Representation of motor skills in human long-term memory

Thomas Schack a,b, Franz Mechsner c,d,∗

a Department of Psychology, German Sports University, Carl-Diem-Weg 6, D-50933 Cologne, Germany
b Department of Psychology and Sportscience, University Bielefeld, P.O. Box 100131, D-33501 Bielefeld, Germany
c Max Planck Institute for Human Cognitive and Brain Sciences, Department of Psychology: Cognition and Action, Amalienstrasse 33, D-80799 Munich, Germany
d Hanse Institute for Advanced Study, Lehmkuhlenbusch 4, D-27754 Delmenhorst, Germany

Abstract
This study uses the example of the tennis serve to investigate the nature and role of long-term memory in skilled athletic performance. Information processing linked with complex movements has always been notoriously difficult to investigate. However, a new experimental method revealed that athletic expertise was characterized by well-integrated networks of so-called basic action concepts (BACs) that each corresponded to functionally meaningful submovements. In high-level experts, these representational frameworks were organized in a distinctive hierarchical tree-like structure, were remarkably similar between individuals and were well matched with the functional and biomechanical demands of the task. In comparison, action representations in low-level players and nonplayers were organized less hierarchically, were more variable between persons and were less well matched with functional and biomechanical demands. It is concluded that, in concert with situational goals and constraints, movement representations of this kind in long-term memory might provide the basis for action control in skilled voluntary movements in the form of suitably organized perceptual-cognitive reference structures.

© 2005 Elsevier Ireland Ltd. All rights reserved.

Keywords: Action control; Action grammar; Cognitive representations; Long-term memory; Motor behavior; Motor learning; Motor programs

There is much debate concerning the representational nature and functional role of the long-term memory structures involved in human movement control. One fundamental issue is the representational medium: is there a special motor memory completely distinct from perceptual-cognitive structures and processes? Or do movements, objects and external events have a common representational medium?[8]? One prominent theoretical position favors the first alternative, while assuming that motor performance basically means to create and use muscle-related motor programs. Characteristic invariants of such motor programs may be stored in long-term memory. To give an example, Schmidt and Lee’s [20] theory of generalized motor programs suggests that relative durations as well as relative forces in patterns of muscular activation define invariants of motor programs that are stored in long-term memory. Absolute duration and absolute force also need to be planned for motor performance but this is done in a situation-specific way.

An alternative view suggests that movements are organized and stored in memory as perceptible events through a representation of anticipated characteristic (e.g., sensory) effects, with the corresponding motor activity automatically and flexibly tuned to serve these effects. Mechsner et al. [15,16] hypothesize that voluntary movements follow perceptual-cognitive representations. In a similar way, Ivry et al. [9] hypothesize that central costs and interference in bimanual movements depend solely on how these movements are represented on a cognitive level. Assuming that the hypothesis of a perceptual-cognitive control is correct, it seems plausible to generalize it to much more complex tasks, such as those in skilled sports. Should this be true, one could expect to find the means for addressing the functional and biomechanical performance in athletes’ perceptual-cognitive movement representations. The present paper investigates whether representations of this kind might be found in the long-term memory of skilled athletes in the form of perceptual-cognitive reference structures for movement control.

A common way of exploring the particular characteristics of expertise is provided by the expert-novice paradigm. Questionnaires, interviews, and specific picture-sorting techniques have already revealed expertise-dependent differences in cognitive
representational structures in sports, such as springboard diving [7], tennis [11–14], and basketball [4]. These studies found that cognitive movement representations in experts are composed of more features than those in novices and also have more numerous connections between their parts. Experts tend to classify the movement characteristics according to functional principles, whereas novices often rely on mere surface perceptual features [1]. However, although these methods have delivered such general results, they do not provide insights into the detailed structure of representations for the whole movement.

Cognitive movement representations might involve different formats, such as propositions, relational structures of many kinds, and concepts. Bernstein [2] and, more recently, Hoffmann et al. [5,6] have hypothesized that concepts are particularly important here. Referring to this research, Schack [19] provided evidence for so-called basic action concepts (BACs) in some analogy to the well-established notion of basic concepts in the world of objects [17]. BACs can be viewed as the mental counterparts of functionally relevant elementary components or transitional states of complex movements. They are characterized by recognizable perceptual features. They can be described verbally as well as pictorially, and can often be labeled with a linguistic marker. “Turning the head” or “bending the knees” might be examples of such BAC in the case of, say, a complex floor exercise.

In cognitive areas, expertise is characterized by hierarchical networks of concepts [3]. We hypothesize that the same holds for athletic expertise. In particular, we propose that the relevant reference structures for movement control are conceptual representational frameworks in long-term memory with BACs as units or nodes. In experts, these frameworks are prototypical cognitive structures that are well adapted to the functional and biomechanical demands of the task. The present study investigates whether cognitive structures of this kind actually can be found in experts, thus fulfilling a minimum prerequisite for the above hypothesized perceptual-cognitive control scheme.

We chose the tennis serve as a complex movement because it seems highly appropriate for investigating such potential conceptual representational structures on different levels of expertise. Obviously, many degrees of freedom in the musculo-skeletal system have to be controlled, and performance quality is influenced considerably by training and expertise. Nonetheless, the tennis serve is a finite, recognizable, and thereby flexible action pattern whose overall structure is well defined by biomechanical demands.

Several studies have used interviews and/or nonstandardized questionnaires to explore the relationship between knowledge and performance in tennis [11–14]. McPherson and Thomas [14] found that 10- to 13-year-old expert tennis players revealed a stronger interconnection between tennis-related elemental concepts compared with novices and also focused on higher level concepts. McPherson [11–13] showed, in addition, that experts possess a more advanced problem representation for their response selection than novices. Though permitting such insights, such methods do not allow a psychometric analysis of the hypothesized perceptual-cognitive control scheme. This becomes possible with our method presented below.

Our expert group contained 11 male tennis players (mean age, 24 ± 3.7 years) in upper German leagues who were ranked between places 15 and 500 in the German men’s rankings. The low-level group consisted of 11 male tennis players (mean age, 26 ± 4.8 years) in lower German leagues (district leagues) who were not listed in the German men’s rankings. The nonplayer group consisted of 11 males (mean age, 24 ± 6.7 years) with virtually no experience of the game (maximum, 5h) and who had never had any tennis lessons.

Because the rating and sorting methods described above do not allow a psychometric analysis of the representational structures, we applied a procedure called structural dimensional analysis (SDA). This is a well-established procedure in the field of cognitive psychology for ascertaining relational structures in a given set of concepts [10]. Schack [18,19] recently modified this method for the analysis of movements, calling this the Structural Dimensional Analysis-Motoric (SDA-M). The SDA-M contains four steps: first, a special split procedure involving a multiple sorting task delivers a distance scaling between the BACs of a suitably predetermined set; second, a hierarchical cluster analysis is used to transform the set of BACs into a hierarchical structure; third, a factor analysis reveals the dimensions in this structured set of BACs; fourth, the cluster solutions are tested for invariance within and between the groups.

In a preparatory step, we characterized the task-adequate functional organization of the tennis serve and compiled a plausible and workable set of BAC in collaboration with nonplayers, athletes with different levels of expertise, and coaches. Reaction-time experiments were used to test whether the concepts were really basic in character. Photographs of the tennis submovements were presented to experts together with linguistic markers of varying generality. The BAC level was then defined, in analogy to classical methods [17], as the shortest time taken to decide whether the photo-word combination was adequate.

A tennis serve consists of three distinct phases, each of which fulfills distinct functional and biomechanical demands. First, in the pre-activation phase, body and ball are brought into position, and tension energy is provided to prepare the strike. The following BACs were identified: (1) ball throw, (2) forward movement of the pelvis, (3) bending the knees, and (4) bending the elbow. Second, in the strike phase, energy is conveyed to the ball. The following BACs were identified: (5) frontal upper body rotation, (6) racket acceleration, (7) whole body stretch motion, and (8) hitting point. Third, in the final swing phase, the body is prevented from falling, and the racket movement is decelerated after the strike. The following BACs were identified: (9) wrist flag, (10) forward bending of the body, and (11) racket follow-through.

As mentioned above, each individual BAC is characterized by a set of closely interconnected sensory and functional features. For example, BAC 7 (whole body stretch motion) is functionally related to providing energy to the ball, transforming tension into swing, stretching but remaining stable, and the like. Afferent sensory features of the corresponding submovement that allow monitoring of the initial conditions are bent knees, tilted shoulder axis, and body weight on the left foot. Re-afferent sensory features that allow monitoring of whether the functional demands of the submovements have been addressed successfully are muscles stretched and under tension, proprioceptive...
and, finally, perhaps visual perception of the swinging arm and ball in view.

We submitted the BACs of the tennis serve to a hierarchical cluster analysis with the distances based on subjective distance judgments over all pair combinations of BACs. To prepare the participants, they were familiarized with the above BACs through pictures of the movement with a verbal BAC name as a printed heading. During the entire experiment, these pictures were positioned in front of each individual participant. To determine subjective distances between BACs, participants performed the following split procedure as the first step in the SDA-M: on a computer screen, one selected BAC was constantly on display as a standard unit in red-colored writing. In addition, the rest of the BACs were presented in yellow-colored writing as a randomly ordered list. For each of these yellow-colored additional BACs, the participant had to judge whether or not they were "functionally close" to the standard red-colored BAC. This produced two subsets that were then submitted repeatedly to the same procedure until the referee decided to perform no further splits. Because this anchor role of standard was assigned to each BAC in succession, we ended up with a total of 11 decision trees whose nodes contained the resulting subsets and whose borders took either a negative or positive sign depending on whether the element was judged as belonging to or not belonging to the standard. To obtain a measure of the distance between the successively judged elements and the standard (with interval scaling), algebraic sums were computed over the subsets located on one branch of the decision tree. These sum scores were then $\lambda$-transformed. In the second step of the SDA-M, the individual partitioning was determined by means of a hierarchical cluster analysis. The third step of the SDA-M was a dimensioning of the cluster solutions through a factor analysis linked to a specific cluster-oriented rotation process resulting in a factor matrix classified by clusters. Finally, the fourth step of SDA-M was to perform a within- and between-group comparison of the cluster solutions using an invariance measure $\lambda$ to indicate whether differences were significant [10,18,19]. An alpha level of $\rho=0.05$ was used in all the analyses. This means that there was a significant difference between the clusters when $\lambda < \lambda_{crit} = 0.68$.

Fig. 1 presents dendrograms for the subjective distances of BACs based on the hierarchical cluster analysis of the means of the three groups (i.e., experts, low-level players, and nonplayers). In experts (Fig. 1a), the cognitive structure came close to the functionally demanded structure of the tennis serve. The three functional phases (i.e., pre-activation, strike, and final swing) were mirrored in clearly separated tree-like structured clusters in the dendrograms. In experts, the BACs seemed to be grouped in memory according to generic terms that conform to the solution of special movement problems. An invariance analysis (step four of SDA-M) confirmed this interpretation. There was no significant difference between the cognitive BAC framework in experts and the biomechanical demand structure of the movement ($\lambda = 70; \lambda_{crit} = 68$). Results looked rather different for the low-level and nonplayer groups (Fig. 1b and c). The clustering of the BACs did not mirror the functionally and biomechanically demanded phases so well. The BACs were less clearly grouped, with no close neighborhoods, and the partial clusters usually failed to attain significance. The difference between the cognitive BAC framework and the functionally demanded structure of the movement was even significant in low-level players ($\lambda = 53; \lambda_{crit} = 0.68$) and nonplayers ($\lambda = 31; \lambda_{crit} = 68$).

The individual clustering of BACs (data not shown here) revealed that, in experts, the three functionally and biomechanically demanded movement phases of the tennis serve were virtually always represented distinctly in the form of significantly separated partial trees. The individual clusterings were rather similar between the individuals, with an invariance analysis revealing no significant differences. Significantly distinct subclusters could also be seen in individual low-level players, though not as functionally well structured as in experts. Although the functionally and biomechanically required phases could be discerned regularly, they were not matched so well and consistently. There were rather arbitrary associations based on surface or unfathomable criteria that often varied from person to person. Interindividual differences were significant. In nonplayers, significantly distinct subclusters were generally rare and arbitrary. The structure of the clustering trees, which varied greatly between persons, revealed no clear grouping principles.

The determinants of the revealed memory structure were evaluated with a factor analysis (third step of SDA-M). Table 1 reports the results for the expert group. Two factors, both with bipolar loadings, explained 74.3% of the variance. One factor had a bipolar loading on the pre-activation cluster (corresponding to phase 1) and the strike cluster (corresponding to phase 2). Its dimension was movement direction, that is, vertical versus frontal. The other factor had a bipolar loading on the strike cluster (phase 2) and the final swing cluster (phase 3). Its dimension was ball-oriented versus follow-through swing movement. Within the context of a skilled tennis serve these factors seem highly plausible.

In sum, our investigation of cognitive representations in the tennis serve reveals that the application of a SDA-M to appropriately determined BACs produces hierarchical clustering structures whose characteristics can be related systematically to the different quality of performance on different levels of expertise.
These results reflect differences in the grouping of BACs in long-term memory and its determinants. Movement-related long-term memory seems to be much better structured and adapted to functional and biomechanical demands in experts compared with novices.

However, are these long-term memory structures functional for movement performance? We consider this to be the case, because they are very plausible within the context of a perceptual-cognitive, or anticipatory, control scheme as hypothesized above. Indeed, we can see no other way of addressing the functional demands related to BACs than by controlling the corresponding submovements directly through their anticipated perceptual effects. As we have emphasized above, characteristic perceptual features of BACs relate meaningfully to corresponding functional features. Sensory feedback tells the athlete whether or not he or she has performed the movement properly and effectively. Taken together, it is plausible that functionally successful movements require the use of an anticipatory control that draws on BAC networks. We conclude that the controlling system may well use the revealed cognitive BAC networks in long-term memory to construct situation-specific reference structures for anticipatory control.

Acknowledgements

We wish to thank Hans-Jurgen Lander and Jurgen Nitsch for assistance with the data collection, as well as Frank Engel, Thomas Hennen, and Carsten Zander for programming work and help with the preparation of the manuscript.

References


