decide to achieve the goal 'hang a picture on the wall' using a hammer and a nail, only to find that the bricks in the wall are so hard that the nail bends. Having selected an appropriate approach to reaching our goal, we might then fail to select an appropriate way of using the selected tool. For instance, we might decide to use a screw instead of a nail and, having drilled the hole and fitted a rawl-plug, we attempt to use an electric screwdriver by turning it on the screw rather than letting the motor do the work. In this instance, we need to effectively 'inhibit' the schema that describes screwdriving in order to 'activate' the schema for using power tools.

2. Forms of engagement

A tool is a physical object that is manipulated by users in such a manner as to change some aspect of the environment and to extend the capabilities of the unaided hand (Drillis, 1963). The manipulation is directed towards a specific goal or purpose, and the action requires a degree of control and co-ordination. From this definition, tools are objects external to the user that support engagement with objects in the world. The term 'engagement', is intended to call to mind the notion of interaction with technology (e.g., as in human–computer interaction), the notion of physically engaging with an object (e.g., as in the case of gears meshing or engaging), and the notion of being involved with something that demands all of one's attention (e.g., as in being engrossed in a film).

Tools mediate our engagement with the world and this engagement can take many forms. Thus, hammering a nail modifies the length of the nail, the contact between nail and hammer and nail and whatever object it is being hammered into, the contact between hand and hammer, the goal relating to the use of the nail, the movement and control of the hammer, etc. The actions are on the tools themselves, the objects that the tools affect, the environment, and the person's perception and understanding of the consequences of these actions in relation to their goal. However, it is my proposal that the existing literature does not fully describe the forms of engagement involved in using tools. Baber (2003) proposes six forms of engagement, i.e.,

- *Environmental engagement*—the ability of an organism to respond to aspects of the environment. Such responses could be innate, such that the presence of a particular feature in the environment will evoke a specific action, or they could be learned, e.g., through stimulus–response conditioning, or they could represent particular perception–action couplings.
- *Morphological engagement*—the ability of an organism to use hands, claws, mouth, beak, mandibles, etc. to grasp and wield objects. The dimensions of the object will relate to the morphology of the organism holding it.
- *Motor engagement*—the ability to manipulate objects. This relates to morphological engagement, in that the type of hold will be affected by the organism's morphology. However, sophisticated motor engagement might involve the organism exhibiting a variety of grips and changing the grips depending on the task at hand. Thus, motor engagement reflects both the postures adopted during the use of tools and also the control and coordination of movement.
- *Perceptual engagement*—the ability to interpret feedback from using the tool, and relate this feedback to a particular set of expectations.
- *Cognitive engagement*—the ability to represent the function of tools and to represent the characteristics of tools, as well as the ability to coordinate actions through psychomotor skills, and the ability to relate tools to goals.
- *Cultural engagement*—the ability of the organism to acquire tool using skills from other animals (as opposed to being born with the ability), and the way in which tool use reflects certain traditions of action. Thus a jig-saw, for instance, is designed to support a particular type of sawing activity which not only involves certain patterns of motor activity, i.e., the 'correct' way to use the saw, but also reflects certain desirable consequences of this activity, i.e., the need to produce decorative shapes from wood.

2.1. Relating schema to forms of engagement

Fig. 1 shows an initial framework for relating the forms of engagement with the topics considered in the previous section. In order to develop an appropriate response to the affordance of objects in the environment, a person needs both the capability of responding to the object, i.e., through some form of neurological hard-wiring, and the capability of organising a response. We know that 'tools' (and other manipulable objects)

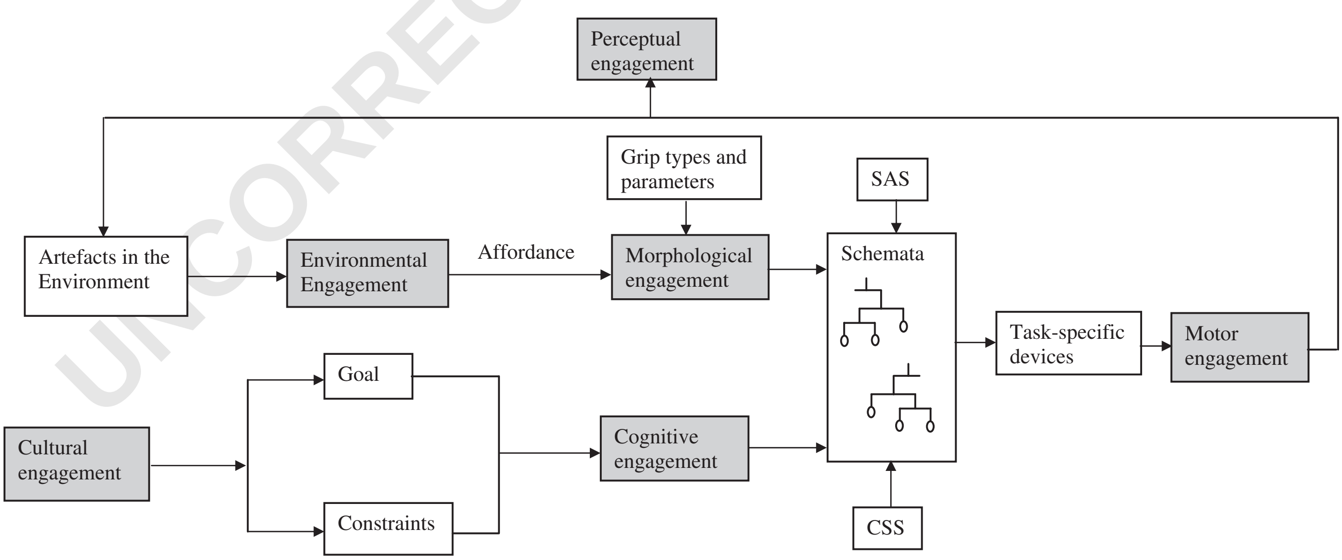

Fig. 1. Framework for forms of engagement.

have specific 'hard-wiring', in that they evoke motor responses even when they are only visually perceived, i.e., they afford grasping. The 'hard-wiring' of visual perception of the tool to the motor cortex (or equivalent structure) means that a response will always be elicited. Thus perhaps a defining feature of tool use is the (paradoxical) fact that one can opt to *not* use a given tool in a given situation. It is also proposed that the management and control of a motor response is covered by an appropriate task-specific device which is selected from possible alternatives on the basis of an appropriate schema.

The notions of morphological and motor engagement have already been alluded to in the discussion of task specific devices above. In broad terms, I am assuming that there is both a 'co-coordinative' structure, through which well-practised tool-using actions are recorded, and a higher order control which monitors, corrects and selects from the sets of co-coordinative structures. Thus, the novice performer will have little option but to use a single, simple co-coordinative structure, but the expert will have developed a set of sophisticated structures and be able to move between them. In this instance, the tool is similar but its manipulation is significantly changed.

The notion of perceptual engagement presents an interesting cross-over between motor and cognitive schema. I have been using environmental engagement, in terms of affordances, to describe some of the properties that are usually ascribed to perception. When I talk of perceptual engagement, I have in mind the interpretation of sensory data. The act of interpretation requires both the prediction or anticipation of data (possibly through motor engagement) and the labelling of these data in terms of known meanings (through cognitive engagement). Consequently, in using tools perceptual engagement is brought to the foreground when the action is not going as planned, i.e., when it is starting to break down. It is the perception of that failing action that leads to decisions to modify, halt or otherwise alter the action.

From the initial definition of tool-use, it is clear that the actions involving tools are goal directed and the primary purpose of cognitive engagement is to translate those goals into appropriate schema in order to select the most effective form of motor engagement. Cognitive engagement not only translates from goal to action, but also attends to the constraints that might influence performance. It is likely that rather than specifying a single plan of action, this process will occur continuously as a process of monitoring and refining the action.

Cultural engagement is presented in terms of stereotypical responses that people learn in their culture. The culture might be defined as a particular country or might be defined in terms of the working practices of a particular domain. In both cases, there is the 'normal' way of doing things, and this way becomes embedded in our expectations of how things work and the accepted procedures for using these tools. I assume that such knowledge is held primarily in cognitive schema.

3. Craftwork

The use of tools can be viewed as a defining aspect of the skill of the experienced craft worker. In his study of industrial skills, Seymour draws several distinctions between the experienced and inexperienced worker. "*First, the experienced worker usually employs 'smoother' and more consistent movements… Secondly, the experienced worker operates more rhythmically, indicating that a higher degree of temporal organization has been achieved. Thirdly, the experienced worker makes better use of the sensory data… . Fourthly, the experienced worker reacts in an integrated way to groups of sensory signals, and makes organized grouped responses to them*" [Seymour, 1966, p. 35–36]. This quotation highlights some key aspects of skilled tool-use, i.e., the rhythmicity of performance, the use of sensory data and integration of actions into organised groups.

3.1. Environmental engagement

In an interesting experiment, Wagman and Carello (2001) asked people to employ dynamic touch (without vision) to classify objects as either 'hammer' or 'poker'. The experiment required participants to reach into a box and feel the handles of different tools. Having felt the handle, the participant then picked up the tool and was asked to make a judgement as to whether it would be most useful to perform a hammering task or to poke a smaller object into a hole. The results from the experiments suggested that "…as an object shows increasing resistance to rotational acceleration about its major and minor axes (i.e., as the object becomes thicker with the mass concentrated further from the hand), so that object is perceived as a better hammer". (Wagman and Carello, 2001, p. 190). The opposite finding was true for tools classified as pokers. Thus, the physical properties of the object that are perceived prior to use can determine the interpretation of the object and influence the action that is deemed appropriate. It is plausible that such a perception-action pairing is possible even before the object is grasped. For example, Rosenbaum shows how the orientation of the hand reaching for a lever is strongly influenced by the direction in which the lever is to be turned. This implies that the orientation of the lever exerts a strong cue on the decision to angle the hand for optimal rotational force. This is similar to the findings (discussed above) relating finger-thumb aperture to object width for grasping experiments.

3.2. Morphological engagement

The skilled craft worker is able to wield tools in ways that make it seem as if the tools have become a part of the hand. From this point of view, the morphology of the tool user is partly a matter of the fit of the tool to the hand, and partly a matter of the reach and shape of the combined hand and tool. Tools are designed to support particular types of grip. A commonly used description of hand grip was originally proposed by Napier (1980), and consists of a simple dichotomy between power and precision grips. While such a distinction can distinguish between classes of grip, it does not provide sufficient detail to explore all types of tools. Kroemer (1986) proposed a classification of grips based on the configuration of the human hand. Table 1 shows the grip types proposed by Kroemer (1986), together with a short description of suggested application. Notice that while the 'power' grip of Napier (1980) is indicated, 'precision' grips can assume several different types.

Morphological engagement is not simply a matter of the hand coming to grasp the handle of a tool; rather it reflects the interaction between tool handle and the posture required to perform the task (or part of a task). It is proposed that such interactions become a significant component of the skilled use of tools. For example, the needle holders in Fig. 2, look as if they should be held in a 'scissor-grip'. However, such a grip effectively locks the wrist and makes rotational movement about the wrist difficult (which, in turn, makes in difficult to use the needle holders for suturing). Consequently, the correct grip is to use the thumb and the third finger—this locks the fingers but allows free rotation about the wrist.

When ergonomists consider tool design, a key area of enquiry is the design of handles. After all, these represent both the point of contact between human hand and tool and the interface between tool and user action. This could be considered from the perspective of the forces that a person needs to exert in order to hold or manipulate the tool (Böhlemann et al., 1994; McGorry, 2001) or the effects of different handle materials of grip and comfort (Fellows and Freivalds, 1991). It can be shown that appropriate handle design can not only alter grip force, but can also reduce stress on muscles within the hand-arm system; Lewis and Narayan (1993) demonstrate how redesigning the handle of a chisel lead to reduced stress on flexor and extensor muscles. Thus, ergonomics has already made significant inroads to understanding the morphological engagement between human and tool. However, what we do not understand is the manner in which this form of engagement is represented within the person. The reason why such an understanding might be useful is to better appreciate the ways in which the user of a tool can monitor potential breakdown in tool use. For example, when the tool slips from the person's grasp, we know that people make anticipatory adjustments in grip force (see above), but do not yet know how this can be sufficiently understood to allow such knowledge to be used either as the basis for training tool users or for design of tools.

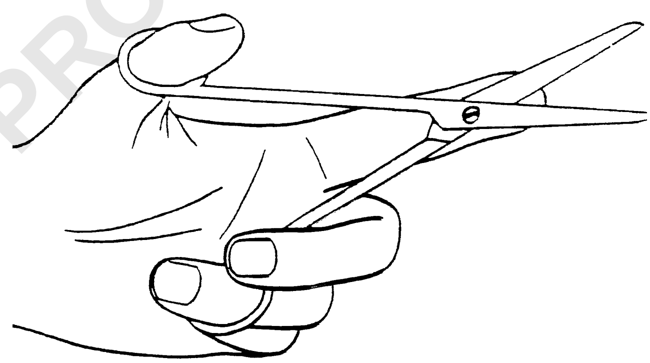

Fig. 2. Needle holders.

Table 1
Types of grip

Contact	Type of grip	Description	Application
Finger	Finger	Single finger placed on surface. Finger either rested or pushed in	Push buttons or touchscreens
Palm	Palmar	Palm placed on surface	Using sandpaper
Finger–palm	Hook	Palm against surface, and fingers hooked around object	Pulling a lever
Thumb–fingertip	Tip	Object held between thumb and (any) finger	Using a sewing needle
Thumb–finger–palm	Pinch	Object resting against palm, and grasped between thumb and fingers	Positioning screwdriver head onto a screw
Thumb–forefinger	Lateral	Object held between thumb and forefinger	Using tweezers
Thumb–two fingers (outside)	Pen	Object rested on thumb and pressed by two fingers	Writing with a pen
Thumb–two fingers (inside)	Scissor	Fingers and thumb placed inside handles	Cutting paper with scissors
Thumb–fingertip	Disk	Thumb and fingers curled around outside of object	Holding sanding block
Finger–palm	Collett	Object rested on palm and enclosed by fingers	Holding a ball
Hand	Power	Object rested across palm and enclosed by fingers	Holding a hammer or a saw

3.3. Motor engagement

Seymour (1966) considered tasks involved in a meat processing plant. He was struck by the apparent complexity of the work, but was greatly assisted by one of the foremen who told him that there were only six ways of using knives for the work (see Table 2). However, it is also apparent that some flexibility needs to be incorporated into these movements, e.g., gristle is not distributed evenly across all pieces of meat and so some modification and correction needs to be made when this is present. In other words, a skilled user of a tool is likely to employ a set of actions that are similar across situations, and to be able to modify these actions in the light of changing circumstances.

In a study of stone-bead manufacture in Khambhat, India, researchers attached accelerometers to hammers that were being used by the workers (Roux et al., 1995). Two groups of bead-makers were studied: group I had some 30+ years of experience following a 12 year apprenticeship; group II had some 20+ years of experience following a 3 years apprenticeship. Both groups consisted of 6 people. Each worker was asked to produce 80 stone and glass beads during the study. The workers were used to working with stone, but glass was a novel material for them. In the studies, group I produced superior (more spherical and symmetrical) beads than group II. Furthermore, while both groups were able to adapt their technique as measured through accelerometry for the familiar stone, only group I was able to adjust their activity to compensate for the properties of glass. Fig. 3 shows that both groups modify acceleration when producing large or small beads from stone, but only group I shows similar modification with the less familiar glass (compare Large I with Small II for stone and glass).

From the ergonomics literature, it has been shown that designing tools to support specific motions can greatly enhance performance. This was initially shown in the classic account of Tichauer (1976) on angled design of handles for wire-cutters, and more recently in work showing how angled design of handles for hammers can also be beneficial (Knowlton and Gilbert, 1983). This suggests that modifying a tool to support specific types of motor activity can be sound ergonomics. Indeed, Groenesteijn et al. (2004) show how a purpose-designed pair of pliers can be beneficial to tasks in installation. Furthermore, understanding the motor engagement associated with tool use in the context of the work being performed can provide insight into potential musculo-skeletal problems (Cederqvist and Lindberg, 1993).

3.4. Perceptual engagement

Keller and Keller (1996) provide a first-hand account of the skills involved in blacksmithing, by way of a participant—observation study of artist—blacksmiths.

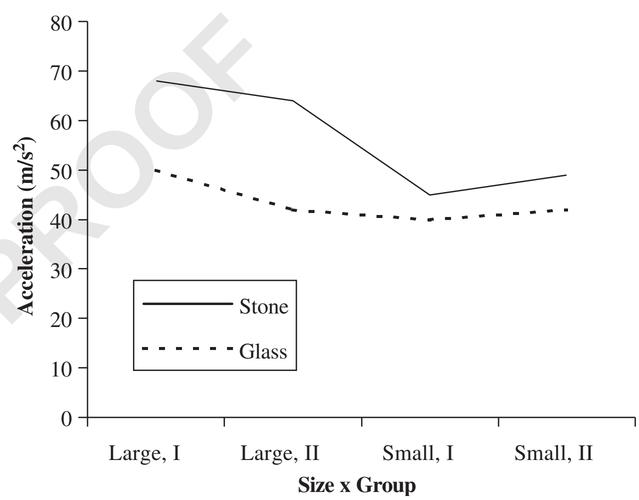

Fig. 3. Results from stone bead study.

Table 2
Grips in butchery

Movement #	Goal	Left hand	Right hand	Attention points
I (a)	Remove fat from meat or gristle	Grip joint 1, 2, 3, 4, T at side. Fingers arched and gripping joint at end and behind knife	Grasp knife between base of 1, 2, 3, 4 and first knuckle intersection with an angle of approx. 80° between 4 and 1, T on back of blade just beyond guard	Wrist of the R/H moves through 90° clock-wise. Slight flick of the knife… Knife must be grasped firmly. L/H might be used for lifting the fat clear of the knife blade
III	Cutting meat into strips	Grasp furthest edge of meat from body 1, 2, 3, 4. T approx. 3” from point of knife insertion (to the left). Raise slightly and pull upwards and backwards	Nick the seam at end furthest from body. Only use tip of the knife at an angle of approx. 45° to joint. Grasp knife as per I (a) but when the hand is closed place the thumb parallel to the blade with the tip of the thumb at the knife end of the guard	Draw knife through, don’t saw. Keep wrist up at an angle. Don’t put the 1st finger down the back of the blade

The primary means of working in this domain is the transformation of hot iron by working on it with tools. In order to work with metal, a smith needs a knowledge of the temperature of the material being worked.

Knowing that the metal is at the right temperature clearly requires a well developed ability to perceive differences in the metal's colour. Whether this perception relates to interpretation and pairing a colour with a temperature and with a state of the metal, or whether it relates to simply 'knowing' that a given state of the metal will afford a given type of working, would relate to the experience of the smith.

3.5. Cognitive engagement

In one of our studies of jewellery making, an experienced jeweler (with some 40 years experience) was observed and interviewed over the course of several weeks (Baber and Saini, 1995). One of the activities that we asked him to perform was a set of verbal protocols (i.e., commentaries upon his actions) whilst making models. The protocols typically began with a general statement of activity and of the problem at hand, for example, whether to produce a shank without a split or curl. The statement of the problem and consideration of options and constraints reflect the previous experience of the jeweler. The 'plan' develops according to a 'visualization' of the finished product (or, at least, some concept of the form of the finished product) and defining an appropriate course of action that will progress from the current state to the finished product. For example, when interviewing another jeweler, who was cutting material for necklaces from a sheet of metal, it was apparent that the main constraint was not efficient use of metal (which could be resold at face value) but ensuring that one cut finished with sufficient space to allow a subsequent cut to be made. Of particular note is the fact that the 'plan' is continuously developed. Fig. 4 shows a sketch that the jeweler drew of the proposed work. Note the relative lack of detail and the somewhat limited information it contains. This sketch suggests not a blueprint for a design so much as a suggestion for a course of action.

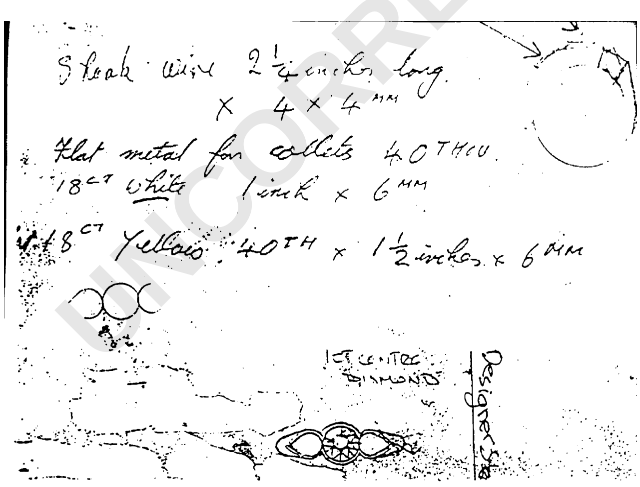

Fig. 4. Jeweler's sketch.

What is apparent from this discussion, it that the 'plan' that guides the work of the jewelers we have spoken to is not a prepared, precise list of actions (as one might assume from the word plan) so much as the rewriting of a course of action based on current options and constraints. This is very much akin to the notion of 'situated action' that Suchman (1992) contrasted with traditional notions of planning. In other words, the intentionality for the action is not something that is predetermined but something that arises from working.

3.6. Cultural engagement

The rules and conventions to which the practitioners in a domain adhere, represent shared beliefs, values and expectations concerning how that work is to be done. One could consider the layout of the workers' workplace as an example of the culture of the work. Thus, an operating theatre tends to be laid out in a particular manner, not only to provide access to the patient and space for the equipment but also to allow communication between members of the surgical team and to provide easy access to relevant equipment and instruments. Indeed, since the 1950s, surgery has been supported by specific kits of instruments that are put together for particular types of operation. In their analysis, Keller and Keller (1996) observe that the layout of a smith's workshop reflects the tools that have been acquired to do the work, and the layout of these tools in relation to specific tasks. In other words, the collection of tools and their layout represents an aspect of knowledge of the tasks at hand. The basic layout relates to the need to heat metal, hammer (or otherwise work) that metal and quench it, with equipment related to these actions being grouped together and equipment related to peripheral actions, such as drilling, being moved to other locations. Thus, the layout of the workplace implies a particular way of working.

What these examples share is the notion of segmenting the work into constituent components. For blacksmithing, the crucial aspect is working on the metal at the right temperature, and working before the metal cools. This means that tools have to be ready to hand, that the course of action needs to be established and that the smith needs to coordinate activities as rapidly and coherently as possible. A similar example of workplace layout can be seen in Fig. 5. Tools are grouped according to function, size and process. At the centre of the bench is a block against which rings and other objects are held for filing, and at the right of the jeweler a gas jet is used for softening the metals being worked.

Fig. 5. The jeweler at work.

4. Discussion

It is interesting to note how little attention ergonomics has devoted to the study of tools over the years (particularly if one compares this activity to research relating to computer design). Presumably a factor in this difference lies in the fact that tool-use research was reaching some interesting conclusions just when human-computer interaction research was gaining ground and when the world of work was seen as moving from the physical to the cognitive. However, attending the manner in which people use tools can be beneficial to contemporary and future ergonomics. Not only can a study of tool use help understand the potential risks and injuries arising from such activity (Mital, 1991), but it can also help inform design activity. For example, appreciating the difference between morphological and motor engagement helps to understand that a handle suitable for grasping might not be suitable for movement. This is borne out by the development of angled handles for hammers (Kadefors et al., 1993) and wire-cutters (Tichauer, 1976). Understanding that tool-use is not simply a matter of motor engagement, but also is influenced by environmental and perceptual engagement might influence the design of training simulators. Often haptic virtual reality has difficulty in presenting appropriate morphological engagement to its users, but this need not be a problem. For example, Moody et al. (2001) demonstrated that the use of haptic feedback in a virtual training simulator could be used to train suturing skills when people were given a pairs of needle holders to grasp in order to manipulate the virtual model.

This paper has presented a notion of tool-use based on Forms of Engagement. Fig. 1 showed a tentative relationship between these Forms of Engagement, schema and task-specific devices. It is proposed that this view extends the conventional perspective on tool-use from a psychomotor activity and helps introduce contemporary ideas from cognitive neuroscience.

5. Uncited references

Luria, 1973; Martin et al., 1996; Sirigu et al., 1995.

References

Aghazadeh, F., Mital, A., 1987. Injuries due to handtools: Results of a questionnaire. Appl. Ergon. 18, 273–278.

Baber, C., 2003. Cognition and Tool Use. Taylor and Francis, London.

Baber, C., Saini, M., 1995. Craft Skills in Jewellery Manufacture, Contemporary Ergonomics 1995. Taylor and Francis, London, pp. 92–97.

Bartlett, F.C., 1932. Remembering: a Study in Experimental and Social Psychology. Cambridge University Press, Cambridge.

Beek, P.J., Bingham, G., 1991. Task-specific dynamics and the study of perception and action: a reaction to von Hofsten (1989). Ecol. Psychol. 3, 38–39.

Bernstein, N., 1967. The Coordination and Regulation of Movements. Pergamon Press, Oxford.

Bingham, G.P., 1988. Task-specific devices and the perceptual bottleneck. Human Movement Sci. 7, 225–264.

Böhlemann, J., Kluth, K., Kotzbauer, K., Strasser, H., 1994. Ergonomic assessment of handle design by means of electromyography and subjective rating. Appl. Ergon. 25, 346–354.

Butler, S., 1912. On tools. In: Keynes, G., Hill, B. (Eds.), Samuel Butler's Notebooks. Jonathan Cape, London.

Cederqvist, T., Lindberg, M., 1993. Screwdrivers and their use from a Swedish construction industry perspective. Appl. Ergon. 24, 148–157.

Chao, L.L., Martin, A., 2000. Representation of manipulable man-made objects in the dorsal stream. NeuroImage 12, 484–487.

Chapanis, A., Lindenbaum, L., 1959. A reaction time study of four control-display linkages. Human Factors 1, 1–7.

Cooper, R., Shallice, T., 1997. Modelling the selection of routine actions: exploring the criticality of parameter values. In: Shafto, M.G., Langley, P. (Eds.), Proceedings of the 19th Annual Conference of the Cognitive Science Society. Norton, Stanford, CA, pp. 131–136.

Drillis, R.W., 1963. Folk norms and biomechanics. Human Factors 5, 427–441.

Eklund, J., Freivalds, A., 1990. Hand tools for the 1990s: An Applied Ergonomics special issue based on presentations at the symposium on hand tools and hand-held machines. Appl. Ergon. 24, 146–147.

Ellis, R., Tucker, M., 2000. Micro-affordance: the potentiation of components of action by seen objects. Br. J. Psychol. 91, 451–471.

Fellows, G.L., Freivalds, A., 1991. Ergonomics evaluation of a foam rubber grip for tool handles. Appl. Ergon. 22, 225–230.

Fitts, P.M., Seeger, C.M., 1953. S–R Compatibility: spatial characteristics of stimulus and response codes. J. Exp. Psychol. 46, 199–210.

Forde, E., Humphreys, G.W., 2000. The role of semantic knowledge and working memory in everyday tasks. Brain Cognition 44, 214–252.

Freivalds, A., 1987. The ergonomics of tools. In: Oborne, D.J. (Ed.), International Review of Ergonomics, vol. I. Taylor and Francis, London, pp. 43–76.

Freivalds, A., Eklund, J., 1993. Reaction torques and operator stress while using powered nutrunners. Appl. Ergon. 24 (3), 158–164.

Gerhardsson, L., Balogh, I., Hambert, P.-A., Hjortsberg, U., Karlsson, J.-E., 2005. Vascular and nerve damage in workers

exposed to vibrating tools. The importance of objective measurements of exposure time. Appl. Ergon. 36, 55–60.
Gibson, J.J., 1996. The Senses Considered as Perceptual Systems. Houghton Mifflin, Boston.
Goodale, M.A., Milner, A.D., 1992. Separate visual pathway for perception and action. Trends Neurosci. 15, 20–25.
Greenberg, L., Chaffin, D., 1977. Workers and their Tools. Pendell Publishing, Midland, MI.
Groenesteijn, L., Eikhout, S.M., Vink, P., 2004. One set of pliers for more tasks in installation work: the effects on (dis)comfort and productivity. Appl. Ergon. 35, 485–492.
Jeannerod, M., 1997. The Cognitive Neuroscience of Action. Blackwell, Oxford.
Johansson, R.S., Westling, G., 1984. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. Exp. Brain Res. 56, 550–564.
Johnson-Frey, S., 2004. The neural bases of complex tool use in humans. Trends Cognitive Sci. 8, 71–78.
Kadefors, R., Areskoug, A., Dahlman, S., Kilbom, A., Sperling, L., Wikström, L., Oder, J., 1993. An approach to ergonomic evaluation of hand tools. Appl. Ergon. 24, 203–211.
Keller, C.M., Keller, J.D., 1996. Cognition and Tool Use: the Blacksmith at Work. Cambridge University Press, Cambridge.
Kempler, D., 1997. Disorders of language and tool use. In: Gibson, K.R., Ingold, T. (Eds.), Tools, Language and Cognition. Cambridge University Press, Cambridge, pp. 193–215.
Kihlberg, S., Kjellberg, A., Lindbeck, L., 1993. Pneumatic tool torque reaction: reaction forces; displacement, muscle activity and discomfort in the hand-arm system. Appl. Ergon. 24, 165–173.
Knowlton, R., Gilbert, J., 1983. Ulnar deviation and short-term strength reduction as affected by a curve-handled ripping hammer and a conventional claw hammer. Ergonomics 26, 173–179.
Kroemer, K.H.E., 1986. Coupling the hand with the handle: an improved notation of touch, grip and grasp. Human Factors 28, 337–339.
Kuijt-Evers, L.F.M., Groenesteijn, L., de Looze, M.P., Vink, P., 2004. Identifying factors of comfort in using hand tools. Appl. Ergon. 35, 453–458.
Lederman, S.J., Klatzky, R.L., 1996. Action for perception: manual exploratory movements for haptically processing objects and their features. In: Wing, A.M., Haggard, P., Flanagan, J.R. (Eds.), Hand and Brain: the Neurophysiology and Psychology of Hand Movements. Academic Press, San Diego, CA, pp. 431–446.
Lewis, W.G., Narayan, C.V., 1993. Design and sizing of ergonomic handles for hand tools. Appl. Ergon. 24, 351–356.
Lockman, J.J., 2000. Perception–action perspective on tool use development. Child Develop. 71, 137–144.
Luria, A.R., 1973. The Working Brain: an Introduction to Neuropsychology. Penguin, Harmondsworth.
Martin, A., Wiggs, C.L., Ungerleider, L.G., Haxby, J.V., 1996. Neural correlates of category-specific knowledge. Nature 379, 649–652.
McCullough, M., 1989. Abstracting Craft. MIT Press, Cambridge, MA.
McGorry, R.W., 2001. A system for the measurement of grip forces and applied moments during hand tool use. Appl. Ergon. 32, 271–279.
Mital, A., 1991. Hand tools: injuries, illnesses, design and usage. In: Mital, A., Karwowski, W. (Eds.), Workspace, Equipment and Tool Design. Elsevier, Amsterdam.
Napier, J., 1980. Hands. Pantheon, New York.
Norman, D.A., Shallice, T., 1980. Attention to Action: Willed and Automatic Control of Behavior (CHIP Report 99). University of California, San Diego, CA.
Preston, B., 1998. Cognition and tool use. Mind Language 13, 513–547.
Roux, V., Bril, B., Dietrich, G., 1995. Skills and learning difficulties involved in stone-bead knapping in Khambat, India. World Archaeol. 37, 63–87.
Schank, R.C., 1982. Dynamic Memory. Cambridge University Press, Cambridge.
Schank, R.C., 1999. Dynamic Memory Revisited. Cambridge University Press, Cambridge.
Seymour, W.D., 1966. Industrial Skills. Pitman, London.
Sirigu, A., Cohen, L., Duhamel, J.R., Pillon, B., Dubois, B., Agid, Y., 1995. A selective impairment of hand posture for object utilization in apraxia. Cortex 31, 41–56.
Smitsman, A.W., 1997. The development of tool use: changing boundaries between organism and environment. In: Dent-Read, C., Zukow-Goldring, P. (Eds.), Evolving Explanations of Development. American Psychological Association, Washington, DC, pp. 301–329.
Sperling, L., Dahlman, S., Wikström, L., Kilbom, A., Kadefors, R., 1993. A cube model for the classification of work with hand tools and the formulation of functional requirements. Appl. Ergon. 24, 212–220.
Suchman, L.A., 1992. Plans and Situated Actions. Cambridge University Press, Cambridge.
Tichauer, E., 1976. Biomechanics sustains occupational safety and health. Ind. Eng. 8, 46–56.
Turrell, Y.N., Li, F.-X., Wing, A.M., 1999. Grip force dynamics in the approach to a collision. Exp. Brain Res. 128, 86–91.
Vygotsky, L.S., 1928. The instrumental method in psychology. In: Rieber, R.W., Wollock, J. (Eds.), The Collected Works of L.S. Vygotsky: Problems of the Theory and History of Psychology, vol. 3. Plenum Press, New York.
Wagman, J.B., Carello, C., 2001. Affordance and interial constraints of tool use. Ecol. Psychol. 13, 173–195.
Warrick, M.J., 1947. Direction of movement in the use of control knobs to position visual indicators. In: Fitts, P.M. (Ed.), Psychological Research on Equipment Design. Army Air Force Aviation Psychology Program, Columbus, OH.