Knowledge and performance in action

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Abstract *This article addresses the functional links between knowledge and performance in human activity. Starting with the evolutionary roots of knowledge and activity, it shows how the combination of adaptive behavior and knowledge storage has formed over various stages of evolution. The cognitive architecture of human actions is discussed against this background, and it is shown how knowledge is integrated into action control. Then, methodological issues in the study of action knowledge are considered, and an experimental method is presented that can be used to assess the structure of action knowledge in long-term memory. This method is applied in studies on the relation between object knowledge and performance in mechanics and between movement knowledge and performance in high-performance sportswomen. These studies show how experts' knowledge systems can be assessed, and how this may contribute to the optimization of human performance. In high-level experts, these representational frameworks were organized in a highly hierarchical tree-like structure, were remarkably similar between individuals, and matched well the functional demands of the task. In comparison, the action representations in low-level performers were organized less hierarchically, were more variable between persons, and were not so well in accordance with functional demands. These results support the hypothesis that voluntary actions are planned, executed, and stored in memory directly by way of representations of their anticipated perceptual effects. The method offers new possibilities to investigate knowledge structures. Based on such results it is possible to improve performance via special training-techniques. This paper fulfils an identified research need concerning the interaction of knowledge and performance and offers new perspectives for future forms of knowledge management.*

Keywords *Knowledge management, Performance management*

Introduction

Knowledge plays a central role in the control and organization of actions. In different fields of action, it makes it possible to evaluate and select effective information. Regardless of whether a surgeon has to select the appropriate instrument for an operation, a mechanic a suitable tool for repairing an engine, or a basketball player which member of the team to pass the ball to, actors have to use their knowledge as a basis to sort through an exceptionally large amount of information. Frequently, the action-relevant information is only available under extreme time pressure. Hence, knowledge has to be available quickly and provide clear criteria for selecting information. At the same time, knowledge forms the functional basis for a meaningful, and thereby task-related reduction in the large number of potential behaviors available to our social and technological systems. Knowledge does not just facilitate information input, but also more

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generally permits a target-related and purposeful adaptation of behavioral potentials to conditions in the environment. This also includes storing the outcomes of learning processes as information in long-term memory. Performance does not just involve knowledge but also and always a learning-dependent modification of such information.

Numerous studies on experts have shown that they possess greater knowledge than novices (e.g. Ericsson and Smith, 1991). This is also reinforced by everyday experience. Performance seems to accompany knowledge, and experts clearly know more about the fields in which they are active. However, closer inspection of such studies and everyday experiences reveals a frequent failure to distinguish between knowledge that is functionally relevant for the control and organization of actions and knowledge that merely accompanies actions or justifies them in retrospective. As a result, we cannot assume that the knowledge that high performers (experts) report is the same as the knowledge responsible for their performance. Several expert-training studies have demonstrated this impressively (see Hacker, 1998; Prümper *et al.*, 1992). Generally, such studies train participants over several weeks as an expert group and teach them, for example, certain problem-solving rules. A second group receives no training at all. Interviews then show that members of the expert group will report knowledge of the rules and also say that they apply it. However, observations during task performance often reveal that these rules are applied only in exceptional cases, and group comparisons reveal no clear performance effects. So, there seems to be a difference between the knowledge that persons verbalize as being relevant for their actions and the knowledge that is responsible for their actual performance.

Because this knowledge often cannot be verbalized, it has also been called tacit knowledge (e.g. Sternberg, 1995). It is built up from experience and is generally tied to routines and automatisms (Schack and Whitmarsh, in press). It is only activated when situations arise in which the corresponding tasks have to be solved (Schack, 2002; Sternberg, 1995). This is why it is important to start off by considering the functional purpose of, in particular, real-time or concurrent knowledge within action. It is also necessary to find criteria to characterize action knowledge more precisely and experimental methods for assessing action-relevant knowledge structures empirically. To gain a better understanding of the functionality of knowledge, this article will start by looking at evolutionary links between knowledge and action. This leads to the formulation of a model that can place knowledge in a functional relation to action organization and performance. The article then considers relevant issues in research methodology and presents a method that can assess action-relevant knowledge structures experimentally. Experimental studies based on this method are used to show relations between object knowledge and performance and between movement knowledge and performance. The article closes by taking a look at future research questions addressing knowledge and performance in action.

Evolutionary links between knowledge and action

An evolutionary perspective clearly reveals the functional value of cognitive memory representation for all living beings. The oldest form of information storage is without doubt genomic. The first living beings on this planet, approximately 3.5 billion years ago, possessed only a genetically inheritable species memory. This imposed limits on their adaptive and environmentally appropriate behavior potentials. An evolutionary advance of a qualitative kind was the emergence of organisms with an intracerebral individual memory. Such beings first entered the history of evolution during the Cambrian period (about 570 million years ago). At the same time, older life forms with only a species memory rapidly became extinct. An example is the stromatolites that used to cover the entire seabed in meter-thick blankets. Nowadays, we can marvel at them as meter-high layers of fossilization (the so-called Ediacara fossils named after one of their sites in Australia) throughout the world (in Canada, Australia, Rhodesia, Namibia, etc.). The advantage enjoyed by the species that spread in impressive variety at the onset of the Cambrian period was their ability to store information on searching for food and avoiding danger. This is an early form of knowledge. The memory-like storage of behaviorally relevant environmental states granted these species a qualitatively new kind of orientation and flexibility. Just as remarkable, by the way, is the fact that they could forget. Forgetting environmental states when they lose their behavioral relevance is crucially important for all species. Those that possess only a genomic species memory pays a high price for not being able to forget: They become extinct.

A further crucial evolutional stage in the development of cognitive representation systems occurred round about the Oligocene epoch (37 to 23 million years ago). The old-world apes emerged, including the modern baboon, and a new type of adaptive behavior program emerged with these anthropoids. The frontal extremities shifted increasingly into the binocular visual field. This did not only just lead to the emergence of flexibility in movements but also a new kind of precision. Being able to manipulate objects in a qualitatively novel way led to complete sets of new and individually learnable movements such as breaking open nuts or using sticks to search for food. However, this also required an ability to store such behavioral programs and specific situation-action associations in memory. Put specifically, this led to the emergence of a new type of ''knowledge'': knowledge about which action (object manipulation) can be used to attain which type of goal (see Klix, 1993; Klix and Lanius, 1999; Schack, 2002). Studies of chimpanzees indicate that anthropoids are also capable of forming concepts (e.g. Premack, 1977; Rensch, 1973). Although unable to name tools, after a learning phase, they will confidently select the appropriate tools to solve specific problems (experimental tasks). The crucial factor is for the tools to exhibit a behavior-related relevance and a functional equivalence. In other words, the proof that an anthropoid has registered in its memory which group of tools (e.g. screwdrivers) is appropriate for a certain group of object manipulations (turning screws or screw-like objects) indicates a new kind of order formation in memory. This type of order formation is based on equivalence classes and thus on concepts – even when stored without the necessary word ''screwdriver'' (see Hoffmann, 1986; Klix, 1993).

A further critical stage of development was the transition from animals to humans. This period of evolution started about 17 million years ago and extended up to about 2.5 million years before our time. It marks the shift from subhuman evolution (*Ramapithecus*) across *Australopithecus* to *Homo habilis* and then to *Homo erectus* in which the biological foundations of behavioral control changed drastically. Brain size increased. The *hominids* increasingly had freely movable front limbs at their disposal, a brain case of at least 600 cubic centimeters, and a sensorimotor fine coordination of their hands. At the end of this development, evolution began to pay more attention to the group rather than the individual. A socio-cultural framework for communication and action emerged.

Early human beings were not only able to apply tools; they could also produce them for specific purposes. This led to new framing conditions for the further development of the species and for individual survival. The oldest known stone tools come from the Olduvai Gorge in Tanzania and are about 2.5 million years old. The production of such tools meant that not only the goal but also a chain of action steps had to be stored in memory (see Klix, 1993; Klix and Lanius, 1999). It had to be possible to compare the goal with the sensory and functionally detectable effects of the tool produced. This led knowledge to acquire a new kind of functionality. Those who did not possess this knowledge were, depending on their gender and the degree of division of labor, at a disadvantage within their community. Such knowledge can be passed on through new forms of communication and through imitation. This introduced the first major stage of purely human evolution. It had to be supplemented with the stepwise development of group rituals and cultural means of expression such as dance and body language (see Donald, 1993).

A second crucial phase of human development was the transition from *Homo erectus* to the Preneanderthals. This probably took place during the so-called Mindel Ice Age in the northern hemisphere beginning approximately 450,000 years ago and lasted approximately 120,000 years. The surge in cognitive development attributable to this age seems to have commenced with the increase in the division of labor and the consolidation of human speech and narrative thought (see Donald, 1993; Klix, 1993). The integration of knowledge elements into stories led to a dramatic increase in the storage capacity of memory. Semantic networks formed between the single units of knowledge. However, the functional relevance of these knowledge units was no longer necessarily to control one's own action programs. Recounting and recalling stories could also serve social and communicative purposes. In the context of the division of labor, knowledge became increasingly necessary for a variety of performance domains. The medicine man required other forms of knowledge than the hunter. Furthermore, both required knowledge on how to make themselves understood and how to store knowledge in the form of stories and communicate it to each other.

The final phase of human development, continuing up to the present day, has seen the increasing emergence of an extra-cerebral species memory. More and more symbols are being created such as speech signs, numbers, or visual codes. This qualitatively new kind of information storage within the framework of the culture is drastically changing the adaptive performance of the brain and the entire organism (see Klix, 1993; Donald, 1993; Schack, 2002, 2003b; Vygotsky, 1929/1992). This increasingly facilitates the use of signs to code objects in the environment and one's own actions semantically. Things and actions acquire labels and are given meaning on the basis of symbols, and it also becomes possible to stimulate behavior in a new way. Symbols scratched into the cave wall can also be understood as a stimulus for certain magical rituals. Furthermore, action sequences (e.g. of a hunt) can be coded symbolically in a cave drawing, making them easier to grasp as a visual representation. It is highly probable that this phase of development, which has attained its peak during the last 8,000 years, also marks the emergence of more hierarchical representation systems that integrate phylogenetically older types of representation and ontogenetically acquired information on objects and movements (see Donald, 1993; Vygotsky, 1929/1992).

The cognitive architecture of action

In sum, such an evolutionary perspective shows that the output, or performance, of the *prehominids* and *hominids* was accompanied by the development of representations and knowledge systems. It also becomes clear that the evolution of species is always an evolution of the motor system as well. Eye-to-hand coordination, making tools, painting on cave walls, writing, and many other new forms of human performance each became possible through qualitatively new types of movement. One could now ask which combination of knowledge, movement, and performance this evolutionary development has produced in modern humanity (*Homo sapiens sapiens*).

A number of studies have addressed the architecture of cognition (see, e.g. Anderson, 1983; Anderson and Lebiere, 1998). However, if one maintains a rigorous evolutionary stance and tries to view knowledge in functional terms, it seems appropriate to examine the cognitive architecture of action as well. This concerns how knowledge representations are built into action organization in humans and which functional role they correspondingly take in the performance of the action system.

One major property of human actions is that they are volitional (see, Ach, 1921). Human volition (or will) can be analyzed functionally and broken down into its main components. From the functional perspective taken here, we shall call this ability (volition) mental control. One major functional component of mental control is the coding of the intended action goal. Such a coding is needed before an action goal can adopt the function of a cognitive benchmark for the further process. This intention-related coding is followed by the generation of a mental model of the

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future to which all control and monitoring processes can be related. Another functional component closely related to this action plan is the action acceptor (see Anochin, 1978). This translates the intended action outcome into a sensory (perceptive) model of the action effects and thus provides guiding criteria for the system's comparison and control processes. The outcome of this process is knowing how, for example, a product feels at the end of the work process, what it looks like, and how one can use it. This functional component (the action acceptor) is simultaneously responsible for evaluating the action steps performed in terms of the criteria that have been generated. Neuropsychology provides examples confirming the presence of such a functional component. If the action acceptor has broken down (e.g. through frontal lobe brain damage), patients are still able formulate an intention and even control the enactment of this task by third persons (recognizing any errors they make), but they no longer either possess control over their own actions or evaluate errors in their own action performance (see Luria, 1992; Luria *et al.*, 1964).

Inner speech strategies are a further functional component of mental control. These are applied particularly when difficulties emerge in action performance. They are a means of stabilizing activities leading toward the goal (see Donald, 1993; Vygotsky, 1962, 1929/1992).

If we provisionally locate these functional components of voluntary movement regulation on a level of mental control, we still have to ask in what form knowledge is integrated into behavior control. What sort of system ensures that when intended effects are anticipated, it is precisely the motor actions eliciting these effects that are triggered?

From the evolutionary perspective, conscious mental functions can be assumed to emerge on the basis of elementary functions. As shown already in the discussion on the evolution of the human action system, signs convey higher, mentally controlled functions. Hence, whereas elementary functions (e.g. reflexes) are influenced directly by stimulus constellations, mental control functions are guided intentionally; the self regulates them. For example, it is not possible for a mentally controlled action to emerge from the grasp reflex in humans. This reflex has to be inhibited actively before verbal or other cognitive means can be applied and a goal-directed action can be formed. If, at this point, children fail to develop any (sign-conveyed) inhibitive activity, they cannot manipulate objects. They will grasp and that is all. These remarks on the grasp reflex also apply on an ontogenetically more advanced level to associations (between stimuli and action schemes) that were found appropriate at one time in the past, but have now become (automatized and) purposeless. This points to the vertical dimension of cognitive control. Together with an increasingly effective organization of the organism-environment interaction, various levels of functional organization also seem to have formed. It is assumed that the functional construction of actions is based on a reciprocal assignment of performance-oriented regulation levels and representational levels (see Table I). These levels differ according to their central tasks on the regulation and representation levels. Each level is assumed to be functionally autonomous.

The function of the mental control level (IV) has already been sketched for voluntary movement regulation and the coding or the anticipated outcome of movement. The level of mental representations (III) predominantly forms a cognitive benchmark for the mental control level (IV). It is organized conceptually and responsible for transferring the anticipated action outcome into a model of the action structure it requires (or into a movement program). Because an action is ''no chain of details, but a structure subdivided into details'' (Bernstein, 1988, p. 27, translated),

Table I Levels of action organization

Code	*Level*	*Main function*	*Subfunction*	*Means*
IV	Mental control	Regulation	Volitional initiation control strategies	Symbols; strategies
III	Mental representation	Representation	Effect-oriented adjustment	Basic-action-concepts
II	Sensorimotor representation	Representation	Spatial-temporal adjustment	Perceptual effect-representations
I	Sensorimotor control	Regulation	Automatization	Functional systems; basic reflexes

action organization has to possess a working model of this structure. The corresponding abilities to use such targets and representations have been acquired – as shown above – stepwise during evolution. Hence, the current level of human development can draw on hierarchically organized representations of either states in the environment, objects, or goal-directed movements. These knowledge representations are the subject of the next section and the experimental analyses reported in this article. They hold the knowledge that relates directly to performance. However, the model also reveals clearly that these representations are functionally embedded in further levels and components of action organization. It also becomes clear that knowledge is not just located on the level of mental representations.

Therefore, the functioning of the lower levels (I and II) will also be sketched. The level of sensorimotor control is linked directly to the environment. In contrast to the level of mental control (IV), which, as explained above, is induced intentionally, the level of sensorimotor control (I) is induced perceptually. Hence, it is not just essential to understand what this level integrates but also in which relations to the environment it is integrated. This can be illustrated in studies of patients whose range of movement is restricted through injury or illness (see, e.g. Leontjev and Zaporoshets, 1960; van der Weel *et al.*, 1991). Leontjev and Zaporoshets (1960) studied patients whose elbow and shoulder movements were limited because of peripheral nerve injuries. They found that the ability to move the dominant arm differed as a function of the concrete feedback obtained from the environment. For example, these patients could move their arm further when their eyes were open than when their eyes were closed. Their range improved even further when they had to touch a point on a screen. However, their range was greatest when they had to grasp an object. This study reveals vividly that the execution of movements can only be considered in the context of the intended sensory effect. The level of sensorimotor control is built on functional units composed of effectors, perceptual effect representations, and afferent feedback, whose essential invariant is the movement effect within the framework of the action. The system is broadly autonomous. Automatisms emerge when this level possesses sufficient correction mechanisms to ensure the stable attainment of the intended effect.

It is obvious why a level of sensorimotor representation is necessary in this context. It can be assumed that this is where, among others, the modality-specific information representing the effect of the particular movement is stored. The relevant modalities change as a function of the level of expertise in the learning process and as a function of the concrete task. Representations involving the kinesthetic modality should also be assigned to this level. It is clear that eye-to-hand coordination has emerged during the course of evolution. Whereas, in prior stages of evolution, the extremities were controlled predominantly through kinesthetic feedback, grasping movements are now associated with kinesthetic, tactile, optical, and, in part, also auditory feedback (e.g. when cracking a nut). This involves the representation of perceptual patterns of exteroceptive and proprioceptive effects that result from the structure of the particular movement and refer back to the goal of the action. Empirical evidence for such a perspective can be found particularly in recent studies on bimanual coordination (Mechsner *et al.*, 2001) and in experimental studies on complex movements (Schack, 2002, 2003a; Schack and Mechsner, 2003).

What is interesting for the current topic of knowledge and performance in action is that routines, dynamic stereotypes, and skills emerge particularly in the interaction between the two lower levels. From a certain stage of learning onward, these levels are broadly autonomous. However, during the learning process, they are embedded within the action and thus in a functional interaction with levels III and IV (Schack, 2002). With increasing automatization on levels I and II, tacit knowledge emerges. The routines that develop here are direct components of a high-level performance. According to the model formulated here, the emergence and stabilization of such routines is supported not only by sensorimotor representations but also by mental representations. This means that tacit knowledge also builds on knowledge structures that are localized on the level of mental representations. This is what makes it possible to also assess this knowledge base of performance experimentally.

Units and structure of action knowledge

As already shown in the discussion on the evolutionary stages of human development, action knowledge refers to states in the environment (events), objects, and specific movements toward attaining a goal. To perform acts successfully and flexibly, knowledge from these different domains has to be activated and integrated in real time. This formation of units and structures of knowledge drastically reduces the effort involved in information storage and thereby the effort involved in behavioral control.

Knowledge units have to gather together temporally stable information over which objects fulfill a similar purpose. This makes objects concepts necessary. However, knowledge units also have to gather together temporally stable information about which starting conditions lead actions to which goal states. This requires movements and movement concepts. Therefore, at this point, we shall focus on object concepts and movement concepts as major units of action knowledge.

What leads these objects to be summarized into a concept is their functional equivalence within the framework of individual actions (see Ach, 1921; Hoffmann, 1990). Both a pencil and a ballpoint pen are useful for writing down an important message and are therefore summarized under the term ''writing tool''. As long as a vessel holds water and also releases this water when one puts it to one's mouth, then it will very probably be stored under the concept ''cup'' or ''glass''. Hence, object concepts are nothing other than cognitive groupings of objects according to the functions they share in the attainment of action goals (see Hoffmann, 1986, p. 11).

Accordingly, concept formation deals with the determination of a functional equivalence of objects or movements for the purpose of ensuring that behavior will be successful under changing conditions. The criterion of functional equivalence seems to be met when movements or objects fulfill the same function in attaining a certain behavior. Accordingly, they must be exchangeable without this threatening the attainment of the behavior goal (Hoffmann, 1990). Object concepts generally refer to the invariance properties of object sets. They are determined by a set of features for the objects within them and assessed through these attributes.

The task of movement concepts, in contrast, is to classify movements or action steps that lead to certain effects. Thus, it lies in the spatiotemporal control of actions. Drawing on experimental studies, these concepts have been labeled basic action concepts (BACs) (see Schack, 2002). BACs are cognitive compilations of movements based on their shared functions in the attainment of action goals. They do not refer to behavior-related invariance properties of objects like object concepts, but to perception-linked invariance properties of movements. Their characteristic set of features results from the perceptive and functional properties of movement effects. In this way, they finally serve to maximize the control of actions with the lowest possible cognitive and energetic effort.

The function of such movement concepts is highly significant for the human motor system in particular. Walking upright has led to a dramatic increase in the number of freely movable joints and, thus, degrees of freedom in the movement system. A variety of submovements have become available for attaining intended action effects, and these can also vary in, for example, joint amplitudes. When learning to write, children solve the problem of equivalent submovements in a very simple way. They ''freeze'' their distal joints and thereby reduce the amount of equivalent movements and, finally, the degrees of freedom of the entire system (see Heuer, 1994). It is only after longer practice that further degrees of freedom are gradually ''introduced'' into the movement step by step (see Bernstein, 1996; Vereijken *et al.*, 1992). One can observe similar strategies in adults when forced to write with the nondominant hand (Neweel and van Emmerik, 1989). The set of possible movements to attain the goal is initially restricted to prevent control demands from being too high. Once cognitive units have been formed to control the movement, further, more complex, but nonetheless equivalent movements are permitted – the breadth of the concept is extended step by step. Accordingly, movements are functionally equivalent when one can substitute one for the other within the context of a behavior without this threatening the behavioral goal. This is the case in, for example, volleyball when the movement concept ''extending leg'' summarizes all movements that complete a take off and prepare the hit. However, the relevant movements vary as a function of the player's position on the court, the positions of the opponents, and the current course of play. Hence, this movement concept ''extending leg'' summarizes all movements that functionally fulfill the same purpose when generating the hit.

Object concepts and BACs are generally not represented in isolation. They are part of hierarchical concept systems. It is very likely that the two types of concept may also be integrated into joint concept systems and refer to each other reciprocally as concurrent knowledge. Both are located on the level of mental representations and are structured hierarchically. The structure of a knowledge representation is understood as the internal grouping or clustering of conceptual units in individual subdomains. This approach views relations between conceptual units as being feature-based. They can be characterized according to the type (feature classes), number, and weighting (relevance) of the features of a conceptual representation system. This assignment of features is labeled dimensioning here. Dimensioning is given in object concepts through shared features of objects (e.g. color, size, purpose) or in BACs through the shared properties of movements (e.g. temporal control, amplitude, purpose). Hence, it is not just the structural design of a concept system that is of interest, but also its dimensioning (feature binding and feature weighting) as well as the relation between these two aspects of a movement representation (Lander, 1991; Schack, 2002).

In these considerations on the structure of action knowledge, it should finally be emphasized that selection pressure during the course of evolution favors the simplification of behavior and memory structures. The less effort an organism needs to expend in order to, for example, gather food, protect itself from enemies, or, on the human level of development, manufacture tools, the greater the chances of survival (see Klix, 1993). Simplification in the domain of cognitive operations and structures is accompanied by order formation. Order formation in action knowledge leads to a reduction in the necessary cognitive effort to activate relevant information (Krause, 2000). This is where individual differences in the type and efficiency of problem solving also appear. For example, it has been shown that different persons form different knowledge structures on one and the same task when engaged in real-time problem solving (Schack, 2002). In general, cognitive structures improve when more problem-solving-related classifications (concepts) are formed. Hence, one can judge the task-related order formation of action knowledge. Such structures in action knowledge can be assessed and judged with the help of specific methods.

Experimental access to action knowledge

When studying tacit knowledge, it is important to know its properties. One major property of knowledge in general and tacit knowledge in particular is that the structures of this action knowledge cannot be explicated directly. However, many methodological approaches to ascertaining such knowledge structures disregard this. For example, expert research often studies action knowledge with survey methods like interviews and questionnaires. However, this neglects the fact that a major part of tacit knowledge cannot be verbalized.

In principle, there are two methodological approaches to the experimental study of knowledge structures: to determine them either from response behavior or from reaction times (see Krause, 2000; Schack, 2002). This article focuses on the former method. The first major step is to use a specific procedure to obtain data on the proximity of representation units in long-term memory.

Various scaling procedures can be used to obtain such proximity data. These include the popular sorting method (see Champagne and Klopfer, 1981; Kluwe, 1988), the paired and triple comparison (e.g. Friendly, 1977), or the Struktur-Set-Test (Tergan, 1989). The first- and the last-mentioned procedures will not be considered further because they are not very productive psychometrically. They do not deliver the metric data necessary for a structural measurement of action knowledge. Moreover, the sorting method and the triple comparison provide only one individual incidence matrix with binary data (0, 1) that is difficult to analyze so as to obtain knowledge structures.

These and other problems with existing procedures led us to develop our own specific method. In line with the assumptions on the structure and dimensioning (feature assignment) of action knowledge formulated here, this method is conceived as a structure-dimensional analysis (SDA) of mental representations. The SDA is a procedure that tries to present the structure-dimensional relations of conceptually ordered knowledge psychometrically for both single cases and groups (Lander, 1991; Schack, 2002). The following steps are necessary to assess the structure-dimensional relations between the object concepts or BACs of a knowledge representation. The SDA method proceeds in four steps:

1. As with the methods discussed above, an SDA of a concept system initially seeks to gain information on the distance between selected representation units (concepts) that are relevant for a problem-solving domain. Because it can be assumed that the structure of movement representations can only be explicated to a limited extent, this is done with a special splitting technique. It is based on the selection and presentation of a group of concepts that are a valid component of that set of concepts that is absolutely necessary for a certain problem-solving or working domain. As in the methods mentioned above, this group of concepts is initially obtained through work analysis, survey, or experiment. This can be illustrated with an example of research (see, also, next section). For the work of an automobile mechanic, we found that the essential concepts in the action control for real-time problem solving in the repair shop included: (1) piston; (2) cylinder (3) valve; (4) cylinder head; (5) drive shaft; (6) contact breaker; (7) ignition coil; (8) spark plug; (9) distributor; (10) wheel mounting; (11) shock absorber; (12) disc brake: (13) coil spring; (14) leaf spring.

The experimental procedure took the N elements (in this case, 14) from a given set of concepts and selected one as an anchor to which the other N–1 elements had to be assigned or not assigned according to an individually given similarity criterion. This procedure (while retaining the original anchor) was repeated with each new positive or negative subset until either only indivisible sets with one object remained, or an individually selected break-off criterion was attained at which the set should not be broken down further.

As each concept took the position of anchor once, we obtained a total of N (14) decision trees whose nodes contained the subsets produced and whose edges had a negative or positive sign depending on whether the elements were assigned or not assigned to the anchor concept. A measure of the distance between the successively assigned or not assigned elements and the anchor concept (on an interval scale level) was obtained as follows: first, the algebraic sums were formed for the subsets lying on one branch of the decision tree. These sum scores (X) were then standardized with a z transformation. The Z scores for all N decision trees were then summed to form a Z matrix (z_{ik}) with the columns containing the N (14) concepts as anchors and the rows containing them once again as classified concepts.

2. The structured relations between the N concepts were obtained by compiling a distance matrix through the scaling procedure presented above and subjecting it to a hierarchic cluster analysis.

3. The dimensioning of the set of concepts was performed with factor analysis and a special cluster-oriented rotation procedure. This factor analysis delivered the features (factors) and their weights (factor loadings) according to which the cluster formation (structuring) proceeded in each single case.

4. As cluster solutions could differ interindividually (as a function of expertise) and intraindividually (as a function of learning), it was necessary to subject them to an invariance analysis. This was based on a specially defined structural invariance measure λ (Lander and Lange, 1992; Schack, 2001, 2002). When two structures possessed a higher value than the invariance measure $\lambda_0 = 0.68$, they were held to be invariant.

Special computer programs were developed to apply this method so that such experiments could be carried out within a reasonable time (10 to 15 minutes; the programs are available from the author on request). On the basis of these and other methods (Schack, 2002), it is possible to determine tacit knowledge economically and to compare persons or groups in terms of the structure of their knowledge. At the same time, such an experimental diagnosis delivers important information for deriving intervention procedures designed to improve performance (Blaser *et al.*, 2000; Schack, 2002; Schack and Heinen, 2000). The following two sections present studies illustrating relations between performance and knowledge.

Object knowledge and performance

Before one can study functional relations between knowledge and performance, it is necessary to find methods to assess the two components separately. We shall start by presenting a study comparing high-performing automobile mechanics with laypersons. Using the SDA method presented above, we compared the action knowledge of five mechanics working in renowned workshops (Daimler-Benz, BMW) with that of four sports students with driving licenses and automobiles but no relevant experience in repairing them.

When repairing automobiles, mechanics continuously have to solve problems that require a sound knowledge of the single subsystems of the vehicle (electrical system, chassis, engine) and the function of their corresponding parts. When repairing an engine, a mechanic has to discriminate very clearly, even when just looking, between spare parts that are relevant to the current job and any other parts that may also lie in reach. The problem solving involved in diagnosing the damage to the vehicle and how to overcome it also requires a functionally applicable knowledge of the systems and parts of the vehicle as well as the appropriate tools to repair them. A closer inspection of the participants revealed that the experts in this domain seemed to achieve this effortlessly. However, when asked, they could not report which sort of knowledge had enabled them to perform this real-time problem solving or how it was structured. Hence, we used a survey of another group of experts ($n = 3$) and a functional analysis of automobile construction to develop the list of concepts reported above: (1) piston, (2) cylinder; (3) valve; (4) cylinder head; (5) drive shaft; (6) contact breaker; (7) ignition coil; (8) spark plug; (9) distributor; (10) wheel mounting; (11) shock absorber; (12) disc brake: (13) coil spring; (14) leaf spring.

Concepts 1 to 5 refer to parts of the engine (drive), concepts 6 to 9 refer to the electrical system, and concepts 10 to 14 to the chassis. These concepts were read into a computer program, and participants performed the split procedure described above on a screen. For all concepts, they had to decide whether or not they were linked together functionally for carrying out the action during their work. Concepts were presented in random order.

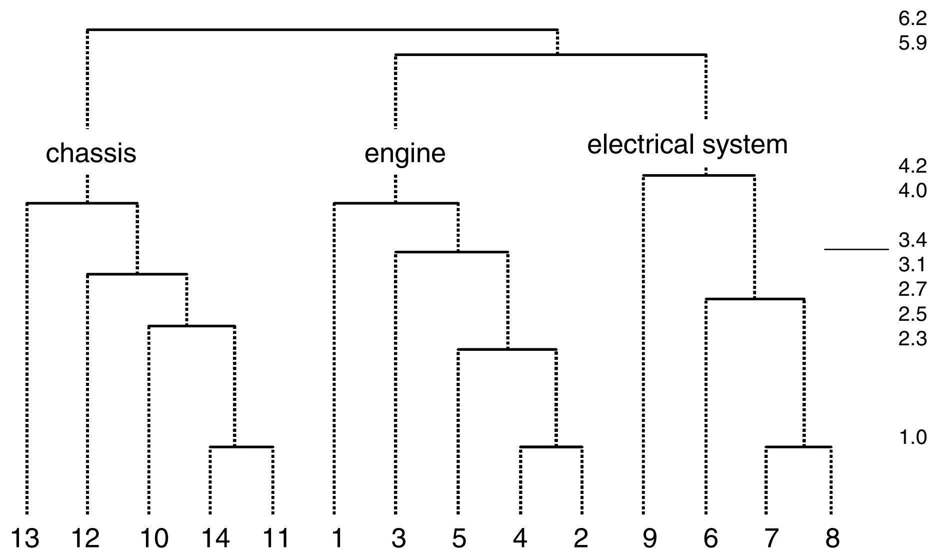
One major issue in the analysis was whether the degree of structuring would be larger in the experts' than in the laypersons' action knowledge, and which features were used to structure the concepts in memory. Findings on one expert in Figure 1 are used to present the results of the hierarchic cluster analysis. We shall compare individuals from the two groups in order to demonstrate the value of the method for analyzing individual knowledge structures.

As Figure 1 shows, the expert has a strong hierarchical knowledge structure with three concept clusters. This structuring points initially to a high degree of order formation in the expert's action knowledge. The content of this knowledge structure is highly interpretable: each cluster refers to a specific subsystem of the vehicle. These cognitive substructures, which refer to the representation units (concepts) of the engine, electrical system, and chassis systems, are highly distinct. As the results of factor analysis show, the features of these concepts are linked to problem-solving processes within these action systems (engine, electrical system, chassis). Hence, functional features of the concepts predominantly determine the structure. The expert predominantly knows for what (for what purpose) the single parts can be used. The results of this analysis will now be compared with findings on a low performer (Figure 2).

The knowledge structure of the person depicted in Figure 2 reveals a poor performance in the automobile repair domain. According to self-reports and a test of automobile repairing skills, this person is only able to change a wheel. Compared with the expert in Figure 1, the knowledge system determined for the 14 concepts is broadly unstructured. One cluster can be determined referring to the chassis. This knowledge substructure seems to be due to frequent wheel changes. Further substructures cannot be recognized. This also means that no structured knowledge is available for other performance domains of automobile repair (engine, electrical system).

Hence, this study shows clearly that performance has a conceivable relation to the structuring of action knowledge. A comparable systematic structuring of knowledge was found in all five experts. It is clear that the structure is also functionally relevant, and the performance

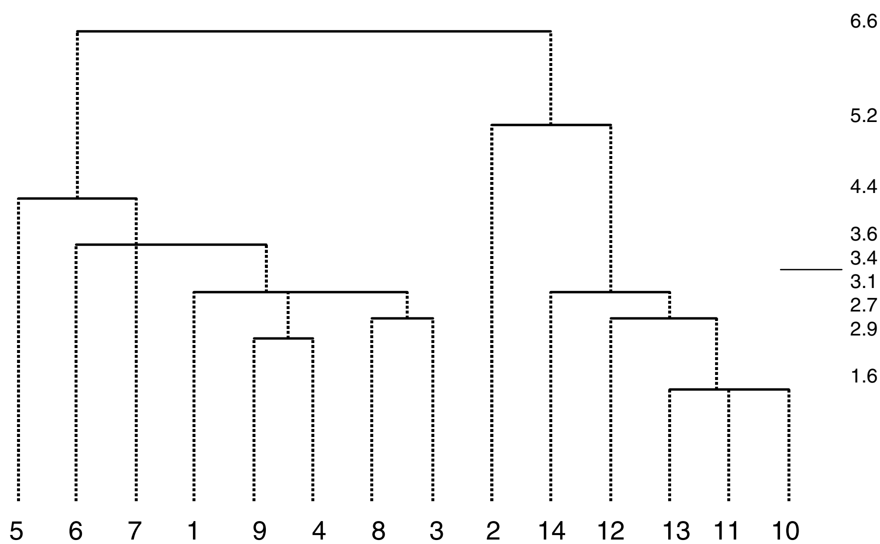
Figure 1 Results of hierarchic cluster analysis of object concepts in a high-performance (expert) mechanic.



Note: (1) piston; (2) cylinder; (3) valve; (4) cylinder head; (5) drive shaft; (6) contact breaker; (7) ignition coil; (8) spark plug; (9) distributor; (10) wheel mounting; (11) shock absorber; (12) disc brake; (13) coil spring; (14) leaf spring

The lower the value of a cross-connection between the study units (see the Euclidean distance scale on the right), the shorter the distance between the concepts in long-term memory ($\alpha = 5\%$, $d_{crit} = 3.42$). d_{crit} is the random critical distance between the concepts for a given a probability

Figure 2 Results of hierarchic cluster analysis for a low performer (layperson) in mechanics



Note: (1) piston; (2) cylinder; (3) valve; (4) cylinder head; (5) drive shaft; (6) contact breaker; (7) ignition coil; (8) spark plug; (9) distributor; (10) wheel mounting; (11) shock absorber; (12) disc brake; (13) coil spring; (14) leaf spring ascertained is functionally efficient for real-time problem solving in the field of automobile repair. Such problem-solving processes are linked continuously to specific movements, routines, and automatisms. Therefore, it can be assumed that specific movement knowledge is also assigned to this object knowledge. The relation between movement knowledge and performance will now be studied and discussed with an example from high-performance sports.

Movement knowledge and performance

This study refers to the attack hit in volleyball. Performing a attack hit in volleyball requires conceptual representations of not only certain environmental states (e.g. block positions of the opponents) but also the movement sequences to be performed. The following movement concepts were determined (Schack, 2002): (1) taking arms back; (2) stamp step; (3) bending knees and trunk; (4) swinging both arms forward; (5) extending legs; (6) body arching; (7) spiking arm back; (8) high elbow; (9) glance toward opponent's block; (10) spike emphasizing the wrist; (11) whipping extension of arm; (12) draw-through of hitting arm.

Concepts 1 to 3 are relevant for the run-up movement phase; concepts 4 and 5, for the take off; concepts 6 to 8, for the hit preparation; and concepts 10 to 12, for the attack hit itself. Concept 9, glance toward opponent's block, refers to an environmental constellation that is of central importance for the success of the hit. One can assume that specific problems have to be solved in each movement phase. For example, the attack hit phase involves the goal-directed application of the energy generated in the previous movement phases.

We studied female players from the German women and juniors' national volleyball team ($n = 15$) who were high performers in carrying out hits (mean age: 18.3 years). We also studied regional-division players with a much lower performance ($n = 14$; mean age: 21.5 years) and persons with no volleyball experience ($n = 6$; mean age: 25.5 years). The results of the experimental studies showed clear and significant between-group differences in knowledge structures. Among the experts, several functionally plausible and highly interpretable clusters could be confirmed. The four phases run-up, take off, hit preparation, and attack hit were clearly separated. Furthermore, this functional separation revealed a temporal-sequential order. In the lower-performance groups, in contrast, no functionally plausible structuring of action knowledge could be found (detailed results are reported in Schack, 2002; Schack and Engel, 2003).

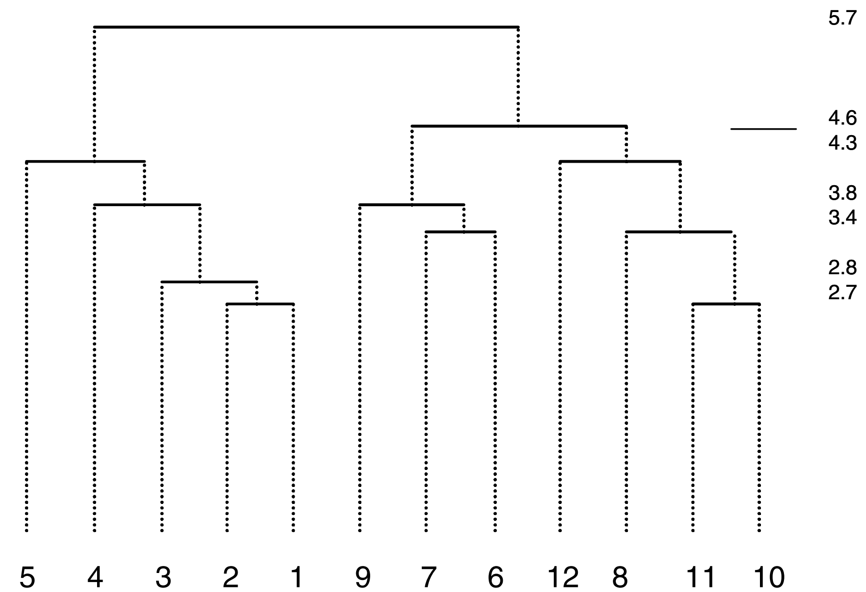
A closer look at potential mechanisms of concurrent knowledge is revealed by inspecting the dependence of the mental representation of the hit itself on the player's position. First of all, some of the particular features of each position have to be considered: hits in volleyball are made from the quick-spiker and ace-spiker positions. The setters prepare these hit actions, or provide the basis for the hit itself within the framework of an attack hit action. On the national women's level (according to Papageorgiou and Spitzley, 2000, p. 117), specific differences can be found in the demands concerning the attack hit performance at single player positions. For example, the time from one attack hit movement to the next is 36.8 s for ace spikers, and 24.6 s for quick spikers. The number of take offs in competitions is 49.4 for ace spikers and 76.7 for quick spikers.

It becomes clear that performing a hit places other demands on quick spikers than on ace spikers and passers. However, these more complex demands can be explained through the strategic situation of the player's position. Quick spikers have far less time to perform a hit than ace spikers. This places greater demands to make their technique rapidly available.

According to our model assumptions, this increased demand should also be reflected in the structure of mental representations. We tested this by assessing the mental structures of the players in relation to their positions. The results of the SDA for the player positions ace spiker and quick spiker are reported in Figures 3 and 4.

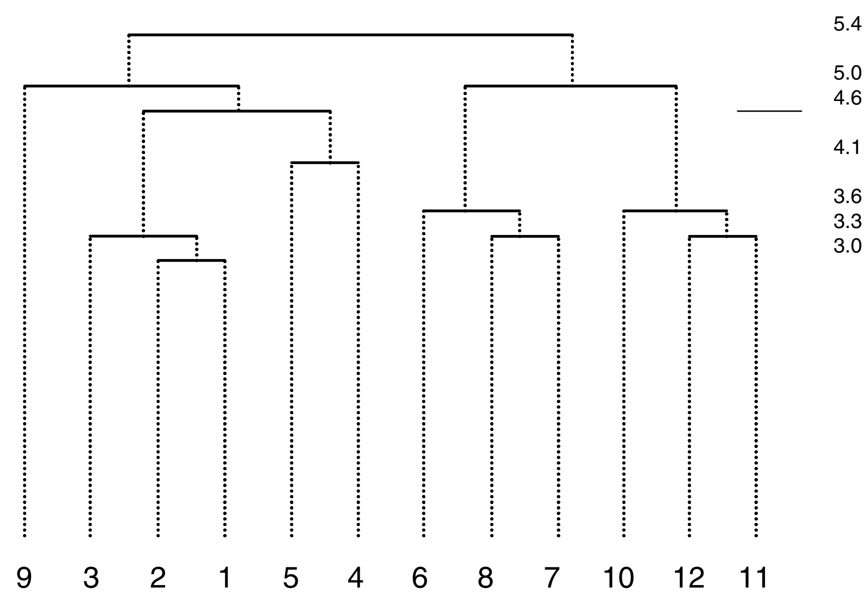
This player-position-related analysis first shows that the structures determined for these player positions (ace spiker, quick spiker) differed significantly (tested with the invariance measure $\lambda = 0.46$). It is worth analyzing these structures in more detail and comparing them. We shall start with the mental structure of the ace spikers. The cluster analysis produced three clusters. These could be labeled run up and take off, hit preparation, and hit (see Figure 3). What is

Figure 3 Results of hierarchic cluster analysis of experts in the player position ace spiker ($n = 4$, $\alpha = 1\%$, $d_{crit} = 4.55$)



Note: (1) taking arms back; (2) stamp step; (3) bending knees and trunk; (4) swinging both arms forward; (5) extending legs; (6) body arching; (7) spiking arm back; (8) high elbow; (9) glance toward opponent's block; (10) spike emphasizing the wrist; (11) whipping extension of arm; (12) drawthrough of hitting arm

Figure 4 Results of hierarchic cluster analysis of experts in the player position quick spiker ($n = 6$, $\alpha = 1\%$, $d_{crit} = 4.55$)



Note: (1) taking arms back; (2) stamp step; (3) bending knees and trunk; (4) swinging both arms forward; (5) extending legs; (6) body arching; (7) spiking arm back; (8) high elbow; (9) glance toward opponent's block; (10) spike emphasizing the wrist; (11) whipping extension of arm; (12) drawthrough of hitting arm interesting is that the play-related node glance toward opponent's block is assigned to the hit preparation, and that this cluster is composed of two further movement-related nodes (body arching, spiking arm back).

In comparison, the analysis of quick spikers produced four clusters following exactly the same pattern as the movement phases. The main difference to the cluster structure of the ace spikers was that the relevant BAC for run up and take off were in two separate clusters. Hence, the first two movement phases had a differentiated representation. A further characteristic for the structure of quick spikers was that the play-related node glance toward opponent's block was linked to the total cluster of run up and takeoff and not the total cluster hit preparation and hit as in the ace spikers. This idiosyncrasy of representation structure was also linked to player-position-related movement tasks. In a quick spiker hit, the opposing block has to be tackled at an early stage if the hit is to be implemented explosively and successfully without major preparation times and spaces. In contrast, ace spikers can take long and diagonal paths, enabling them to search for gaps in the opposing block in a long-drawn hit preparation phase. Another interesting finding worthy of discussion is that the cluster-hit preparation is composed of three movement-related nodes (6, 7, 8). In contrast to ace spikers, the node high elbow cannot be found in the hit cluster of quick spikers. This seems to be related to the demands imposed by this player position. As discussed above, quick spikers have less time to hit than ace spikers. Hence, the hit has to be faster and have a more effectively organized movement structure. This seems to be made possible through the more comprehensive hit preparation (compared with ace spikers) and a structurally reduced hit itself. All three aspects mentioned here: (a) a differentiated representation structure in quick spikers (four movement clusters); (b) demand-appropriate anticipation structure (structurally and sequentially adequate placement of the node glance toward opponent's block); and (c) demand-related representation structures for the phases, run up, take off, hit preparation, and hit indicate a functional and differentially confirmable relation between performance and representation structure. We were able to derive a specific mental training program from such analyses designed to improve specific aspects of performance. This mental training based on mental representations (MTMR) (Schack and Heinen, 2000) is now being applied in various fields of high-performance sport (e.g. free climbing, wind surfing, artistic gymnastics, volleyball).

Outlook

The model assumptions and experimental studies presented here show various ways in which the relations between knowledge and performance in action can be determined more precisely. This not only reveals the evolutionary link between knowledge and performance, but also shows steps that could make a substantial contribution to the study of various knowledge systems and modern knowledge management (see Wiig, 2000). Although this article has not dealt with several questions on knowledge and performance in action addressing, for example, the processing and storage of images and other symbols or chunking processes in working memory, preliminary studies and specific methods are available for these issues (Schack, 2000, 2003a; Schack and Guthke, 2003). Up to now, these methods have been applied predominantly in high-performance sports for diagnosing knowledge structures and deriving mental training procedures. As a result, we now have sufficient experience of highly observable actions and clearly measurable performance in this field. What is interesting and seems promising is to generalize the application of these methods to other research domains or various business fields. Exchanging information over experimentally derived knowledge systems of experts in various workfields could provide revealing insights into the functioning of tacit knowledge. Furthermore, the assessment, documentation, and integration of such expert knowledge systems in a comprehensive exchange of information could make a major contribution to future knowledge management. These new ways of determining and evaluating the knowledge of experts also open up new potentials for intervening actively in the evolution of human performance.

References

Ach, N. (Ed.) (1921), *Untersuchungen zur Psychologie und Philosophie, Bd.3. Über die Begriffsbildung. Eine experimentelle Untersuchung*, C.C. Buchners Verlag, Bamberg, Anderson, J.R. (1983), *Rules of the Mind*, Erlbaum, Hillsdale, NJ.

Anderson, J.R. and Lebiere, C. (1998), *The Atomic Components of Thought*, Erlbaum, Hillsdale, NJ.

Anochin, P.K. (1978), *Beiträge zur Allgemeinen Theorie des funktionellen Systems*, Fischer, Jena.

Bernstein, N.A. (1988), *Bewegungsphysiologie*, Barth, Leipzig.

Bernstein, N.A. (1996), *Die Entwicklung der Bewegungsfertigkeiten*, IAT, Leipzig.

Blaser, P., Stucke, C., Körndle, H. and Narciss, S. (2000), *Auswirkungen eines Leistungstrainings im Brustschwimmen auf den Zusammenhang von Bewegungs-repräsentation und Bewegungsausführung*, Sport und Buch Strauß, Köln.

Champagne, A. and Klopfer, L. (1981), ''Structuring process skills and the solution of verbal problems involving science concepts'', *Science Education*, Vol. 65, pp. 493-511.

Donald, M. (1991), *Origins of Modern Mind*, Harvard University Press, Cambridge, MA.

Ericsson, K.A. and Smith, J. (Eds) (1991), *Toward a General Theory of Expertise. Prospects and Limits*, Cambridge University Press, Cambridge.

Friendly, M.L. (1977), ''In search of the m-gram: the structure of organization in free recall'', *Cognitive Psychology*, Vol. 9, pp. 188-249.

Hacker, W. (1998), *Allgemeine Arbeitspsychologie*, Huber, Bern.

Heuer, H. (1994), ''Koordination'', in Heuer, H. and Keele, S.W. (Eds), *Psychomotorik (Enzyklopädie der Psychologie: Themenbereich C. Theorie und Forschung: Serie 2. Kognition)*, Vol. 3, Hogrefe, Göttingen, pp. 147-222.

Hoffmann, J. (1986), *Die Welt der Begriffe*, Verlag der Wissenschaften, Berlin.

Hoffmann, J. (1990), ''Über die integration von wissen in die verhaltenssteuerung'', *Schweizerische Zeitschrift für Psychologie*, Vol. 49, pp. 250-65.

Klix, F. and Lanius, K. (1999), *Wege und Irrwege der Menschenartigen. Wie wir wurden wer wir sind*, Kohlhammer, Stuttgart.

Klix, F. (1993), *Erwachendes Denken*, Spektrum, Heidelberg.

Kluwe, R.H. (1988), ''Methoden der psychologie zur gewinnung von daten über menschliches wissen'', in Mandl, H. and Spada, H. (Eds), *Wissenspsychologie*, Psychologie Verlags Union, München, pp. 359-85.

Krause, W. (2000), *Denken und Gedächtnis aus Naturwissenschaftlicher Sicht*, Hogrefe, Göttingen.

Lander, H.-J. and Lange, K. (1992), ''Eine differentialpsychologische analyse begrifflich-strukturierten wissens'', *Zeitschrift für Psychologie*, Vol. 200, pp. 181-97.

Lander, H.-J. (1991), ''Ein methodischer ansatz zur ermittlung der struktur und der dimensionierung einer intern-repräsentierten begriffsmenge'', *Zeitschrift für Psychologie*, Vol. 199, pp. 167-76.

Leontjew, A.N. and Zaporoshets, A.V. (1960), *Rehabilitation and Hand Function*, Pergamon, London.

Luria, A.R. (1992), *Das Gehirn in Aktion*, Rowohlt, Reinbek.

Luria, A.R., Pribram, K.H. and Chomskaja, E.D. (1964), ''An experimental analysis of the behavior disturbances produced by a left frontal arachnoidal endothelioma (meningioma)'', *Neuropsychologia*, Vol. 2, pp. 257-80.

Mechsner, F., Kerzel, D., Knoblich, G. and Prinz, W. (2001), ''Perceptual basis of bimanual coordination'', *Nature*, Vol. 414, pp. 69-72.

Newell, K.M. and van Emmerik, R.E.A. (1989), ''The acquisition of coordination: preliminary analysis of learning to write'', *Human Movement Science*, Vol. 8, pp. 17-32.

Papageorgiou, A. and Spitzley, W. (2000), *Leistungsvolleyball*, Aachen, Meyer.

Premack, D. (1977), *Intelligence in Ape and Man*, Erlbaum, New York, NY.

Prümper, J., Zapf, D., Brodbeck, F. and Frese, M. (1992), ''Some surprising differences between novice and expert errors in computerized office work'', *Behavior and Information Technology*, Vol. 11, pp. 319-28.

Rensch, B. (1973), *Handgebrauch und Verständigung bei Affen und Frühmenschen*, Bern.

Schack, T. (2000), ''Experimental studies on the speed of information processing in sports related memory'', *Journal of Sport & Exercise Psychology*, Vol. 22, p. 94.

Schack, T. (2002), ‘‘Zur kognitiven architektur von bewegungshandlungen – modelltheoretischer zugang und experimentelle untersuchungen’’, Unveröff. Habil., Psychologisches Institut, Deutsche Sporthochschule Köln.

Schack, T. (2003a), ‘‘The relationship between motor representation and biomechanical parameters in complex movements – towards an integrative perspective of movement science’’, *European Journal of Sportscience*, Vol. 2, pp. 1-13.

Schack, T. (2003b), ‘‘Von der ursuppe zum skysurfen-evolutionäre wurzeln von gedächtnis und bewegung’’, in Schack, T., Engel, F. and Heinen, T. (Eds), *Kognition und Bewegungssteuerung. Proceedings zum Symposium ‘‘Kognition und Bewegungssteuerung’’ vom 12.-13.12. 2002 an der Deutschen Sporthochschule Köln*, medial unterstützte CD-ROM, MRI, Köln.

Schack, T. and Guthke, J. (2003), ‘‘Dynamic testing’’, *International Journal of Sport and Exercise Psychology*, Vol 1 No. 1, pp. 40-60.

Schack, T. and Heinen, T. (2000), ‘‘Mental training based on mental representation’’, in Carlsson, B.A., Johnson, U. and Wetterstrand, F. (Eds), *Sport Psychology Conference in the New Millennium – A Dynamic Research-Practise Perspective*, Halmstadt University, Sweden, pp. 333-37.

Schack, T. and Mechsner, F. (in press), ‘‘Mental representation of highly skilled voluntary movements’’.

Schack, T. and Whitmarsh, B. (in press), ‘‘Movement-routines’’, in Taylor, J. (Ed.), *Comprehensive Perspectives on Applied Sport Psychology: From Researcher and Consultant to Coach and Athlete*, Human Kinetics, Champaign, IL.

Sternberg, R.J. (1995), ‘‘Theory and measurement of tacit knowledge as a part of practical intelligence’’, *Zeitschrift für Psychologie*, Vol. 203, pp. 319-34.

Tergan, S.-O. (1989), ‘‘Psychologische grundlagen der erfassung individueller wissensrepräsentation. Teil 1: Grundlagen der wissensmodulierung’’, *Sprache und Kognition*, Vol. 8, pp. 152-65.

Van der Weel, F.R., Van der Meer, A.L.H. and Lee, D.N. (1991), ‘‘Effect of a task on movement control in cerebral palsy: implications for assessment and therapy’’, *Developmental Medicine and Child Neurology*, 33,pp. 419-426.

Vereijken, B., Van Emmerik, R.E.A., Whiting, H.T.A. and Newell, K.M. (1992), ‘‘Free(z)ing degrees of freedom in skill acquisition’’, *Journal of Motor Behaviour*, Vol. 24, pp. 133-42.

Vygotsky, L.S. (1992; orig. 1929), *Geschichte der Höheren Psychischen Funktionen*, Lit, Münster.

Vygotsky, L.S. (1962), *Language and Thought*, MIT Press, Cambridge, MA.

Wiig, K.M. (2000), ‘‘What future knowledge management users may expect’’, *Journal of Knowledge Management*, Vol. 3 No. 2, pp. 155-66.