INTERNATIONAL JOURNAL OF SPORT AND EXERCISE PSYCHOLOGY

VOLUME 2 – NUMBER 4 – DECEMBER 2004

SPECIAL ISSUE

**THE CONSTRUCTION OF ACTION:
NEW PERSPECTIVES IN MOVEMENT SCIENCES**

PART 2: REPRESENTATION AND PLANNING

EDITORS: THOMAS SCHACK & GERSHON TENENBAUM

Meyer & Meyer Sport

INTERNATIONAL SOCIETY OF SPORT PSYCHOLOGY MANAGING COUNCIL

President

Keith Henschen, U.S.A.

Past President

Gershon Tenenbaum, U.S.A.

Vice Presidents

Dorothee Alferman, Germany; Howard K. Hall, England;
Bola Ikulayo, Nigeria

Secretary General

Ronnie Lidor, Israel

Members

Duarte Araujo, Portugal; Likang Chi, Taiwan;
Natalie Durand-Bush, Canada; Dieter Hackfort, Germany;
Akihiko Kondo, Japan; Athanasios Papaioannou, Greece;
Dietmar Samulski, Brazil; Natalie Stambulova, Russia;
Judy van Raalte, U.S.A.

INTERNATIONAL JOURNAL OF SPORT AND EXERCISE PSYCHOLOGY

VOLUME 2 – NUMBER 4 – DECEMBER 2004

CONTENTS

PREFACE

- Effect Representation and Action Planning: A Preface343
Thomas Schack and Gershon Tenenbaum

ORIGINAL CONTRIBUTIONS

Anticipatory Control and Representation

- Anticipatory Control of Actions346
Joachim Hoffmann, Christian Stoecker, and Wilfried Kunde
- The Ideomotor Approach to Action Control: Implications for Skilled Performance362
Iring Koch, Peter Keller, and Wolfgang Prinz

The Construction of Representations in Action

- Actions from Within376
Marc Jeannerod
- The Cognitive Architecture of Complex Movement403
Thomas Schack

Action Planning

- What is the Point of Motor Planning?439
David A. Rosenbaum, Ruud G. J. Meulenbroeck, and Jonathan Vaughan

BULLETIN BOARD470

ISSP WORLD CONGRESS IN AUSTRALIA 2005479

EDITORIAL TEAM

Editors

GERSHON TENENBAUM: College of Education, Dept. of Educational Psychology and Learning Systems, Florida State University, 307 Stone Building, Tallahassee, FL 32306 USA

DIETER HACKFORT: Dept. QESA – Sports Academy, P.O. Box 23833, Doha, Qatar

Section Editors

EXPERTISE AND INFORMATION PROCESSING ISSUES

CHRIS M. JANELLE: University of Florida, College of Health and Human Performance, Department of Exercise and Sport Sciences, P.O. Box 118207, 25 FLG, Gainesville, FL 32611, USA

EXERCISE & HEALTH: BIOLOGICAL ASPECTS OF BEHAVIOUR

ROD DISHMAN: University of Georgia, Department of Exercise Sciences, School of Health and Human Performance, Athens, Georgia 30602, USA

MOTOR CONTROL/LEARNING/DEVELOPMENT

MARK WILLIAMS, Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, The Henry Cotton Campus, 15-21 Webster Street, Liverpool L3 2ET, England

APPLIED ISSUES IN SPORT & EXERCISE

TRISHA LEAHY, Head, Technical Services, Hong Kong Sports Institute, 25 Yuen Wo Rd., Sha Tin, N. T., Hong Kong SAR

SOCIAL ASPECTS IN SPORT & EXERCISE

JEAN COTE: Associate Professor, Queens University, School of Physical and Health Education, Kingston, Ontario, K7L 3N6, Canada. Phone: 613-533-3054, E-mail: jc46@post.queensu.ca

METHODOLOGICAL & STATISTICAL ISSUES

GERSHON TENENBAUM: College of Education, Dept. of Educational Research, Florida State University, 307 Stone Building, Tallahassee, FL 32306, USA

THEORETICAL ASPECTS IN SPORT & EXERCISE

DIETER HACKFORT: ISWS der Uni BwM, Werner-Heisenberg-Weg 39, D-85577 Neubiberg, Germany

GOAL SETTING, MOTIVATION AND ATTRIBUTION

HOWARD K. HALL: Faculty of Humanities, Sport and Education, Bedford College of Higher Education, 37 Landsdowne Rd., Bedford MK 40 2B2, England

CROSS CULTURAL RESEARCH

SI GANGYANG: Sports Science Department, Sport Institute, Shatin, New Territories, Hong Kong

MORAL AND ETHICAL ISSUES

BRENDA BREDEMEIER, Mendelson Center for Sport, Character and Culture, University of Notre Dame, Notre Dame, IN 46556, USA

Bulletin Board

SIDONIO SERPA & DUARTE ARAUJO (Assistant): FMH-UTL, Estrada Da Costa-Cruz Quebrada, 1499 Lisboa Codex, Portugal

Book Reviews

TONY MORRIS: University of Victoria, Department of Psychology, P.O. Box 14428 MMC, Melbourne VIC 3000, Australia

EDITORIAL BOARD

ALBERT CARRON, *Faculty of Kinesiology, University of Western Ontario, London, ON N6A 3K7, Canada*

JOAN L. DUDA, *School of Sport and Exercise Sciences, The University of Birmingham, Edgbaston, Birmingham, B15, 2TT, United Kingdom*

SANDY GORDON, *School of Human Movement and Exercise Science, University of Western Australia, 35 Stirling High Crawley, WA, 6009, Perth, Australia*

ROBERT GROVE, *School of Human Movement and Exercises Sciences, University of Western Australia, 35 Stirling High Crawley, WA, 6009, Perth, Australia*

HERBERT MARSH, *University of Western Sydney, Macarthur, P.O. Box 555, Campbell Town, NSW 2560, Australia*

WILLIAM P. MORGAN, *University of Wisconsin, Sport Psychology Laboratory, Department of Kinesiology, Madison, Wisconsin 53706 - 1184, USA*

TONY MORRIS, *University of Victoria, Department of Psychology, Box 14428, MCMC, Melbourne, VIC, 3000 Australia*

JÖRN MUNZERT, *Institute of Sport Science, University of Gießen, Kugelberg 62, 35394 Gießen, Germany*

ATHANASIOS PAPAIOANNOU, *Democritus University of Thrace, Department of Physical Education and Sport Science, Komotini 69100, Greece*

HUBERT RIPOLL, *Faculty of Sport Sciences, Université de la Méditerranée, 163, Av. de Luminy, Case Postale 910, 13009 Marseille (France)*

DIETMAR SAMULSKI, *UFMG/Escola de Educacao Fisica, Av. Presidente Carlos Luz, 4664 - Pampulha, Belo Horizonte - MG, 31.310-250, Brazil*

R. J. VALLERAND, *Université du Québec à Montréal, Laboratoire de Recherche sur le Comportement Social, Département de Psychologie, Montréal, Canada*

ROBIN S. VEALEY, *Department of PHS, Phillips Hall, Miami University, Oxford OH 45056, USA*

ROBERT WEINBERG, *Department of Physical Education Health & Sport Sciences, Phillips Hall, Miami University, Oxford OH 45056, USA*

YANNIS ZERVAS, *Athens University, Department of Physical Education & Sport Science, 41 Ethnikis Antistastis Street, Dafne 172 37 Athens, Greece*

EFFECT REPRESENTATION AND ACTION PLANNING: A PREFACE

THOMAS SCHACK¹ AND GERSHON TENENBAUM²

¹German Sport University Cologne, Germany

²Florida State University, USA

Actions in sport, just like actions in any other field of daily life, are associated with effects. However, the effects attained do not always correspond with those intended. While watching the Olympic Games at Athens, for example, we have often seen an athlete standing dejectedly next to the high jump bar, because she did not clear the crossbar, thus failing to attain her desired movement? Or gymnasts had to realize that their somersault did not bring them to the intended final position? Nonetheless, one can also observe how various subsidiary movements seem to fit together effortlessly to form a specific effect such as a successful and visually exhilarating pole vault.

Hence, the intended movement effect seems to be an essential control variable for planning action, for assessing action effects, and for action control (see Nattkemper & Ziessler, 2004). One could even go so far as to claim that the effect of an action may simultaneously become the cause of a current action in the form of a goal or in the form of an effect representation. The movement scientist Nikolai A. Bernstein (1957/1975) already pointed this out some time ago when he wrote: "If we consider the program of the movement act macroscopically as a whole, then the only determining factor we are able to find for it, is the image of that effect ... action toward which this act is directed through comprehension of the given movement task" (p. 155, translated).

However, for many years, this work along with other works on effect representation or, as Bernstein called it, "the model of the needed future," had no systematic impact on movement science. To some extent this is also the case in sport psychology where cognitive components such as anticipation were overlooked (e.g., Abernethy, 1987, Nitsch, 2000). It seems as if topics such as goal-directedness of action, anticipated perceptual effects, or the crucial role of mental representations in action control have moved backstage in the debate between a more ecologically oriented action approach and a motor approach (see Abernethy & Sparrow, 1992; Schack & Tenenbaum, 2004). In contrast, a perspective that conceives effect representation and action planning as building blocks of actions, can draw on the support of such fields as cognitive psychology, neurophysiology, and biocybernetics. Over the last 10-15 years several approaches have emerged in cognitive psychology that systematically study the function of effect anticipation, effect representations, and action planning. These include anticipated behavior control (ABC; see Hoffmann, 1993, this issue), the theory of event coding (TEC; see Hommel, Müsseler, Aschersleben, & Prinz, 2001), and the ideomotor approach (IM; Koch, this issue; Hoffmann et al., this issue). These approaches assume that human movement control is based on the representation of anticipated effects, leading to the establishment of a perceptual-cognitive control system.

Thomas Schack & Gershon Tenenbaum

A second basic principle underling this special issue entitled, *"The Construction of Action: New Perspectives in Movement Science"* is that single elements must be considered within the whole. Immanuel Kant already expressed it in his 1770 dissertation, something particularly worth noting toward the end of the year celebrating the 200th anniversary of his death. Kant was interested in the organization principle of organisms in general. He argues that the organism could be explained only by looking at its construction as a whole. Proceeding from this whole, or from this construction, the individual parts (organs) should be defined according to the function they fulfill in the service of the whole. Applying this idea to human movement control opens up new possibilities for integrative perspectives. Therefore, Parts I and II of this special issue present a collection of papers from highly regarded scientists working in the fields of general psychology, neuropsychology, biocybernetics, and sport psychology in order to map out the construction of action. These papers from various scientific disciplines and laboratories address different aspects of the construction of action, each contributing its own building blocks that may be pieced together with the others. One main focus of this special issue is to bring together those research perspectives that can be grouped to form a perceptual-cognitive approach. The papers are organized into two main groups. The first part contained papers that can be classified under the topic of *"Perceptual and Cognitive Control in Action"*, the current issue contains papers in the research area that can be entitled *"Representation and Planning"*.

The section *"Anticipatory Control and Representation"* begins with a paper from **Joachim Hoffmann, Christian Stoecker, and Wilfried Kunde** on *"Anticipatory Control of Action."* The authors start with a historical overview of approaches that can be summarized under the heading "ideomotor principle." They report a series of experiments examining the influence of effect anticipations on the preparation, initiation, and control of movements. These clearly show the functional role of sensory anticipations in motor control. The paper from **Iring Koch, Peter Keller, and Wolfgang Prinz** on *"The Ideomotor Approach to Movement Control: Implications for Skilled Performance"* is also assigned to this first section, and shows a systematic relation to the first paper. The authors present the basic principles of the ideomotor approach. Several experiments reveal, among others, that actions are represented in terms of their anticipated effects. Links are forged to performing and learning movement skills and to mental practice. Indeed, it is worth recalling that, for many years, mental practice was also called ideomotor training, particularly in Eastern Europe.

The section *"The Construction of Representations in Action"* starts with a paper from **Marc Jeannerod** on *"Action from Within."* The author pursues the revolutionary idea that covert mechanisms should be treated like actions just as much as overt actions. He examines whether it is possible to find indications for a causal relationship between mental states and actions. He uses various studies to show that the process of imaging a movement is based on the same mechanisms as performing an action. Conclusions for mental training and motor learning are discussed. In the same section, **Thomas Schack** presents a paper on the *"Cognitive Architecture of Complex Movement."* He orders the structure of mental representation within the construction of an act. His cognitive architecture of movement focuses on the hierarchic construction and the interplay between representation and regulation levels. Drawing on experimental studies on the measurement of mental representation, he uncovers the functional relations between the structure of these representations and performance in sport. Conclusions are drawn for new mental-training perspectives and new approaches to technical preparation.

The special issue concludes with a section on "Action Planning," which consists of one contribution by **David Rosenbaum, Jonathan Vaughan, and Ruud Meulenbroek** entitled "What is the Point of Motor Planning?" This paper gives a detailed account of the theory of posture-based motion planning. The authors find support for goal posture planning in a number of studies. Their model makes it possible to explain a range of phenomena in human movement control. They use it as a basis to present a series of interesting and far-reaching implications for sport and exercise.

As editors, we hope that this special issue on "The Construction of Action: New Perspectives in Movement Science" will not only help to overcome the current invariants of thinking in movement science, but also encourage a reconsideration of the need for a cognitive sport psychology (see for example Straub & Williams, 1984). We believe that this special issue will open up new perspectives for practical applications; and hope that these papers on the construction of action will generate a degree of interest along with the knowledge gained from addressing new perspectives.

REFERENCES

- Abernethy, B. (1987). Anticipation in sport: A review. *Physical Education Review*, 10, 5-16.
- Abernethy, B., & Sparrow, W. A. (1992). The rise and fall of dominant paradigms in motor behavior research. In J. J. Summers (Ed.), *Approaches to the study of motor control and learning* (pp. 3-45). Amsterdam: Elsevier Science.
- Bernstein, N. A. (1975). *Bewegungsphysiologie*. Leipzig: Barth.
- Hoffmann, J. (1993a). *Vorhersage und Erkenntnis*. Göttingen: Hogrefe.
- Hoffmann, J. (1993b). Wird Wissen in Begriffen repräsentiert? In J. Engelkamp & T. Pechmann (Hrsg.), *Mentale Repräsentation* (S. 81-92). Göttingen: Huber.
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action. *Behavioral & Brain Sciences*, 24, 849-937.
- Knuf, L., Aschersleben, G., & Prinz, W. (2001). An analysis of ideomotor action. *Journal of Experimental Psychology: General*, 130, 779-798.
- Nattkemper, D., & Ziessler, M. (2004). (Eds.), *Cognitive control of action: The role of action effects*. Special Issue of *Psychological Research*, 68.
- Nitsch, J. R. (2000). Handlungstheoretische Grundlagen der Sportpsychologie. In H. Gabler, J. R. Nitsch, & R. Singer (Hrsg.), *Einführung in die Sportpsychologie. Teil 1: Grundthemen* (Bd. 2, 3. Aufl., S. 43-164). Schorndorf: Hofmann.
- Straub, W. F., & Williams, J. M. (1984). *Cognitive sport psychology*. New York: Sport Science Associates.

ANTICIPATORY CONTROL OF ACTIONS

JOACHIM HOFFMANN¹, CHRISTIAN STOECKER¹, AND WILFRIED KUNDE²

¹University of Würzburg, Germany

²University of Halle, Germany

ABSTRACT

The article presents an overview of notions of anticipatory control of behavior, meaning the control of behavior through advance representations of sensory effects. First, a brief historical overview of concepts regarding sensory effects as the intra-psychic raw material of actions is presented. These concepts are generally subsumed under the term *ideo-motor principle*. Evidence is presented that associations between actions and their sensory effects are formed even if the effects are not intended by the actor. Specifically, the impact of redundant tone effects on the acquisition of movement sequences is discussed. Further evidence suggests that effect anticipations also influence the selection and initiation of choice responses. This is exemplified above all by a phenomenon referred to as *response-effect-compatibility*. It is then specified that the impact of effect anticipations on the preparation and the execution of responses differs, suggesting that different processes are influenced by them. In conclusion, the importance of sensory anticipations for motor control is acknowledged and a number of open questions are pointed out.

Key Words: behavioral control, anticipation, motor learning

SENSORY ANTICIPATIONS ACCOMPANY AND PRECEDE VOLUNTARY BEHAVIOR

Every movement of the body affects subsequent sensorial input. This is true not only for the complex motion sequences typically considered in sports psychology but also for actions as simple as lifting a finger or turning one's head. Organisms that could not distinguish between sensory changes caused by their own behavior and sensory changes occurring for other reasons would be unable to make any reasonable use of the sensory input at all. This is a fundamental problem for all active organisms. The most probable solution of the problem is the *reafference principle* (RP, von Holst & Mittelstaedt, 1950). According to the RP, each efferent activation pattern goes along with a collateral activation – the *efference copy* – which is assumed to carry

Correspondence concerning this article should be addressed to Joachim Hoffmann, Department of Psychology, University of Würzburg, Röntgenring 11, 97070 Würzburg, Germany; E-mail hoffmann@psychologie.uni-wuerzburg.de

the information about the sensory effects of the ongoing action. The tenet of the RP says that the efference copy and the reafference cancel each other out (von Holst & Mittelstaedt, 1950, p.467-468) so that higher stages of perception exclusively reflect those sensory changes that are not due to own behavior. Thus, even for apparently motor-unrelated perceptual processes it is mandatory that actions are accompanied by anticipations of their reliable sensory effects.

Behaviorally induced sensory anticipations, however, do not only serve to stabilize perception but also affect the online control of action execution. Feed forward of sensory anticipations provides a *reference* signal to which the real feedback of the ongoing action can be compared – so that each deviation causes an instantaneous correction of the motor commands to compensate for it (e.g. Adams, 1971). Likewise, sensory anticipations also may be used to *substitute* sensory feedback. For example, it has been shown that goal-oriented movements adapt to non-detected goal displacements even if there is neither visual nor proprioceptive feedback from the moving limb (e.g. Bard, Turrell, & Fleury, 1999). Such an adaptation without feedback convincingly suggests that there are other sources of information about the shape of the ongoing movement. Presumably, beginning the movement brings about a forward model of the dynamics of the moving limb by which the end point of the movement is predicted and continuously compared to the target location. If the anticipated destination of the moving limb deviates from the given target location (due to a displacement) a corresponding correction is immediately initiated (cf. Desmurget & Grafton, 2000). Whatever the precise mechanism, it is widely accepted that motor activations call forth anticipations of their reliable sensory effects and that deviations of the actual effects from these anticipations serve to stabilize perception as well as to control execution.

In the present paper, we will discuss evidence for the broader notion that sensory anticipations do not only accompany behavior but that voluntary behavior is also selected and initiated through sensory anticipations.

This notion, that "...a current response is selected on the basis of its own anticipated sensory feedback" (Greenwald, 1970, p.93) is the core of the *ideo-motor principle* (IMP) already discussed in the 19th century (Harleß, 1861; Herbart, 1825; James, 1981/1890; Lotze, 1852; Münsterberg, 1889). In contrast to feed-forward models, the *ideo-motor principle* reverses the cause-effect relation: While feed-forward models assume that motor activation calls forth sensory anticipations, the IMP assumes that the anticipation, the mere idea of the desired effects, calls forth those motor activations that have previously been experienced as producing the desired effects.

The IMP necessarily presumes that movements become associated with their contingent effects, as it is impossible to see how effect anticipations could otherwise attain the power to address the movements they are usually effects of. How such action-effect learning may take place was already discussed by Johann Friedrich Herbart (1825) more than 150 years ago:

Right after the birth of a human being or an animal, certain movements in the joints develop, for merely organic reasons ... each of these movements elicits a certain feeling ... In the same instance, the outside senses perceive what change has come about... If, at a later time, a desire for the change observed earlier arises, the feeling *associated* with the observation reproduces itself. This feeling ... corresponds to all the

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

inner and outer states in nerves and muscles through which the intended change in the sphere of sensual perception can be brought about. Hence, what has been desired actually happens; and the success is perceived. Through this, the association is reinforced: the action, once performed, makes the following one easier and so on. (p. 464, shortened translation by the authors).

The latter part of these "classic" speculations (see Hoffmann, 1993; Hommel, 1998; Prinz, 1987, 1992 for recent formulations) concerns a self-evident consideration. It can be taken for granted that goals are associated with the actions that led to achieving them, and that the strength of these associations increases with every additional success. For example, when trying to find out how to switch on a new mobile phone, one might press various buttons and try to memorize the action that was successful. When the mobile phone has to be switched on again, the previously successful action is remembered and every additional success strengthens this association. Thus, the scientific challenge of the IMP is not the formation of associations between actions and goals but rather the claim that actions become associated also to their incidentally produced effects which they did not strive for. Furthermore, it has to be demonstrated that such latently formed associations can also be activated in the reverse direction so that the idea of an effect can address an action through which this effect has only been produced incidentally before. In the next sections, experimental evidence concerning both issues are reported.

THE LATENT FORMATION OF BEHAVIORALLY INDUCED EFFECT ANTICIPATIONS AND THEIR IMPACT ON THE CONTROL OF RESPONSE SEQUENCES

An instructive example of latent action-effect learning is provided by a recent study of Hoffmann, Sebal, and Stöcker (2001). Participants responded to asterisks presented at one of four horizontally aligned locations by pressing one of four response keys which were also horizontally aligned (cf. Nissen & Bullemer, 1987). The keys were assigned to the asterisk locations in a spatially compatible fashion, i.e., the response keys from left to right were assigned to the respective asterisk locations from left to right. Each key stroke triggered the presentation of the next asterisk, so that participants performed a sequence of key strokes in response to a sequence of self-triggered asterisks. In the first two blocks, the sequence of asterisks as well as the sequence of the required responses was random. In six following blocks, a fixed sequence of stimuli was cyclically repeated resulting in a cyclic repetition of a fixed response sequence as well. In a subsequent test block the sequence of stimuli and responses was switched back to random, before, in a last block the fixed sequence was presented again. Typically, reaction times (RTs) and errors continuously decreased with repetitions of the fixed sequence and they increased in the test block. This increase indicates serial learning, as it reveals that the preceding decrease of RTs was due to acquired knowledge about the serial structure of the fixed sequence, which becomes useless if a random sequence is presented again.

Hoffmann, et al. (2001) argued that serial learning should be improved if each key stroke would produce a contingent tone-effect, so that an anticipation of the fixed tone sequence could be used in order to control the fixed key stroke sequence, just like a pianist may control his

strokes by an anticipation of the melody to be played (Bangert, Parlitz, & Altenmüller, 1998). In the corresponding experiment, the four tones of a C Major chord were assigned to the keys from left to right in an ascending order (condition Contingent Tones or CT). Consequently, when participants responded to the fixed sequence of asterisks they cyclically produced a fixed sequence of tones that could be integrated into a "melody." There was a first control condition in which no tones were presented (condition No Tones or NT) and a second control condition in which the fixed tone sequence was presented one serial position ahead to the fixed asterisks/response sequence. This manipulation resulted in the same tone sequence but with the tones no longer contingently mapped to the keys (condition Non-Contingent Tones or NCT).

Figure 1. Mean reaction times (RT) in an SRT task in dependence on whether the responses produced contingent tone effects (CT), non-contingent tone effects (NCT), or no tones (NT), plotted against random (R) and structured (S) blocks (after Hoffmann, et al., 2002).

Figure 1 shows the mean RTs for the three groups plotted across experimental blocks. The results indicate that the mere presentation of an additional tone sequence does not affect RTs, as there were no differences between the conditions with no tones (NT) and with non-contingent tones (NCT). In contrast, RTs decreased substantially more when the tones were contingently mapped to the key strokes (CT). As RTs increased in the test block to the same level as in both control groups, the data confirm that the contingent tone effects improved the acquisition and use of serial knowledge about the fixed sequence. Obviously, key presses and tone effects became associated so that anticipations of the tones gained control over the to-be-executed fixed sequence of key presses, otherwise their impact on response speed would be hard to explain (cf. also Greenwald, 1970; Ziessler 1998; Ziessler & Nattkemper, 2001).

Note that the tone effects were completely irrelevant with regard to the task demands. The fact that the tones, nevertheless, influenced the performance strongly supports the notion that effects need not be intended in order to become associated with the actions they are results of. Rather, it seems that attending the effects and temporal overlap of code activation suffices in order to integrate action and effect representations in a bidirectional connection (cf. also Elsner & Hommel, 2001, 2004).

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

Subsequent experiments aimed at an elaboration of the impact the contingent tone effects had on performance (Stöcker & Hoffmann, 2004; Stöcker, Sebald, & Hoffmann, 2003). In particular, the experiments were aimed at clarifying the mechanisms through which the tones led to faster sequence acquisition and faster responses.

In one study (Stöcker & Hoffmann, 2004), participants practiced short sequences of key presses they had to enter with the ring, middle, and index fingers of both hands. Six element sequences were contrasted with three element sequences. Typically, this kind of experimental setup yields a specific pattern of results called the sequence-length effect: Longer sequences take longer to initiate than shorter ones, that is, participants take longer to press the first key in a longer sequence (e.g. Hulstijn & Van Galen, 1983; Rosenbaum, Gordon, Stillings, & Feinstein, 1987; Verwey, 2003). This is usually interpreted as a sign for time-consuming preprogramming of the sequences, occurring before sequence execution begins. Preprogramming is considered a process by which advance representations of movements are constructed that allow fast execution afterwards, independent of error feedback.

In the study in question, some participants practiced the sequences by responding to visual stimuli, with the instruction to try to memorize the sequences so they would eventually be able to enter them without key-specific stimuli, "by heart." In another group, participants had the same task but their key presses also produced tones of different pitch. Both groups practiced the same sequences, only the presence or absence of tone effects separated them.

In correspondence to the results from the serial-learning experiments reported above, the tone effects again helped acquiring, initiating, and executing the sequences. Interestingly, the tones led, in one experiment, to a significant reduction of the sequence-length effect, that is, participants who experienced tone effects initiated the six element sequence almost as quickly as the three-element sequence (35 ms sequence-length effect vs. 101 ms in the control condition). In another experiment the sequence-length effect in the tones group was also reduced in comparison to the sequence-length effect in the no-tones group (from 112 ms to 24 ms). Thus, preprogramming seems to have benefited from the effects: Longer sequences could be preprogrammed almost as fast as short ones. This is usually the case only after extensive practice (cf. Klapp, 1995), and is interpreted as a sign of movement chunking. Chunked-together movements can be preprogrammed as a single unit, saving preparation time. Converging evidence for this interpretation comes from interresponse time data. As Figure 2 shows, the interresponse time profiles, that is, the profiles of the times between two subsequent key presses within one sequence were far more homogenous in the group producing tone effects than those of the control group. This indicates that the sequence of six single movements is not only efficiently sampled into proper subsequences but also that the formed subsequences are integrated into a representation which comprises the whole sequence. Tone effects seem to aid the development of compact representations for movement control by facilitating chunking of single units into larger groups. This fits well with the evidence presented so far: Tone effects facilitate the generation of anticipatory representations for movement production – keep in mind that initiation times are measured before the first tone effect is presented. These anticipatory representations lead to more efficient preprogramming, faster initiation, and faster execution of the sequences. It is hard to imagine that this could occur without those sensory effects becoming integrated in the respective motor representation or "motor program."

Figure 2. Mean interresponse-times (T2 – T6) for 6 element sequences, shown separately for the groups with and without tone effects.

EFFECT ANTICIPATIONS INFLUENCE THE SELECTION AND THE INITIATION OF CHOICE RESPONSES

Probably the most challenging assumption of anticipative behavioral control is that actions are exhaustively represented in terms of their reafferences. Consequently, there would be no other way to recruit a movement than by recollecting these effects. In other words, every voluntary movement must be preceded by an anticipation of the movements' sensory consequences. Kunde (2001) suggested an experimental paradigm for the study of these proposed anticipatory effect codes. He based his argument on well-established findings from stimulus-response compatibility research: In choice reaction tasks with overlapping stimulus-response sets, responding is faster and less error prone with compatible S-R assignments than with incompatible S-R assignments (cf. Kornblum, Hasbroucq, & Osman, 1990). For example, responding to a left stimulus is accomplished faster with a left response than with a right response, and responding to a right stimulus is accomplished faster with a right response than with a left response (e.g. Simon, 1969; Simon, Hinrichs, & Craft, 1970). Kunde reasoned that if generating a response actually requires an anticipation of its sensory effects, similar compatibility phenomena as those between stimuli and responses should manifest between (anticipated) effects and responses as well.

Such Response-Effect (R-E) compatibility effects occur indeed. Figure 3 illustrates an example. Participants were requested to press one of four horizontally aligned keys in response to the presentation of one of four centrally presented color patches. Each key press contingently produced the onset of one of four visual effects, which were horizontally aligned on the screen. In the compatible condition, each key stroke triggered a spatially compatible effect on the

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

screen, whereas in the non-compatible condition the assignments of the effect locations to the key locations were scrambled. As participants had to press the keys to imperative color signals, dimensional overlap existed exclusively between the response set and the set of the response effects. Responding was significantly faster (490 ms vs. 511 ms) and less error prone (4.9% vs. 5.3%) if the keys triggered spatially compatible effects than if they triggered spatially incompatible effects.

Figure 3. Illustration of spatially compatible as well as incompatible visual effects of key presses as used by Kunde, 2001.

Similar results were obtained with response-effect sets that overlap with respect to intensity (Kunde, 2001), duration (Kunde, 2003), spatial-tonal location (Koch, Keller, & Prinz, this issue), or verbal meaning (Koch & Kunde, 2002). Thus, response-effect compatibility is a phenomenon of broad empirical validity. Importantly, in all these studies response effects were presented only *after* the response had been carried out. Thus, their impact on response latencies strongly suggest that effect representations were activated *before* response onset, hence during response selection or initiation.

Although these results suggest that anticipatory effect codes precede response onset, they do not specify for which aspects of response production such codes are particularly important. To explore this question Kunde, Koch, and Hoffmann (2004) combined the response-effect compatibility paradigm with a response-preparation paradigm. Participants responded to a color stimulus with a soft or forceful key press. In the compatible condition, soft responses produced a quiet tone and forceful responses produced a loud tone, whereas in the incompatible condition this mapping was reversed. In most trials the response was validly cued ahead of the response signal allowing participants to prepare the afforded response in advance. In the remaining trials there was a non-informative neutral cue.

Figure 4. Mean response times in dependence on cue validity for trials with compatible vs. incompatible response-effect-mapping, plotted over the different cue-stimulus-intervals.

Figure 4 depicts the reaction times for compatible and incompatible R-E mappings, as a function of cue type (valid vs. neutral) and cue-stimulus interval (CSI: 200 ms...1500 ms). Three results are particularly important: First, cuing was effective. With valid cues RTs decreased the longer the CSI. After 1000 ms, response preparation seems to be completed as a further prolongation of the CSI provokes no further response acceleration. Second, there is a significant response-effect compatibility effect: responses with compatible effects are faster than responses with incompatible effects. Finally, and most important, the compatibility effect is reduced in valid trials in comparison to neutral trials but is still significant even in trials in which the required response is already selected and only remains to be initiated. This compatibility effect for completely prepared responses convincingly demonstrates that response effects not only have an impact on the selection of the response but also on its initiation (cf. Brass, Bekkering, & Prinz, 2001; Kunde & Weigelt, 2003, for similar observations).

Figure 5. A simple threshold model to illustrate the assumed impact of corresponding and non-corresponding effects on response selection and initiation.

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

These results accord with a simple threshold model of effect-based response production (Figure 5). The model assumes that motor responses are recruited by increasing the activation of the distal (e.g. auditory, visual) and proximal (e.g. proprioceptive, tactile) response-representing effect codes. If overall code activation exceeds a certain execution threshold, the effect-associated motor patterns are automatically emitted. Distal and proximal effects prime each other by virtue of similarity, which allows mutually compatible effects to reach execution threshold earlier than mutually incompatible effects. If response execution has to wait for the presentation of a go-signal, as in the described experiments, activation must be stopped intentionally to avoid premature responding. After go-signal presentation, response times reflect the residual activation increase necessary to push the motor pattern over the execution threshold. This results in still significant but numerically reduced influences of response effects. This admittedly simple model certainly requires further specification, but even in this preliminary state it allows some testable predictions. For example, response production is assumed to proceed simultaneously to stimulus processing, rather than having to wait until stimulus processing is completed (e.g. Kornblum, et al., 1990; Sanders, 1980). Therefore, an orthogonal manipulation of the ease-of response production by effect compatibility and of the ease-of-stimulus processing, e.g. by varying stimulus quality, should exert interactive rather than additive influences on response times (cf. Sternberg, 1969) — a prediction that has been confirmed in a recent series of experiments (Kunde, Paelecke, & Kiesel, 2004).

EFFECT ANTICIPATIONS HAVE A DIFFERENT IMPACT ON THE PREPARATION AND THE EXECUTION OF RESPONSES

So far we focused on the impact of action effects on the mental antecedents of motor actions apparent in response times. Yet, sensory effects also affect the way actions are carried out, albeit in a different manner.

Figure 6 illustrates an example. The figure shows the peak forces for required strong and soft key presses with either quiet or loud tone effects. The data reveal a remarkable difference to the impact of response-effects on RTs: Loud effect-tones reduce peak forces in comparison to quiet effect tones, irrespective of whether a strong or a soft key press is required. Thus, there is no longer a compatibility effect as with response latencies but a contrast effect: Intense effects reduce response intensities and weak effects increase response intensities. Moreover, response times and peak force are uncorrelated on a trial-by-trial basis. These findings suggest that with response onset a new process evolves where anticipated tone effects have a different impact on response execution than they have on response selection/initiation. This impact can be described as contrast bias: Anticipated quiet tones generally increase response force, and anticipated loud tones decrease response force. Similar contrast effects have been found for responses and effects of varying duration. Short tones increase response duration and long tones decrease response duration (Kunde, 2003).

Figure 6. The impact of quiet and loud effect tones on the peak forces of intended soft and strong key presses (after Kunde, et al., 2004).

How can one explain these contrasting influences? We suggest that the proximal (tactile, proprioceptive) response intensity that has been anticipated prior to response onset (i.e. for response selection), serve as a reference value for response execution control. The perceived feedback is continuously compared with this reference value and force output stops when feedback and reference value match. Distal (e.g., auditory) effects could affect this comparison in two ways: First, distal effects might affect the setting of the proximal reference value. Conceivably, proximal and distal intensity become combined into an overall reference value (cf. Figure 7a). For a given intended overall intensity, proximal intensity (and thus force) must consequently be higher the lower the distal component of the combined reference value is, and vice versa. A similar account was quite successful in explaining contrasting influences of delayed auditory feedback on the timing of actions (Aschersleben & Prinz, 1997). Second, anticipated distal effects might bias the feedback of proximal consequences (cf. Figure 7b). Following this view, the perceived proximal feedback is biased towards the anticipated distal intensity. In other words, a given force output “feels” more intense when expecting a loud tone than when expecting a quiet tone. As a result, force output stops earlier with a forthcoming loud tone than with a quiet tone, and vice versa. These accounts are not mutually exclusive. Thus distal effects might affect the setting of a proximal reference signal (Figure 7a) as well as the feedback of proximal reafferences (Figure 7b).

Figure 7. Illustration of the presumed impact of irrelevant distal response effects on execution control.

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

REVIEW AND OUTLOOK

We started with the statement that sensory anticipations not only essentially accompany voluntary behavior but also precede it. That voluntary behavior has to be preceded by an "idea" of the to-be-attained goal is self evident. How could a behavioral act be called goal oriented if the goal is not present in advance? Thus, the theoretical challenge is not the claim that an idea of a to-be-attained goal precedes voluntary behavior, but rather that anticipations of the concrete sensory consequences determine the motor activations through which the corresponding behavior is generated.

The notion that voluntary behavior is determined by the anticipation of its sensory effects can be traced back more than 150 years. In the 19th century, the ideo-motor principle was a common speculation on the determination of voluntary behavior (e.g. Harleß, 1861; Herbart, 1825; James, 1981/1890; Lotze 1852; cf. also Stock & Stock, 2004). At the beginning of the 20th century, however, the IMP was discredited, since the notion that behavior might be determined by mental states like an idea was a sacrilege for the rising school of behaviorism. Only recently the notion of an anticipatory control of behavior is being discussed theoretically again (e.g. Hoffmann, 1993, 2003; Hommel, 1998; Prinz, 1987). At the same time, the ideas of anticipatory control of behavior are experiencing substantial experimental elaborations (e.g. Hommel, 1996; Kunde, 2001; Ziessler & Nattkemper, 2001)

In the present paper we discussed some of the available experimental evidence in support of an anticipative control of voluntary behavior. We have shown that intentional acts are also associated with their non-intended effects, and that these incidental effects exert an influence on action generation. When practicing fixed stimulus-response sequences, contingent effects lead to a switch of execution control from the imperative stimuli to the anticipated effects. Moreover, effects like tones that are easily integrated, facilitate the generation of representations for sequence fragments, and thus aid the parsing of the sequence into adequate chunks as well as their integration into a unitary-sequence representation.

In further experiments it was demonstrated that effects influence the selection as well as the execution of responses. If responses and effects share common dimensions, responses with compatible effects are selected and initiated faster than responses with incompatible effects. This corresponding influence of action-effect compatibility on selection and initiation suggests that both processes are based on the same mechanism that can presumably be described as an accumulation of activations. According to the tentative activation model (Kunde, et al., 2004) the selection as well as the initiation of a response is achieved through a gradual activation of effect representations, execution being initiated when a threshold is exceeded (see Figure 5). Corresponding effects from different sensory modalities activate each other while activations of non-corresponding effects interfere. This way, the model explains the finding that responses with compatible effects are selected and initiated faster than responses with incompatible effects.

Finally, it was shown that incidental response effects also influence response execution via a contrast bias: High-intensity effects reduce response intensity while low-intensity effects increase response intensity. Correspondingly, long-lasting effects reduce response duration,

while short effects increase it. We assume that this contrast bias is mediated by a modulation of anticipative execution control. Distal effects either affect the setting of a proximal reference value or they bias the proximal reafferences.

Altogether, the given evidence convincingly confirms the impact of incidental distal response effects on the generation of voluntary responses and the control of their execution. Moreover, the reported results allow detailed speculations on the mechanisms by which these influences are mediated. There remain, however, unresolved questions.

Among the numerous issues which are still to be resolved, the conditions under which action-effect relations are latently formed deserves attention. Are actions inevitably associated with all sensory effects that contingently accompany their execution or must certain conditions be met for the latent formation of action-effect associations? In the majority of the reported experiments, it was shown that actions become associated with irrelevant effect-tones which participants did not intend to produce. However, the effect tones were salient as they were the only effects of the to-be-performed actions which could hardly be ignored. Thus, it might well be that only attended effects become associated. Likewise, it remains to be explored to which extent delayed effects also become associated and which degree of contingency is needed for a latent formation of an action-effect association (cf. Elsner & Hommel, 2004).

Another open issue concerns the integration of initial conditions into the representations of actions. It is obvious that contingencies between actions and effects often depend on the given context. For example, pressing the right-mouse button results in very different effects depending on the location of the cursor. However, if the initial conditions are fixed, the effect of a mouse click is almost always the same. Like in this case, the success of most of our actions depends on giving the proper initial conditions. Consequently, the generation of an appropriate action does not only require the anticipation of the to-be-produced effects, but also an anticipation of the initial conditions that usually have to be given for this action to be executed successfully. For example, if one is going to mail a letter one instantaneously looks for a mail box, that is, one anticipates the image of a mailbox as the necessary situational context to accomplish the intended act.

Besides Kurt Lewin (1926), who coined the "mail box" example, the interdependence of "goal anticipations" and anticipations of suitable initial conditions was already acknowledged by Ach (1913). According to him, a voluntary act has to be characterized, besides other features, by an objective moment (gegenständliches Moment) which relates an image of what one strives for (Zielvorstellung) to an image of the situation to which the intention refers (Bezugsvorstellung). There are first data indicating that participants very flexibly adapt referential anticipations (Bezugsvorstellungen) of required responses to the concrete initial conditions, i.e. imperative stimuli, they experience (Kunde, Kiesel, & Hoffmann, 2003). However, we are still far from understanding the learning mechanisms the formation and adaptation of referential anticipations are based on.

Finally and perhaps most important, the processes by which sensory anticipations, i.e., anticipations of afferent activation patterns, are converted into actions, that is efferent activation patterns, are not yet appropriately understood. Saying that the transition from

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

anticipation to behavior is ensured through bidirectional connections between both is rather vague and obscures the associated problems more than solving them. For example, it is obvious that not every anticipation results in action. One can very precisely anticipate the sensory effects which will appear when raising one's right hand without doing so. Thus, the anticipation of sensory consequences does not suffice in order to evoke the corresponding action. James (1981/1890, p.1112) already claimed that "on certain occasions" not only anticipations but also a "fiat" that the anticipated consequences shall become actual is necessary in order to make the body move. However, what is a "fiat" and on what does it depend whether it is needed or not? What opens the gate that lets a fully prepared action be carried out and what prevents its execution despite full preparation?

Another fundamental problem is raised by the great number of degrees of freedom of body movements. Consequently, any particular outcome can be attained by practically innumerable body movements, so that the relations between the efferent activation patterns and the resulting afferent activation patterns which refer to distal effects are almost always ambiguous. In other words, a distal effect can never determine a concrete movement but only a class of possible movements, at best. By which mechanisms are the countless remaining alternatives narrowed down to the movement finally performed?

Thus, we finish with more unsettled issues than we started with. Nevertheless, the evidence given confirms anticipative control as a proper groundwork for further exploration of what is still a mystery: The learning-dependent establishment of structures and processes by which the mind controls the body in such a way that what is desired really happens.

REFERENCES

- Ach, N. (1913). Wille. [Volition]. In *Handwörterbuch der Naturwissenschaften* (Bd.10, pp. 659-666). Jena: Fischer.
- Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior*, 3, 111-149.
- Aschersleben, G., & Prinz, W. (1997). Delayed auditory feedback in synchronization. *Journal of Motor Behavior*, 29, 35-46.
- Bangert, M., Parlitz, D., & Altenmüller, E. O. (1998). Audio-motor integration in beginner and expert pianists: A combined DC-EEG and behavioral study. In N. Elsner & P. Wehner (Eds.), *The Göttingen neurobiology report II* (pp. 753ff). Stuttgart, Germany: Thieme.
- Bard, C., Turrell, Y., & Fleury, M. (1999). Deafferentation and pointing with visual double-step perturbations. *Experimental Brain Research*, 125, 410-416.
- Brass, M., Bekkering, H., & Prinz, W. (2001). Movement observation affects movement execution in a simple response task. *Acta Psychologica*, 102, 3-22.
- Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Science*, 4, 423-431.
- Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 229-240.
- Elsner, B., & Hommel, B. (2004). Contiguity and contingency in action-effect learning. *Psychological Research*, 68, 138-154.
- Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: with special reference to the ideo-motor mechanism. *Psychological Review*, 77, 73-99.
- Harleß, E. (1861). Der Apparat des Willens. [Appliance of volition]. *Zeitschrift für Philosophie und philosophische Kritik*, 38, 50-73.
- Herbart, J. F. (1825). *Psychologie als Wissenschaft neu gegründet auf Erfahrung, Metaphysik und Mathematik*. Zweiter, analytischer Teil. [Psychology founded anew on experience, metaphysics, and mathematics]. Königsberg: August Wilhelm Unzer.
- Hoffmann, J. (1993). *Vorhersage und Erkenntnis: Die Funktion von Antizipationen in der menschlichen Verhaltenssteuerung und Wahrnehmung* [Anticipation and Cognition: The function of anticipations in human behavioral control and perception]. Göttingen: Hogrefe.
- Hoffmann, J. (2003). Anticipatory Behavioral Control. In M. Butz, O. Sigaud, & P. Gerard (Eds.), *Anticipatory behavior in adaptive learning systems* (pp. 44-65). Heidelberg: Springer.
- Hoffmann, J., Sebald, A., & Stöcker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 470-482.
- Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research*, 59, 176-186.
- Hommel, B. (1998). Perceiving one's own action - and what it leads to. In J. S. Jordan (Ed.), *Systems theory and apriori aspects of perception* (pp. 143-179). Amsterdam: Elsevier Science B.V.

Joachim Hoffmann, Christian Stoecker, & Wilfried Kunde

- Hulstijn, W., & Van Galen, G. P. (1983). Programming in handwriting: Reaction time and movement time as a function of sequence length. *Acta Psychologica*, 54, 23-49.
- James, W. (1981). *The principles of psychology* (Vol. 2). Cambridge, MA: Harvard University Press (orig. 1890).
- Klapp, S. T. (1995). Motor response programming during simple choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 1015-1027.
- Koch, I., Keller, P., & Prinz, W. (2004). Ideo-motor action. *Journal of Sport and Exercise Psychology*.
- Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory and Cognition*, 30(8), 1297-1303.
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus response compatibility: A model and taxonomy. *Psychological Review*, 97, 253-270.
- Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 387-394.
- Kunde, W. (2003). Temporal response-effect compatibility. *Psychological Research*, 67, 153-159.
- Kunde, W., Kiesel, A., & Hoffmann, J. (2003). Conscious control over the content of unconscious cognition. *Cognition*, 88, 223-242.
- Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation and execution of actions. *The Quarterly Journal of Experimental Psychology. Section A: Human Experimental Psychology*. 57A, 87-106.
- Kunde, W., Paelecke, M., & Kiesel, A. (2004). *Anticipatory effect codes in and before the central bottleneck*. Manuscript in preparation.
- Kunde, W., & Weigelt, M. (2003). *Goal congruency in bimanual object manipulation*. Manuscript submitted for publication.
- Lewin, K. (1926). *Vorsatz, Wille und Bedürfnis mit Vorbemerkungen über die psychischen Kräfte und Energien und die Strukturen der Seele*. [Intention, volition, and need with preliminary remarks about the psychic forces and energies and the structures of the soul]. Berlin: Springer.
- Lotze, H. (1852). *Medizinische Psychologie oder Physiologie der Seele*. [Clinical psychology or the physiology of the soul]. Leipzig: Weidmann'sche Buchhandlung.
- Münsterberg, H. (1889). *Beiträge zur Experimentalpsychologie. Heft 1*. [Contributions to experimental psychology]. Freiburg i.B.: J.C.B. Mohr.
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19, 1-32.
- Prinz, W. (1987). Ideomotor action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 47-76). Hillsdale, NJ: Erlbaum.
- Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology*, 4, 1-20.

- Rosenbaum, D. A., Gordon, A. M., Stillings, N. A., & Feinstein, M. H. (1987). Stimulus-response compatibility in the programming of speech. *Memory & Cognition*, 15, 372-393.
- Sanders, A. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331-354). Amsterdam: North-Holland.
- Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, 81, 174-176.
- Simon, J. R., Hinrichs, J. V., & Craft, J. L. (1970). Auditory S-R compatibility: Reaction time as a function of ear-hand correspondence and ear-response-location correspondence. *Journal of Experimental Psychology*, 86, 97-102.
- Sternberg, S. (1969). The recovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, 30, 276-315.
- Stock, A., & Stock, C. (2004). A short history of ideo-motor action. *Psychological Research*, 68, 176-188.
- Stöcker, C., & Hoffmann, J. (2004). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research*, 68, 126-137.
- Stöcker, C., Sebald, A., & Hoffmann, J. (2003). The influence of response-effect compatibility in a serial reaction time task. *Quarterly Journal of Experimental Psychology*, 56A, 685-703.
- Verwey, W. B. (2003). Effect of sequence length on the execution of familiar keying sequences: Lasting segmentation and preparation. *Journal of Motor Behavior*, 35, 343-354.
- von Holst, E., & Mittelstaedt, H. (1950). Das Reafferenzprinzip. *Naturwissenschaften*, 37, 464-476.
- Ziessler, M. (1998). Response-effect learning as a major component of implicit serial learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24, 962-978.
- Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response-effect learning: Further evidence from serial reaction task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 595-613.

Author's Note

This research was supported by the following grants from the German Research Council (HO 1301/4, 5, and 6). The authors are grateful to Iring Koch for commenting on an earlier draft.

THE IDEOMOTOR APPROACH TO ACTION CONTROL: IMPLICATIONS FOR SKILLED PERFORMANCE

IRING KOCH, PETER KELLER, AND WOLFGANG PRINZ

Max-Planck-Institute, Munich, Germany

ABSTRACT

Ideomotor approaches to motor control focus on the cognitive mechanisms underlying voluntary action selection. Ideomotor theory states that actions are cognitively represented in terms of their anticipated sensory consequences (response effects) and that there are bidirectional associations between movements and ensuing response effects. Accordingly, the anticipation of response effects may serve as a mental cue to activate the corresponding movement. The aim of the present paper is to describe the general principles of ideomotor theory and to review recent empirical work that supports this theory. Specifically, we describe studies on the role of response effects for the selection and initiation of simple actions and for learning and performing action sequences. Finally, we discuss potential implications of these results for sport psychology, in particular with reference to the role of motor imagery in mental practice.

Key Words: motor control, ideomotor theory, action control, response effect

In sports ranging from table tennis to trampolining, athletes perform complex movement sequences at a highly skilled level. While we may marvel at how such skilled performance is controlled, important questions remain unanswered about the control of much simpler movements, that are often taken for granted, such as pressing the keys on a computer keyboard when typing a word. Explaining the basic mechanisms of movement control continues to be a challenge for the field of physiology, biomechanics, and psychology.

In psychology, motor accounts attempt to explain movement control in terms of invariant features and variable parameters of a movement (see, e.g., Schmidt & Lee, 1999). Motor accounts are usually less concerned with the cognitive basis of movement selection processes than with the factors that determine the actual performance of movements. In contrast, "ideomotor" accounts are concerned predominantly with the cognitive antecedents of voluntary action selection and are less concerned about motor constraints during movement execution. In the context of the ideomotor approach, the term "action" is used to refer to goal-directed movements that bring about intended effects in the environment.

Correspondence concerning this article should be addressed to: Iring Koch, Max-Planck-Institut für Psychologische Forschung, Amalienstrasse 33, 80799 München, Germany, Tel: +49-89-38602-249, Fax: +49-89-38602-199, E-mail: koch@psy.mpg.de

The aim of the present paper is to describe the ideomotor approach to action control. First, we describe the general theoretical approach, then we review recent empirical work related to that approach. Finally, we discuss potential implications of the results of this work for sport psychology with reference to the role of motor imagery in mental practice.

THE IDEOMOTOR APPROACH TO ACTION CONTROL

According to ideomotor theory, the typical reason for performing a movement is to produce an effect in the environment. Based on this assumption, the theory proposes that actions are cognitively represented in terms of their anticipated sensory consequences, or "effects." In this sense, thinking of the intended effect can also be the cause of the movement that produces this effect. That is, the ideomotor principle states that actors select and initiate voluntary actions by activating an anticipatory "image" of the movement's intended effects, which then triggers execution of the associated movement itself.

Early formulations of the ideomotor principle can be traced back to the writings of authors in the nineteenth century (Harleß, 1861; James, 1890; Lotze, 1852). However, this approach to action control lay dormant during the era of behaviorism, which disregarded internal (voluntary) mechanisms as viable explanation of behavior in favor of action control by external stimuli. Yet, the ideomotor approach has been revived in more recent decades (e.g., Greenwald, 1970; Prinz, 1987). Currently, the basic idea of the ideomotor approach, emphasizing the role of anticipatory representations of intended movement effects for action control, has been the source of inspiration for empirically guided theorizing (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1997) and experimental studies on both motor performance (e.g., Knuf, Aschersleben, & Prinz, 2001) and learning (e.g., Wulf & Prinz, 2001, for a review with respect to motor learning).

The ideomotor principle is based on two conditions (cf. Elsner & Hommel, 2001). First, it is required that movements and their ensuing effects become associated, so that it is possible to predict an effect given a movement. Second, and at the heart of the ideomotor principle, this association is required to be bidirectional, so that it becomes possible to predict the required movement given the anticipatory representation of the intended effect (see also "forward" models and "inverse" models, respectively, in computational modeling, e.g., Wolpert, Gharamani, & Flanagan, 2001).

These two components of the ideomotor principle have been the departure point for different lines of empirical research. The general experimental approach to study the cognitive mechanisms underlying the ideomotor principle focuses on investigating the exact role of anticipated representations for action control. In the next section, we review recent empirical studies that demonstrate, first, that bidirectional associations between movements and effects are learnt, and, second, that effect anticipations indeed have a profound influence on action selection and initiation.

Iring Koch, Peter Keller, & Wolfgang Prinz

REVIEW OF RECENT EMPIRICAL RESEARCH

Recent empirical research has focused on demonstrating the role of response effects for action control. In fact, response effects, seen as sensory feedback resulting from a response, have also played a major role in other classic approaches to motor control, such as the closed-loop theory of Adams (1968). In the closed-loop theory, the widely acknowledged function of response feedback is that it is used for a comparison with an internal representation of the correct movement, and the outcome of this comparison allows for correction of the movement in a subsequent trial. That is, response effects provide some sort of "knowledge of results" (see Schmidt & Lee, 1999) that can be used to fine-tune the execution of the movement when it is needed again. In this sense, response effects serve an evaluative function, and this function is primarily tied to feedback from earlier incorrect responses. In contrast, the role of representations of response effects in ideomotor theory is not to evaluate and correct a response but rather to facilitate or generate a response.

In the following sections, we first review empirical research on the facilitative and generative function of anticipated response effects for simple actions. Then, the role of effect anticipation for the selection and initiation of action sequences is discussed in a second section.

EFFECT ANTICIPATION IN SIMPLE ACTIONS

Effect-induced action priming. Greenwald (1970) suggested that the proposed ideomotor mechanism can be studied empirically through the use of an experimental paradigm with two phases. In a training phase, subjects experience contingent response effects. In a second, test phase, these previously learnt response effects are presented either as stimuli or simultaneously with stimuli. If representations of the response effects are indeed integrated in the action control structure responsible for selecting and initiating the action, as proposed by ideomotor theory, the presentation of the response effect should activate a representation that becomes associated with the execution of the movement itself, so that execution of this movement is facilitated, or primed.

In fact, Elsner and Hommel (2001; Hommel, 1996) recently demonstrated this priming effect. In an initial training phase, participants performed key presses, which produced simple auditory effects (tones of varying pitch). In a subsequent test phase, these effects served as imperative stimuli in a choice-reaction task. As a result, a response was selected more quickly when called by its former effect tone than when triggered by the effect tone associated with an alternative response. In another experiment, these authors showed that the presentation of previously learnt response effects increases the frequency of selection of the formerly associated response in a free-choice task, supporting the idea that response effects are involved in the process of actual movement selection. This idea is further supported by a recent brain-imaging study using positron-emission tomography (Elsner, Hommel, Mentschel, Drzezga, Prinz, Conrad, & Siebner, 2002), reporting that effect anticipation implicates the activation of brain structures intimately related to movement planning (in particular the supplementary motor cortex).

Interestingly, the cognitive representation of actions can apparently be fairly abstract. This abstractness is suggested by a study showing that the facilitative influence of presenting a previously learnt response effect also generalizes to stimuli that are related, but not identical to the initially experienced response effect (Hommel, Alonso, & Fuentes, 2003). Furthermore, there is evidence indicating that even affective effects are integrated into the representation of simple actions (Beckers, De Houwer, & Eelen, 2002).

In sum, there exists considerable evidence that learnt response effects are integrated into the cognitive representation of an action, which can then be used to activate the corresponding movement. Note though that the studies reviewed above used artificial movement effects, such as tones, that provide feedback beyond the more proximal, "intrinsic" feedback that occurs as a natural consequence of performing a movement. Strictly speaking, anticipating these proximal response effects would be sufficient to trigger the ideomotor mechanism of action selection, and this kind of response effect was not manipulated in these studies. Clearly though, in many cases movements have goals that are more distal, such as the idea of an illuminated room when pressing the light switch or hearing a tone when pressing a piano key. The studies provide suggestive evidence for the role of these more distal response effects for action control.

Ideomotor compatibility in dual tasks. The basic suggestion of ideomotor theory that actions are cognitively represented in terms of their anticipated sensory feedback (i.e., as "effects") has also been tested in the context of speeded effector coordination in dual-task situations. In dual-task studies, the typical result is that subjects' performance is worse when performing two tasks simultaneously as compared with performing only one task. This dual-task interference effect is usually ascribed to a response selection "bottleneck" (for reviews, see, e.g., Koch, 2003; Pashler, 1994), resulting in queuing of the second response while the first response is selected. This hypothesized bottleneck thus appears to constitute a severe limit in the consecutive selection and initiation of two actions. Importantly, this dual-task interference also occurs when different effectors are used for both tasks, and even if they are in different modalities (e.g., vocal vs. manual).

However, it has been argued by Greenwald (1972; Greenwald & Shulman, 1973) that this bottleneck effect might be overcome, or largely reduced, when the two tasks are "ideomotor compatible." Ideomotor compatibility was defined as occurring when the stimulus "closely resembles the response's sensory feedback" (Greenwald, 1972, p. 52); that is, when the stimulus corresponds to the anticipated response effects, which occurs for example when saying a word in response to its auditory presentation as the stimulus. In that case, the stimulus directly activates representations that form a crucial part of the response representation, which should result in a facilitative priming of this response, so that this response might bypass the postulated response-selection bottleneck.

Greenwald (1972; Greenwald & Shulman, 1973) tested this ideomotor approach to dual-task interference by comparing dual-task performance for two ideomotor compatible tasks with that for other task combinations of one or two non-ideomotor compatible tasks. Consistent with ideomotor theory, the dual-task interference effect was largely reduced with two ideomotor compatible tasks (see also Greenwald, in press; Lien, Proctor, & Allen, 2002, for further discussion).

Iring Koch, Peter Keller, & Wolfgang Prinz

The finding that dual-task interference is largely reduced with two ideomotor compatible tasks supports the conclusion drawn from the single-task priming studies reviewed in the preceding section. Together, these two types of empirical studies provide ample evidence for the important role of response effects in action control.

However, this research primarily demonstrated priming exerted by physically presented stimuli, whereas the initial proposal of ideomotor theory was that the voluntary selection and initiation of actions is triggered by anticipatory representations of response effects, or, to put it differently, by *mentally anticipated* stimuli. In fact, strictly speaking, prior physical presentation of the anticipated response effect might even suggest to the performer that the response intention is already partially fulfilled, so that the actual execution of the effect-associated response might even be inhibited rather than facilitated. However, this theoretical issue was already anticipated by Greenwald (1970), who argued that this potentially inhibitory influence of presenting response effects as stimuli (or together with stimuli) would not occur because the response effect only partly matches the real feedback, so that actors would normally not confuse the effect stimulus with the actual response.

Response-effect compatibility. Priming effects caused by presenting response effects as stimuli demonstrate bidirectional response-effect associations, which is an important step in exploring the role of response effects in action control (see also Ziessler, 1998). Nevertheless, while these priming effects show the existence of bidirectional associations, they do so in a way that does not correspond to the functional use of anticipated response effects as envisaged by ideomotor theory. That is, priming studies do not prove that anticipated action effects ultimately guide action control because these effects were physically presented, so that effect representations were exogenously activated. In contrast, the original ideomotor idea is that it is the *endogenous* activation of representations of future, intended effects that actually prime actions.

Recently, Kunde (2001) argued that, if anticipatory representations of action effects really act as mental movement cues, influences similar to those typically resulting from stimulus perception should result from stimulus (i.e., effect) anticipation as well when there is "dimensional overlap" (see Kornblum, Hasbroucq, & Osman, 1990) between responses and their effects. That is, anticipated effects should prime corresponding responses and hence exert influences of "response-effect" compatibility in a similar way as stimuli do in stimulus-response compatibility.

To demonstrate this hypothesized influence of anticipated response effects, Kunde (2001) had subjects perform either soft or forceful presses on a touch-sensitive plate. Each key press produced either a quiet or loud tone, respectively. Consistent with ideomotor theory, in blocks of trials in which the to-be-produced tone effect always (i.e., predictably) matched the to-be-produced manual key press in intensity (e.g., soft press resulting in a quiet tone), response times were much faster than in blocks in which the intensity of the tone effect always did not match the response intensity. Importantly, observing this response-effect compatibility effects suggest that *anticipatory*-effect representations are created and influence response selection because the effect stimulus was not physically present at the time of movement initiation.

In another study, Kunde, Koch, and Hoffmann (2004) gave subjects response pre-cues, so that the response could be planned in advance. In fact, clear RT benefits of planning the movement in advance were observed, but the facilitatory effect of anticipating compatible response-effects (i.e., tones) was still present, albeit slightly reduced. Finding an influence of anticipated effects even with highly prepared movements is important because it suggests that effects play a role not only for the selection but also for the actual initiation of movements.

We have already discussed that the actual sensory consequences of a movement are very rich and comprise both proximal, proprioceptive effects, and more distal effects. Distal response effects can be rather abstract and indirect, like patting the shoulder of a teammate in a sports competition to motivate them. In this case, the intended and anticipated effect of the action is actually movement unrelated. To demonstrate that such distal, abstract response effects can indeed be part of the action representation, Koch and Kunde (2002) conducted another experiment. In this experiment, subjects were required to say one out of four color words (e.g., blue). Saying a word resulted in the visual presentation of a color word. In a compatible condition, saying, for example, the word blue predictably resulted in the presentation of the word BLUE in blue letters, whereas, in an incompatible condition, the effect word (e.g., GREEN in green) did not match the response word. RT was substantially shorter in the compatible condition than in the incompatible condition, indicating that subjects indeed had anticipated the semantic response effect. Note, again, that this compatibility effect is based on stimulus anticipation because the printed word was only presented after subjects had already initiated their vocal response.

Taken together, the empirical evidence so far has revealed that response effects have bidirectional associations to their corresponding movements, as proposed by the ideomotor theory. The impact of response effects is not restricted to situations in which the effects are physically presented as stimulus but extends to situations in which the effect is anticipated rather than actually presented, suggesting the role of effect anticipation as mental movement cue. Furthermore, the impact of response effects holds even for well-planned movements, and, finally, even quite abstract anticipated effects can prime movements, suggesting that the functional response representation usually contains the anticipation of both proximal and distal effects.

So far, we have discussed empirical evidence for the ideomotor theory as it relates to the selection, planning, and initiation of simple discrete actions. Of course, playing sport as well as engaging in other common activities such as dancing and making music requires the production of relatively complex action sequences in which strings of actions trigger effects that can be chunked to form meaningful goal-directed units, for example, dribbling a ball across a basketball court or soccer field. In the next section, we extend our discussion to the role of response effects for learning and executing sequential actions.

EFFECT ANTICIPATION IN ACTION SEQUENCES

The role of response-effects in motor sequence learning. The mechanisms that underlie the learning of action sequences have been studied using a serial reaction time (SRT) task, in which participants are required to make quick responses to individual stimuli within recycling

Iring Koch, Peter Keller, & Wolfgang Prinz

series of stimuli. In the SRT task, sequence learning is measured as the increase in RT that occurs with a change from a repeating sequence to a random stimulus sequence. Lively debate surrounds the question whether learning under such circumstances involves information about structural relations between (a) stimuli; (b) responses; (c) stimulus-response pairs, or most recently and relevant to the current paper; and (d) response-effect pairs (e.g., Hoffmann, Sebold, & Stöcker, 2001; Koch & Hoffmann, 2000; Ziessler & Nattkemper, 2001).

To investigate the role of response-effect learning, Ziessler and Nattkemper (2001) conducted a series of SRT experiments in which each response triggered the immediate presentation of the next stimulus, thus encouraging the stimuli to be perceived as response effects. The impact of response-effect associations on learning was isolated by using a flexible stimulus-response mapping that allowed the stimulus sequence to vary while the response sequence was held constant. Thus, the same sequence of responses resulted in different effects across various experimental conditions. Under such precisely controlled conditions, Ziessler and Nattkemper found that sequence learning was better when response-effect relations were simple and predictable than when they were complex and unpredictable. Hoffmann et al. (2001) went further by demonstrating that sequence learning is influenced even by response effects that are ostensibly irrelevant to the task. Specifically, they found that learning in an SRT task was facilitated by the presentation of response-contingent tones (see also Hoffmann, Stöcker, & Kunde, this issue). Finally, Zirngibl and Koch (2002) observed that sequence learning in the SRT task was more pronounced for verbal responses (pronunciation of numbers) than for manual responses (key presses). The authors suggested that this difference in sequence learning may be related to natural differences in response-effect "distinctiveness." That is, each verbal response results in a highly distinct response effect (both in terms of motor activation and auditory effect), whereas key presses with different fingers are presumably more confusable in terms of their sensory feedback. This suggestion is consistent with how Hoffmann et al. explain the facilitative effect of contingent tone-effects on sequence learning (Hoffmann et al.).

Recently, the role of response-effect compatibility in sequence learning has also been investigated using the SRT task. Stöcker, Sebold, and Hoffmann (2003, Experiment 2) used a version of the SRT task in which participants responded to each of four centrally presented letters by pressing one of four horizontally aligned response keys. In a control condition, key presses had no (tone) effects, and in three test conditions, key presses triggered tones that were mapped to response key location either (a) with pitch ascending from left to right (as on a piano keyboard), (b) pitch descending from left to right, (c) in a mixed, but fixed, fashion such that the relationship between pitch and location was arbitrary. Stöcker et al. (2003) found that learning was significantly better in the ascending condition than in the descending, mixed, and control conditions, and that there were no reliable differences in learning for the latter three conditions. They also observed that RTs were generally faster in the ascending condition than in the descending and control conditions. Thus, ascending pitch is compatible with left to right movement (as implied by the fact that this mapping is used on the piano), and this pitch-based form of response-effect compatibility facilitates sequence learning.

In general, research using the SRT task has demonstrated that, in accordance with ideomotor theory, response-effect associations play a role in learning how to perform sequential actions. However, in order to acquire skill in most, if not all, motor domains-including sport and music-

the performer is usually required to practice certain movement sequences until they are well learnt. This raises questions about the impact of response-effect associations on the planning of action sequences once they have been learnt.

The role of response-effects in planning action sequences. Action planning necessarily precedes the execution of voluntary actions (see Rosenbaum & Krist, 1996, for review). A study by Stöcker and Hoffmann (in press) addressed the role of response effects in sequential action planning by examining their influence on a robust empirical phenomenon known as the sequence length effect. The *sequence length effect* refers to the finding that the time taken to initiate an action sequence, even if the sequence is well learnt, increases as a function of increasing sequence length. Participants in Stöcker and Hoffmann's study first practiced sequences of either three or six key presses until they were learnt, and then produced the sequences either in the presence or in absence of response-contingent tones (i.e., response effects). When response-effect tones were present, they could be either of distinct pitch (consistently mapped to the keys) or of uniform pitch. Stöcker and Hoffmann found that the sequence length effect was relatively reduced in the presence of distinctive response-effects. Thus, planning sequential actions involves anticipating their effects (see also Hoffmann et al., this issue).

In another study of sequential actions, Keller and Koch (2003) investigated how the planning of short music-like sequences is affected by response-effect compatibility. Participants were required to respond as quickly as possible to each of four arbitrary (color patch) stimuli by producing a unique sequence of three taps on three vertically aligned keys. Response effects consisted of tones that were triggered by the taps. Across a series of three experiments, the compatibility of the mapping between response location (key) and effect (tone) pitch was varied. Based on the assumption that there is a conceptual correspondence between pitch height and spatial height, response-effect mapping was manipulated to be either (a) compatible-taps on the top, middle, and bottom keys triggered high, medium, and low pitched tones, respectively; (b) incompatible-key-to-tone mapping was scrambled or reversed; or (c) neutral-taps on different keys triggered the same tone. Keller and Koch found that action planning was facilitated (i.e., RTs were fastest) by compatible response-effect mappings relative to incompatible and neutral mappings.

In that study, the authors also assessed the participants' level of musical experience to explore whether the role of anticipated response effects varies as a function of the stage of skill acquisition (i.e., level of experience) in the domain under investigation. It was found that the amount of the facilitative influence of response-effect compatibility increased with increasing musical experience, as evidenced by a clear positive correlation (about $r = 0.5$) between the magnitude of the compatibility effect and the number of years of formal musical training. Assuming that musical experts are so well trained that they can imagine their (musical) auditory action-effects (i.e., the music they play) more vividly than novices, this finding suggests that the functional importance of effect anticipation for the control of actions changes with skill acquisition. We return to this issue when we discuss implications for mental practice in sports.

Taken together, the above findings suggest, first, that action sequences are planned according to their anticipated effects, and, second, that such "ideomotor planning" is modulated by domain-specific expertise. Indeed, proficient ideomotor planning may be a hallmark of skilled performance.

Iring Koch, Peter Keller, & Wolfgang Prinz

CONCLUSIONS

We have reviewed recent research inspired by the ideomotor theory that proposes actions are controlled by the anticipation of their sensory consequences. The empirical studies strongly suggested the functional importance of anticipatory representations of action effects in both simple and sequential actions. However, the reviewed studies used experimental paradigms that clearly differ in terms of the functional role of effect stimuli. In S-R priming paradigms, the to-be-anticipated effect stimulus is itself presented as a stimulus to facilitate the associated movement, whereas, in the response-effect compatibility paradigm, the effect stimulus is presented as a response effect *after* response initiation, so that this paradigm appears to be able to demonstrate the role of mental representations of anticipated response effects in a more functional way as a mental cue to movement.

Apart from differences in the role of action effects in the experimental design, these studies have in common that the response-effects used are (in most cases) quite arbitrary, artificial stimuli (e.g., tones). Such artificial stimuli have the merit of easy experimental manipulability. With artificial effects, one might argue though that the ecological validity of such studies is a crucial issue, but it should be noted that the goal of many sports is to control a more or less artificial and distal action effect, like the trajectory of a ball in tennis, golf, or soccer, for example. Still, it is true that the goal of some sports, such as gymnastics, may lie primarily in more proximal (or intrinsic) movement effects, like the smoothness and elegance of a movement sequence. However, with respect to this issue, it is noteworthy that those studies that varied action effects in terms of sensory feedback that occur as a natural consequence of action execution - as in dual-task studies on ideomotor compatibility (Greenwald, 1972) or response-modality effects on sequence learning (Zirngibl & Koch, 2002) - the obtained data were entirely consistent with the ideomotor approach to action control. Taken together, the overarching conclusion from these recent studies inspired by ideomotor theory, is that action effects play a crucial role in performing and learning any movement skill (Wulf & Prinz, 2001, for review).

It is clear though that the theoretical fruitfulness of ideomotor theory to inspire empirical research should be expanded to research investigating the role of effect anticipation in more applied settings. One such applied field of research may be mental practice.

Mental practice can be defined as "the symbolic, covert, mental rehearsal of a task in the absence of actual, overt, physical rehearsal" (Driskell, Copper, & Moran, 1994, p. 481). Empirical research on the effectiveness of mental practice suggests that it has indeed positive effects on motor performance (for meta-analyses, see Driskell et al., 1994; Feltz & Landers, 1983). Importantly, the definition of mental practice implies that it actually consists of generating the mental "image" of the movement while suppressing motor execution. In fact, recent neurophysiological and brain-imaging research on motor imagery has obtained convincing evidence that imagining a movement activates cortical motor areas similar to those activated while actually performing this movement (Jeannerod, 1999; 2001). This apparent similarity in neural terms between imagined and executed movements led Jeannerod (2001) to conclude, "that covert actions are in fact actions, except for the fact that they are not executed" (p. S103). Thus, research on motor imagery has yielded results that strongly support

the proposal of ideomotor theory that imagining the sensory consequences of a movement directly functions to activate this movement itself. From a theoretical point of view, it is indeed extremely encouraging that this "ideomotor link" can apparently be used in applied settings to practice movement skills in situations that otherwise prevent the execution (i.e., the physical practice) of this skill, such as in motor rehabilitation after sport injury or neurological damage (e.g., Jackson, Lafleur, Malouin, Richards, & Doyon, 2001).

From the point of view of ideomotor theory, we presently see two issues that clearly invite more empirical research. The first issue refers to the role of degree of expertise with the respective movement skill for the impact of effect anticipation, and the second refers to the role of conscious awareness for effect anticipation.

With respect to the first issue, it seems to be an important observation that subjects in the study by Keller and Koch (2003) showed a stronger influence of the action-related compatibility of anticipated tone stimuli on planning a manual action sequence when they had a higher experience level with musical instruments. This observation suggests that practice with a skill makes the performer more sensitive to the produced action effects, so that they can imagine and anticipate these effects more vividly as well. This suggestion corresponds to the finding that, for example, the effect of mental practice for trampoline skills is stronger for experienced performers with vivid imagery than for relatively inexperienced performers (cf. Isaac, 1992). However, the results of meta-analyses appear to suggest that mental practice is equally sensitive in early and late stages of skill acquisition (cf. Feltz & Landers, 1983), and it even seems that inexperienced subjects can benefit from mental practice even more strongly than experienced subjects when the task has substantial cognitive components (Driskell et al., 1994). It thus appears that the potentially modulating influence of skill-specific experience level on the role of anticipated effects in action control still remains to be further clarified.

The second issue inviting for more empirical research relates to the role of conscious awareness for effect anticipation. Generally, ideomotor theory states that mental anticipation of the sensory effects of a movement tends to elicit this movement, but it does not specify whether this anticipation is necessarily a conscious process. The strongest view would be that the ideomotor linkage between effect representation and movement is strictly automatic, so that conscious awareness plays no role. However, the study by Zirngibl and Koch (2002) described earlier suggests that it does. In that study, it was found that sequence learning in a serial RT task was facilitated when subjects responded verbally, as compared with another group of subjects who responded manually. This difference in the learning effect is most likely due to differences in the distinctiveness and salience of the naturally occurring response feedback. But this difference in the learning effect was not found in those subjects who showed a significant behavioral learning effect but nevertheless did not explicitly notice the sequence (i.e., for which sequence learning was "implicit"). Put differently, the relative learning benefit of the verbal response group was dependent on subjects' conscious awareness of a repetitive sequence. Clearly, this potentially modulating role of sequence awareness for the influence of effect anticipation is not only a relevant research issue for motor learning in the serial RT task (see Hoffmann et al., 2001; Stöcker et al., 2003; Ziessler & Nattkemper, 2001) but relates to more general questions. For example, it is widely assumed that extended practice with a skill leads to "proceduralization," so that the skill can be executed rather automatically without

Iring Koch, Peter Keller, & Wolfgang Prinz

conscious guidance. At the same time, the empirical research discussed above seems to suggest that high experience level is associated with more vivid anticipation of action effects, which has been shown to improve performance. Thus, it appears to be an interesting empirical question for further research whether effect anticipations need to be consciously accessible in order for them to become functionally effective in the ideomotor control of action.

REFERENCES

- Adams, J. A. (1968). Response feedback and learning. *Psychological Bulletin*, 70, 486-504.
- Beckers, T., De Houwer, J., & Eelen, P. (2002). Automatic integration of non-perceptual action effect features: The case of the associative affective Simon effect. *Psychological Research*, 66, 166-173.
- Driskell, J. E., Copper, C., & Moran, A. (1994). Does mental practice enhance performance? *Journal of Applied Psychology*, 79, 481-492.
- Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 229-240.
- Elsner, B., Hommel, B., Mentschel, C., Drzezga, A., Prinz, W., Conrad, B., & Siebner, H. (2002). Linking actions and their perceivable consequences in the human brain. *Neuroimage*, 17, 364-372.
- Feltz, D. L., & Landers, D. M. (1983). The effect of mental practice on motor skill learning and performance: A meta-analysis. *Journal of Sport Psychology*, 5, 25-57.
- Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, 77, 73-99.
- Greenwald, A. G. (1972). On doing two things at once: Time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology*, 94, 52-57.
- Greenwald, A. G. (in press). On doing two things at once: III. Confirmation of perfect timesharing when simultaneous tasks are ideomotor compatible. *Journal of Experimental Psychology: Human Perception & Performance*.
- Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once: II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology*, 101, 70-76.
- Harleß, E. (1861). Der Apparat des Willens. *Zeitschrift für Philosophie und philosophische Kritik*, 38, 50-73.
- Hoffmann, J., Sebald, A., & Stöcker, C. (2001). Irrelevant response effects improve serial learning in serial reaction time tasks. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 27, 470-482.
- Hoffmann, J., Stöcker, C., & Kunde, W. (this issue). Anticipatory control of actions. *International Journal of Sport and Exercise Psychology*.
- Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research*, 59, 176-186.
- Hommel, B., Alonso, D., & Fuentes, L. J. (2003). Acquisition and generalization of action effects. *Visual Cognition*, 10, 965-986.
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action. *Behavioral & Brain Sciences*, 24, 849-937.
- Isaac, A. R. (1992). Mental practice — Does it work in the field? *The Sport Psychologist*, 6, 192-198.
- Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C., & Doyon, J. (2001). Potential role of mental practice using motor imagery in neurologic rehabilitation. *Archives of Physical and Medical Rehabilitation*, 82, 1133-1141.

Iring Koch, Peter Keller, & Wolfgang Prinz

- James, W. (1890). *Principles of psychology*. New York: Holt.
- Jeannerod, M. (1999). The 25th Bartlett Lecture: To act or not to act: Perspectives on the representation of actions. *Quarterly Journal of Experimental Psychology. Human Experimental Psychology*, 52A(1), 1-29.
- Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *Neuroimage*, 14, S103-S109.
- Keller, P. E., & Koch, I. (2003). *Action planning in sequential skills: Relations to music performance*. Manuscript submitted for publication.
- Knuf, L., Aschersleben, G., & Prinz, W. (2001). An analysis of ideomotor action. *Journal of Experimental Psychology: General*, 130, 779-798.
- Koch, I. (2003). *Mechanismen der Interferenz in Doppelaufgaben*. Manuscript submitted for publication.
- Koch, I., & Hoffmann, J. (2000). The role of stimulus-based and response-based spatial information in sequence learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 26, 863-882.
- Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory & Cognition*, 30, 1297-1303.
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility: A model and taxonomy. *Psychological Review*, 97, 253-270.
- Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception & Performance*, 27, 387-394.
- Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *Quarterly Journal of Experimental Psychology (A)*, 57, 87-106.
- Lien, M.-C., Proctor, R. W., & Allen, P. A. (2002). Ideomotor compatibility in the psychological refractory period effect: 29 years of oversimplification. *Journal of Experimental Psychology: Human Perception & Performance*, 28, 396-409.
- Lotze, R. H. (1852). *Medizinische Psychologie oder die Physiologie der Seele*. Leipzig: Weidmann'sche Buchhandlung.
- Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, 116, 220-244.
- Prinz, W. (1987). Ideo-motor action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 47-76). Hillsdale, NJ: Lawrence Erlbaum.
- Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, 9, 129-154.
- Rosenbaum, D. A., & Krist, H. (1996). Antecedents of action. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action, Vol. 2: Motor skills* (pp. 3-69). London, UK: Academic Press.
- Schmidt, R. A., & Lee, T. D. (1999). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human kinetics.

- Stöcker, C., & Hoffmann, J. (in press). The ideomotor principle and motor sequence acquisition: Tone effects facilitate movement chunking. *Psychological Research*.
- Stöcker, C., Sebal, A., & Hoffmann, J. (2003). The influence of response-effect compatibility in a serial reaction time task. *Quarterly Journal of Experimental Psychology*, 56A, in press.
- Wolpert, D. M., Gharamani, Z., & Flanagan, J. R. (2001). Perspectives and problems in motor learning. *Trends in Cognitive Sciences*, 5, 487-494.
- Wulf, G., & Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychonomic Bulletin & Review*, 8, 648-660.
- Ziessler, M. (1998). Response-effect learning as a major component of implicit serial learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 24, 962-978.
- Ziessler, M., & Nattkemper, D. (2001). Learning of event sequences is based on response-effect learning: Further evidence from a serial reaction task. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 27, 595-613.
- Zirngibl, C., & Koch, I. (2002). The impact of response mode on implicit and explicit sequence learning. *Experimental Psychology*, 49, 153-162.

ACTIONS FROM WITHIN

MARC JEANNEROD

Institut des Sciences Cognitives, Bron, France

ABSTRACT

This paper considers the nature of representations that precede the execution of an action. An analysis of the content of these representations is proposed by using classical tools of cognitive psychology, like introspection and mental chronometry. Their neural vehicle is described in normal subjects with neuroimaging methods and by clinical neuroscience methods like transcranial magnetic stimulation. The contribution of pathological conditions, such as paralysis and amputation, to the description of action representation is discussed. A general framework of motor simulation is proposed as a coherent explanation for the various types of action representation during motor imagery, motor decisions, and action observation. This framework is also used for interpreting the effects of mental training, learning by observation, and the use of neuroprosthetic devices in motorically handicapped people.

Key Words: action, representation, simulation, mental imagery, action observation, motor pathways, mental training, neuroprosthetic devices

This paper describes how actions can be generated from within. The term action refers here to a set of mechanisms that are aimed at producing activation of the motor system for reaching a goal. Our main hypothesis is that these mechanisms are largely independent from whether muscular contractions actually arise at the outset (i.e., whether the action is executed or not). An action can be overt and actually reach the intended goal; it may also remain covert, in the sense that it is not executed and the goal is not reached even though all the conditions for potentially reaching it are fulfilled.

The topic of covert actions has been a subject of considerable insight in the recent literature. Before describing the theoretical and empirical arguments which support the existence of covert actions, however, we will review some of the classical debates, which arose about whether actions need to be centrally represented before being executed.

Correspondence concerning this article should be addressed to Marc Jeannerod, Institut des Sciences Cognitives, 67 Boulevard Pinel, 69675 Bron, France; E-mail: Jeannerod@isc.cnrs.fr

A HISTORY OF CONCEPTS ABOUT MOTOR REPRESENTATIONS

The existence of mechanisms for generating endogenous actions (actions from within) was not always clearly accepted. The issue has been, and still is, at the core of a long-lasting debate between two schools of thought holding opposite conceptions. On the one hand, the "peripheralist school" holds that behavior is structured by the incoming flow of sensory information. Accordingly, the organism is considered as being mostly reactive to external events. Philosophically, this line of thought inherits from the classical empiricism, but its modern version is part of the conception held by the behaviorist psychology. In the domain of action, the influential contribution of Gibson (1979) seems to come close to this peripheralist view. Although, in Gibson's terms, information is "obtained" by the subject rather than "imposed" on him, his concept does not require the existence of a representation at the origin of an action (Gibson). The subject is merely conceived as an "ecological self" (Neisser, 1993), a receiver with little or no autonomy with respect to the external world.

The "centralist school," by contrast, holds that experience and knowledge grow from an internal content, which allows the subject to represent to himself goals for action. In other words, the subject is able to initiate spontaneous behavior independently from external stimuli. This theory was initially advocated in Germany by Wundt and the psychologists of the so-called Würzburg School who established the method of *systematic experimental introspection* for studying the organization of mental states (see Boring, 1957, for references). In its recent version, the centralist theory owes much to the study of cognitive development in young infants. Very soon after birth, babies show evidence of knowledge about elementary physical laws, temporal regularities, causal relationships, etc, which testify to the existence of an initial state largely independent from external stimuli (e.g., Spelke, Breinlinger, Macomber, & Jacobson, 1992).

In the domain of action, several models have been proposed to account for the endogenous organization of action. An early formulation of the concept of motor representation was that of *kinesthetic images*. According to this conception, previously executed movements left after them impressions or ideas of actions which, when properly reactivated, could lead to execution of new movements. According to early proponents of this view, the motor cortex was a repository of kinesthetic images ready to transfer the stored information to execution mechanisms. Similarly, Liepmann (1900) held the idea that *motor engrams* are stored in the cerebral cortex and become assembled for producing a desired action. More recently, the same concept of elementary bits of action (motor schemas) was used in different contexts, including psychology (Bartlett, 1926), neuropsychology (Shallice, 1988), artificial intelligence and robotics (Arbib, 1981).

Experimental results demonstrating the ability of humans and animals to generate actions without intervention of sensory afferences were reported by several authors. The observations made by Lashley (1917, 1951) for a human subject with a deafferented limb were quite influential under this respect; this subject was able, when blindfolded, to bring his anaesthetized limb at a predetermined position, hence demonstrating the possibility to build the movement endogenously. Experimentally deafferented monkeys (following a section of the dorsal roots innervating one arm; Bizzi, Kalil, & Tagliasco, 1971) were able to carry out accurate pointing arm movements toward a visual target. The entire structure of the movement

Marc Jeannerod

could be predetermined centrally, including, not only its initial ballistic phase, but also its low-velocity phase and its endpoint. These results were interpreted within the framework of a minimalist form of motor representation, the Equilibrium Point Model of Feldman (1966). In this model, the position of a joint is described as a single equilibrium point determined by the degree of stiffness (itself determined by a central command) of the muscles attached to that joint. A simple change in the equilibrium point generated by a new motor command produces a rotation of the joint to a new position of the limb.

The existence of elements of action (the above motor engrams or schemas) can also be demonstrated experimentally. In monkeys, single neurons in the premotor cortex are selectively activated during specific types of goal-directed hand actions. For example, a neuron will fire when the monkey executes a pincer grip for grasping a piece of food, not for another type of grip. Furthermore, the selectivity of the neuron for a particular type of grip may be retained irrespectively of the hand used by the animal, hence demonstrating the existence of a representation of the action of grasping an object in a certain way, hierarchically higher than the selection of the limb (the concept of motor equivalence) (Rizzolatti et al., 1988). Inactivation of limited cortical areas, e.g., in premotor cortex (Fogassi, Gallese, Buccino, Craighero, & Rizzolatti, 2001) or in the region of the intraparietal sulcus (Gallese, Murata, Kaseda, Niki, & Sakata, 1994), impairs this process of grip selection.

The phenomenon of action representation, however, extends far beyond the possibility to generating actions from within. It also includes the possibility to have mere ideas of actions, i.e., to generate representations of actions without executing them. It is indeed the central theme of this paper to describe the content and the mechanisms of these representations. Already in the second half of the 19th century, a popular theory, the Ideomotor Action Theory, postulated the existence of such ideas of action, which could even escape the voluntary control of the subject and directly cause unwilled actions. Curious phenomena, like table turning or automatic writing, were explained in this way. If, in normal conditions, all ideas of action did not yield immediate actions, it was because the subject was also thinking about not doing them, and the two ideas of doing and not doing counterbalanced each other (see Wegner, 2002). The neuropsychological literature offers clinical cases of patients with frontal lobe lesions, where this inhibitory mechanism fails and the patient is compulsively driven to perform the action of using objects put in his presence inappropriately, or imitating the examiner (the so-called utilization and imitation behaviors; Lhermitte, 1983).

Obsolete as it may be, the Ideomotor Action Theory anticipated several of the critical aspects of the theory of action representation as it will be detailed in this paper. First, it points to the existence of internal representations of actions, which may (or may not) cause actions to occur. This notion of a potentially causal relationship between a mental state and a behavior will be central to the present conception for mapping the content of the mental state onto the neural substrate of the behavior. Second, the Ideomotor Action Theory bridges the gap between ideas of action arising directly from the subject and those triggered by the observation of another agent, by stressing the many examples where watching somebody acting awakens a movement in the observer that accords with the movement he observes (Prinz, 1990). Finally, it points to the need for a parallel mechanism for inhibiting the ongoing transformation of an idea into a motor behavior, which will become central to the notion of covert actions to be developed here.

THE DISTINCTION BETWEEN THE CONTENT AND THE VEHICLE OF MOTOR REPRESENTATIONS

In this section, we will experimentally validate the notions of covert action and internal representations for actions. Our hypothesis thus postulates that covert actions are in fact actions in their own right, except for the fact that they are not executed. Covert and overt stages represent a continuum, so that every overtly executed action implies the existence of a covert stage, whereas a covert action does not necessarily turn out into an overt action. As will be argued below, most of the neural events which lead to an overt action already seem to be present in the covert stages of that action. One might even tentatively propose that a covert action includes everything that is involved in an overt action, except for the muscular contractions and the joint rotations. Even though this contention is factually incorrect, as we know that the musculo-articular events associated with a real movement generate a flow of reafferent signals which are not present as such in a covert action, it captures many aspects of the functioning of the representation.

THE CONTENT OF MOTOR REPRESENTATIONS

We will proceed in two steps. First, we will use experimental data drawn from behavioral experiments to describe the content of motor representations. For this purpose, we will use specific methods, partly based on introspection but also relying on changes of physiological variables, designed to access mental states related to actions but characterized by absence or paucity of overt behavior. One of the most extensively studied cases of these states is motor imagery, the ability to generate a conscious image of the acting self. Other cases will be examined as well, such as judgements about the feasibility of an action or perceptually based motor decisions, where no conscious image is formed. Finally, action representations arising in situations involving the participation of several selves, like those that are formed from the observation of actions performed by others, will also be investigated.

The second step will be to present an explanation for what could be the neural vehicle of these representations. Data drawn from experiments investigating brain activity during the representation of actions will be used for establishing the fact that represented (or covert) actions are simulated actions, i.e., that they involve the same mechanisms as those of the actions they simulate. The notion of simulated action will reveal a powerful tool for clarifying the role of represented actions in learning and rehabilitation.

THE CONTENT OF MOTOR IMAGES AND RELATED STATES

The importance of motor imagery for the study of representational aspects of action was already envisioned more than a century ago. Binet, for example, claimed that mental images in general resulted from excitation of the same cerebral centers as the corresponding actual sensation. In the domain of motor images, it was remarked that the state of the motor centers influenced the possibility to generate a motor image; for example, it was shown to be

Marc Jeannerod

impossible to generate the image of pronouncing the letter b if one kept the mouth wide open. Stricker explained that the motor system cannot be engaged in two contradictory actions at the same time (quoted in Binet, 1886, p. 80). Until quite recently, however, the field of motor imagery was far less developed than that of visual imagery. This difference may be due to the fact that in motor imagery, unlike in visual imagery, there is no clear reference to what the image can be compared; motor images are private events in the sense that they can hardly be shared (if at all) by the experimenter, whereas visual images refer to perceived scenes or objects which pertain to external reality and are common to other perceivers.

Like visual imagery, however, motor imagery can be studied using the classical methods of introspection and mental chronometry. These methods have revealed that motor images retain many of the properties, in terms of temporal regularities, programming rules and biomechanical constraints, which are observed in the corresponding real action when it comes to execution.

The representation of temporal regularities. Already in 1962, Landauer had noticed that thinking or mentally reciting a series of numbers took approximately the same time as saying it aloud. This fact suggested to him that the two behaviors may involve much the same central processes. Landauer's observation was consistently replicated since then. In an experiment where subjects had to walk either physically or mentally to prespecified targets, we found that the subjects took, on average, the same time to achieve the physical and the mental task. In the two conditions, the duration was found to increase with the distance covered (Decety, Jeannerod, & Prablanc, 1989; see Schott and Munzert, 2002 for a replication). Sirigu et al. (1996) using a task of reciprocal tapping of two targets separated by a varying distance, also reported a similar temporal scaling of movement duration to distance in both the physical and the mental conditions (see also Cerritelli, Maruff, Wilson, & Currie, 2000).

The representation of programming rules. In view of the above results, one should also expect that the difficulty of the motor task should influence the duration of the mental performance to the same extent as it does for actual execution. In physical execution, as expressed by the Fitts Law (Fitts, 1954), the duration of an accuracy-demanding task increases with the accuracy demands (e.g., when the target size decreases or the target distance increases). As early as 1987, Georgopoulos and Massey had designed a situation where Fitts Law appeared to apply also in mentally executed movements. They requested subjects to move a lever in a direction different from that indicated by a visual target: The instruction to the subject was that he should move the lever at a given angle with respect to the target. The result was that the duration of the reaction time before moving the lever in the requested direction was a function of the amplitude of the angle. The interpretation given by the authors was that the reaction time was a mental movement time spent to rotate the movement vector until it matched the direction of the mental target. The larger the angle, the more difficult the task and the longer the duration. We further tested this point for mentally executed actions in a virtual reality situation. Subjects were instructed to mentally walk through gates of different widths and positioned at different distances. The gates were presented within a virtual reality helmet which prevented the subject from referring to a known physical environment. Subjects had to indicate the time they started walking mentally and the time they mentally passed through the gate. In accordance with Fitts Law, mental movement times were found to be affected by the difficulty of the task, i.e., they

were longer for walking through a narrow gate placed at a farther distance (Decety & Jeannerod, 1996). In a recent replication experiment, Stevens (in press) had the subjects physically and mentally walking on wooden paths of different lengths and different widths. Again, the same tradeoff between movement duration and task difficulty was observed. In addition, when the subjects imagined the displacement of an object along the same paths (a visual, not a motor, imagery task), the duration of the imagined motion was a function of path length, but was not influenced by the path width. These findings support the view that functional rules which are specific to the planning of goal-directed actions, like Fitts Law, apply to both physically and mentally executed actions.

The encoding of biomechanical constraints. Another set of rules, which account for both the temporal and the spatial characteristics of goal-directed actions, are based on optimization principles that are thought to be represented within the motor system and to operate during execution. One typical example of such principles is the organization of the spatial trajectory of arm movements during the action of grasping. As shown by Rosenbaum and his group (e.g., Rosenbaum et al., 1990), the arm trajectories appear to be so organized as to minimize the discomfort of the final posture of the limb. In other words, the trajectory which is spontaneously selected for grasping an object will be the one that avoids extreme joint rotations and allows the most efficient posture of the hand for optimal object manipulation and use. In the situation described by Rosenbaum et al., the subject, using his right hand, was to grasp a horizontally placed bar with the instruction of placing either the right or the left end of the bar on a stool. The posture of the hand, which was used for grasping the bar, appeared to be conditioned by the instruction: An overhand posture was selected for placing on the right end of the stool, whereas an underhand posture was selected for placing on the left end. In a similar experiment by Stelmach, Castiello and Jeannerod (1994), but where the movement trajectory was recorded, the wrist rotation for placing the hand in the optimal position was found to be initiated very early in movement time, hence suggesting that the selection of the optimal position was made at the level of the representation of the action prior to its execution. The interesting point here is that grip selection in a task of mentally grasping a bar follows the same optimization rules as during real grasping. Johnson (2000) used a situation inspired by Rosenbaum et al., where the bar was presented at different orientations. He showed that the time required to select the grip (overhand vs. underhand) without executing the movement increased as a function of the angle at which the bar was presented, that is, as a function of the angular distance the subject's hand would have to cover to reach the selected posture via the shortest biomechanically plausible trajectory.

Similar findings were reported from experiments based on the concept of mental rotation. In the original experiment using this concept (Shepard & Metzler, 1971), subjects had to compare an object (the test object) presented at different orientations with another object (the reference object) presented in its canonical orientation. The response time to give the response (e.g., were the two objects same or different?) was a function of the angle of rotation of the test object. Parsons (1994) used a task where the subjects had to compare a test hand (right or left) presented on a picture at different orientations, with a reference hand presented upright. Unlike the rotation of abstract visual shapes, the response time for comparing the two hands was influenced by the biomechanical limitation of the rotation of the hand as a body part, as if the movement was physically executed. Along the same line, situations have been designed

Marc Jeannerod

where the subject is not requested to make a mental movement or a mental rotation, but has to make a prospective judgement about a potential action. An example of such a situation was described by Frak, Paulignan and Jeannerod (2001): The subjects were simply requested to determine the feasibility of grasping an object placed at different orientations, some of which afforded an easy grasp and others an awkward one. Again, the response time was a function of the orientation of the object, suggesting that the subjects unknowingly simulated a movement of their hand in an appropriate position before they could give the response. This interpretation is supported by the fact that the time to make this estimate was closely similar to the time taken to physically reach and grasp an object placed at the same orientation (Frak et al., 2001; see also de Sperati and Stucchi, 1997). Finally, merely inspecting graspable objects and tools, or even pictures of them (but not the picture of other object types, like a house or a car) seems to elicit in the observer the covert action of using them. For example, the time taken to determine whether an object can be grasped by the right or the left hand is influenced by the orientation (right or left) of that object. Response times for either hand and orientation are consistent with the classical compatibility effects (Tucker & Ellis, 1998).

The above described situations of grip selection, mental rotation, or decision about feasibility of an action, depart from the canonical motor mental imagery. In these situations, in contradistinction with motor imagery proper, no conscious image is formed and no explicit strategy is used. This indicates that the subject is actually simulating the potential action and that the response time correlates with factors that pertain to the motor execution, in spite of the subject not being asked to mentally perform the action. Covert actions, which retain characteristics of executed movements, like speed-accuracy tradeoff and optimization of biomechanical limitations, seem to be in direct continuity with the implicit preparation processes that take place prior to execution. This point will be detailed in a further section, where the anatomical and functional vehicle of motor representations will be investigated.

THE CASE OF MOTOR REPRESENTATIONS INDUCED BY ACTION OBSERVATION

It is a common experience to any of us that even a brief exposure to the behavior of another person is sufficient for generating an accurate imitation of this behavior. This simple remark indicates that an action observed from another person can be understood and represented as a potential action by the observer. Little is known about the content of action representations created from observation of actions performed by other persons. This ability implies that actions produced by biological systems represent a special type of visual pattern. This pattern reflects the representation from which the action proceeds. Accordingly, a biological action is perceived and recognized as such, because its perception is constrained by the implicit knowledge that the central nervous system has concerning the movements that it is capable of producing. In other words, there is a central representation of what a biological movement should be, and this representation influences visual perception (Viviani, 1990). As an example of the role of motor constraints in shaping action perception, consider the perceptual effect produced by fast sequential presentation of pictures of an actor with an arm at two different postures. This alternated presentation is perceived as a continuous apparent movement between the two arm postures. If, however, the presentation of the two postures is such that the movement would be impossible (e.g., because the arm should go across another body

part), then the apparent movement is perceived going around and not across the obstacle. This striking effect (Shiffrar & Freyd, 1990) reflects the implicit representation built from visual perception of motion when it refers to a biological origin. Obviously, this is not to say that a robot could not be programmed for accurately reaching a goal by using movements which would violate the biomechanical constraints of a real arm: These movements would look "unnatural" and would not match the internal representation that a human subject has of an intentional movement.

THE NEURAL VEHICLE OF MOTOR REPRESENTATIONS

The assumption developed in this section is that imaging or observing a movement relies on the same mechanisms as actually performing it, except for the fact that execution is blocked. This assumption generates a specific prediction, namely, that one should find in motor imagery and related phenomena physiological correlates similar to those measured during real action. A schematic flow chart of the neural mechanisms involved in motor representations can be seen in Figure 1.

Figure 1. A highly schematic flow diagram of action representations.

On the left hand side of the diagram two possibilities are represented for generating an internal representation of an action, e.g., either by observing the action performed by another agent, or by intending an action oneself. The corresponding information is processed by a set of mechanisms for assembling the elements of the action (schemas) according to an internal model. The box which includes these mechanisms is labeled PAR, for parietal lobe. The hypothesis that posterior parietal areas are involved in this process is justified by a vast amount of experimental and clinical work, not detailed in this paper (see Jeannerod, 2001, for review).

Marc Jeannerod

Further steps of processing include premotor cortex (PM) and primary motor cortex (M1). Premotor cortex is known to be densely connected with parietal areas. The role of the premotor-parietal loop is to shape the motor program of the to-be-executed action according to the specifications of the earlier processing stages. The role of M1 is to make possible the execution of the program by generating motor commands compatible with the constraints of the musculoskeletal system. M1 involvement, not only in overtly executed actions, but also in covert actions, is attested by experimental data showing its increased activity (as well as an increased excitability of the corticospinal pathway) during represented actions. The back connection between M1 and parietal lobe is not meant to be a direct connection: it refers to signals sampled from the output of M1 (efference copies). The role of these signals is to influence the selection of schemas according to the constraints of execution. Note that all these mechanisms are included in a larger box labeled SIM, for simulation. Mechanisms within the SIM box correspond to the covert stages of actions. They are meant to be common to both represented actions and executed actions (the concept of shared representations, see text). The distinction between types of representations (e.g. from observed or self-intended actions) can be made by monitoring the mechanisms shown on the left hand side of the diagram, which are specific to each type. The distinction between represented and executed actions can be made by monitoring signals (e.g., visual, proprioceptive) arising from movement execution. The inhibition that blocks the output of the simulation process and prevents motoneuron firing during covert actions is of unknown origin (but see text). The fact that the simulation process involves most of the stages of execution (including the cerebellum) directly explains the influence of action representations on further execution (mental training). Finally, not represented here are the mechanisms responsible for the vegetative changes related to action preparation. Because they are not inhibited, these changes can be seen as a reflection of the covert stages of actions.

CHANGES IN PHYSIOLOGICAL VARIABLES RELATED TO SIMULATED EFFORT

In our experiment on the duration of mentally walking to targets at different distances (Decety et al., 1989), we tested whether mental-walking time remained constant for different levels of effort involved in performing the task. We found that, in the physical condition, normal subjects loaded with a weight (25 kg) on their shoulders took the same time walking to targets as when they were with no load. Subjects achieved this by spontaneously programming greater muscular force in the loaded task (e.g., Gottlieb, Corcos, & Argawal, 1989). However, when the loaded subjects imagined walking to the targets, the mental time increased by up to 30% with respect to the unloaded condition. This surprising result was later confirmed in a task of mentally pointing at targets of different widths with a hand-held stylus loaded with a 2-kg weight (Cerritelli et al., 2000). Not only did this experiment replicate the typical relationship of mental-movement time to target width; it also showed that mental movement time in the loaded condition was longer than in the unloaded condition by about 30%.

Although the interpretation of this result remains unclear, it suggested to us that muscle force was indeed encoded at the representational level. More precisely, it suggested that this encoding should reflect in physiological variables normally involved in adaptation of the organism to an increase in metabolic demands during muscular effort. Our hypothesis was

that the autonomic system responsible for heart and respiration adaptation to effort, not submitted to voluntary control, should present visible changes during motor imagery involving graded changes in mental effort. Earlier work in the field of physiology of exercise has revealed the existence of a central patterning of vegetative commands during preparation to effort: Heart and respiration rates show an almost immediate increase at the onset of exercise, or even prior to exercise (Adams, Guz, Innes, & Murphy, 1987; Krogh & Lindhart, 1913). As this effect precedes the increase in muscle metabolism, it can only be due to central commands anticipating the metabolic change. Similarly, situations where the level of motor command can be manipulated but where muscular exercise is maintained constant, demonstrate the existence of a central activation of the autonomic system (Goodwin, McCloskey, & Mitchell, 1972; for a review, see Requin, Brener, & Ring, 1991). During motor imagery of running at an increasing speed (Decety, Jeannerod, Germain, & Pastene, 1991) or pedaling at an increasing rate (Decety, Jeannerod, Durozard, & Baverel, 1993), we found highly consistent changes in heart and respiration rates, which correlated with mentally represented force (see also Beyer, Weiss, Hansen, Wolf, & Siebel, 1990; Wang & Morgan, 1992; Wuyam et al., 1995). In our experiment, the mean increase in heart rate during mental simulation of running or pedaling at the maximum speed was about 30% above the resting rate, to be compared with a mean increase of about 50% during the corresponding physical effort. Respiration rate also increased during mental simulation, to an even higher rate than during the corresponding physical effort. The absence of muscular activity during mental simulation was verified by measuring end-tidal PCO₂ and anaerobic muscle metabolism (using NMR spectroscopy). Autonomic activation during this condition thus pertains to the same phenomenon of central activation as that observed during preparation to action. An additional argument in this direction is provided by an experiment of Gandevia et al. (1993). They observed graded cardiovascular changes in artificially paralyzed subjects attempting to produce muscular contractions at different intensities. As paralysis was complete, these changes could not be due to residual muscular activity and had to be of a central origin.

Other forms of action representation also involve central activation of the autonomic system. Consider a situation where an immobile subject is requested to observe a scene where an actor performs a running exercise at different speeds. As shown by Paccalin and Jeannerod (2000), the respiration rate of the observer increased while he was watching the actor. Furthermore, the respiration rate of the observer correlated with the amount of effort produced by the actor (e.g., the respiration rate is higher during observation of the actor walking at 7 km/h than at 2.5 km/h). This finding puts close to each other motor imagery and action observation, as two situations where physiological mechanisms related to real actions are activated in the absence of motor execution.

CHANGES IN EXCITABILITY OF THE MOTOR PATHWAYS

Measuring the changes in excitability of the motor pathways during various forms of action representation can also provide further cues on the involved mechanisms. Indeed, it is a frequent finding that some degree of background electromyographic activity (EMG) persists in the muscular groups involved in the simulated action (e.g., Gandevia, Wilson, Inglis, & Burke, 1997; Jacobson, 1930; Wehner, Vogt, & Stadler, 1984). This finding suggests that during

Marc Jeannerod

motor imagery, motor commands to muscles are only partially blocked, and that motoneurons are close to firing threshold. Bonnet, Decety, Requin and Jeannerod (1997) confirmed this point by measuring spinal reflexes during motor-imagery tasks. They instructed subjects to either press isometrically on a pedal, or mentally simulate the same action. Two levels of strength (weak and strong) were used. The H-reflexes in response to direct electrical stimulation of the popliteal nerve and the T-reflexes in response to a tap on the soleus tendon were measured. Both types of reflexes increased during mental simulation, and this increase correlated with the force of the simulated pressure (see also Gandevia et al., 1997).

The excitability of the corticospinal pathway was also extensively tested in several experiments using transcranial magnetic stimulation (TMS). This method allows to measure the amplitude of motor evoked potentials (MEPs) produced in the muscles involved in mental simulation of an action, by a magnetically induced electrical stimulus applied to the corresponding area of the contralateral motor cortex. Authors consistently found a specific increase of MEPs in those muscles involved in an imagined task, e.g., in the flexor muscles during imagination of hand closure, whereas no such increase was found in the antagonist extensor muscles (Fadiga et al., 1999; Hashimoto & Rothwell, 1999; Rossini, Rossi, Pasqualetti, & Tecchio, 1999).

Not surprisingly, very similar results were obtained when MEPs were measured during the observation of actions. In this situation, where the subject is instructed to watch an actor, the MEP increase is also restricted to the muscle group involved in the observed action (e.g., the action of grasping an object; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). Interestingly, the effects of observation are not limited to the visual domain. Fadiga and his colleagues were able to show that listening to specific phonemes increases the excitability of the motor pathway to the relevant tongue muscle (Fadiga, Craighero, Buccino, & Rizzolatti, 2002). Finally, Baldissera, Cavallari, Craighero, and Fadiga (2001) found changes in upper limb H-reflexes during observation of finger flexion or extension.

These results add support to the view that the motor system is involved during different types of mental representation of actions. Indeed, in a recent study, Clark, Tremblay and Ste-Marie (2004) were able to compare MEP amplitude in the same subjects during explicitly imaging, observing, and physically executing the same hand gestures. They found that observation and imagery conditions led to a similar facilitation in MEP amplitude in the relevant hand muscle. In addition, during action observation, a condition of "active" observation (i.e., with the instruction to subsequently imitate) yielded larger MEPs than a purely passive observation. Although MEP facilitation was weaker during action representation than during physical execution of the same action, it clearly calls for a unitary mechanism based on action simulation. This point will be developed further in another section.

CHANGES IN BRAIN ACTIVITY: THE FUNCTIONAL ANATOMY OF MOTOR REPRESENTATIONS

In view of the results demonstrating the activation of the physiological correlates of action execution during action representation, the next logical step is to examine the level of the motor command itself. Neuroimaging techniques have greatly contributed to this

understanding by describing the functional anatomy of those purely mental states devoted to the representation of action. Following the pioneer papers by Ingvar and Philipson (1977), and Roland, Skinhoj, Lassen, and Larsen (1980), showing changes in regional cerebral blood flow during mental imagery, the pattern of cortical activity during both motor imagery and action observation has been extensively investigated. For the purpose of the present review, however, we shall concentrate on changes occurring within the motor system. The main reason for this choice is that activation of the motor pathways is directly relevant to the simulation theory that will be fully developed in the next section as an explanatory framework for action representation.

Many studies, using functional brain imaging by magnetic resonance (fMRI), reported activation of sensorimotor cortex during motor imagery (Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Kim, Jennings, Strupp, Andersen, & Ugurbil, 1995; Leonardo et al., 1995; Lotze et al., 1999; Porro et al., 1996; Roth, Decety et al., 1996). Typically, M1 activation is not consistently found in every subject and, when present, is less intense than during motor execution of the same movement (Hanakawa et al., 2003). The activated zone overlaps that activated during execution, with the same voxels involved in the two conditions (e.g., Porro et al., 1996). The involvement of M1 during motor imagery can also be detected with the magneto-encephalographic (MEG) technique; in this case, the activity of the motor cortex is inferred from a specific change in cortical activity (suppression of the 20-Hz rebound induced by a peripheral nerve stimulation), which is observed in the precentral gyrus during manipulative finger movements, during motor imagery of the same movements (Schnitzler, Selenius, Salmelin, Jousmäki, & Hari, 1997), and also during observation of an actor moving his fingers (Hari et al., 1998). These MEG findings represent a direct demonstration of the existence of a cortical system for matching execution, imagination, and observation of the same movements (see also Cochin, Barthelemy, Roux, & Martineau, 1999).

Experiments reporting activation of primary motor cortex during action representation (like those reporting increased corticospinal excitability) fall under the critique that the observed changes might reveal incomplete inhibition of action or incomplete relaxation of motor activity during the mental process of imagination. In fact, this critique can be ruled out by other findings showing primary motor cortical activation during imagined movements in subjects with an amputated or a paralyzed limb. Ersland et al. (1996) found an increased metabolic activity in the contralateral primary motor cortex in a subject performing imaginary finger tapping with his amputated right hand. Lotze, Flor, Grodd, Larbig, and Birbaumer (2001) found in amputees with impressions of phantom limbs that imagination of moving the phantom hand produced an activation of the contralateral motor and somatosensory cortex that was higher than that produced by imagination of hand movements in control subjects. Brugger et al. (2000) report the striking observation of a woman born without limbs, who presented strong sensations of phantom limbs. Although these sensations did not elicit activation of sensorimotor cortex (only premotor and parietal cortices were activated bilaterally), they were increased by stimulation of sensorimotor cortex by TMS.

These observations raise a key question: Are motor images in amputees represented actions to the same extent as they are in normals, or are they real actions? (i.e., if the muscles were still there or were still connected, would they contract?) This is an almost impossible question.

Marc Jeannerod

One could argue that the difference between the two situations is that motor images involve an inhibitory process, whereas blocked movements do not. Thus, in principle, one should be able to detect (by inspecting the activation pattern during a motor imagery task) whether the inhibitory process is present or not: If yes, then this would mean that the subjects are generating a genuine motor image; if not, that they are simply attempting to perform a movement in spite of the absence of the effector. In the latter case, however, one wonders why there should be an inhibitory process if there is no need to block the output.

THE CONCEPT OF SHARED REPRESENTATIONS

The description of the (motor) brain activity during action representation strongly suggests that the same areas are involved during different types of representations. Consciously evoking a motor image, making an evaluation of the feasibility of a movement, or observing an action performed by somebody else, to name only a few, result in a closely similar activation pattern. In addition, this same activation pattern is also recorded during execution of the corresponding action. In other words, the neural correlates of representing an action are shared by different types of representations. A dramatic illustration of this concept of shared representation is offered by the finding of mirror neurons (e.g., Rizzolatti, Fadiga, Gallese, & Fogassi, 1995). Mirror neurons were identified in the monkey premotor cortex. They are activated in two conditions: First, they fire when the animal is involved in a specific motor action, like picking a piece of food with a precision grip; second, they also fire when the immobile animal watches the same action performed by an external agent (another monkey or an experimenter). In other words, mirror neurons represent one particular type of action, irrespective of the agent who performs it. At this point, it could be suspected that the signal produced by these neurons, and exploited by other elements downstream in the information processing flow, would be the same for an action performed by the self and by another agent: The two modalities of that action (executed and observed) would thus completely share the same neural representation. In fact, other premotor neurons (the canonical neurons) and presumably many other neuron populations as well, fire only when the monkey performs the action and not when it observes it from another agent. This is indeed another critical feature of the shared representations concept: they overlap only partially, and the non-overlapping part of a given representation can be the cue for attributing the action to the self or to the other.

A mechanism similar to the mirror neurons operates in humans. Brain activity during different conditions where subjects were self-representing actions (e.g., executing and imagining actions, inspecting tools, or observing actions performed by other people) was compared (Buccino et al., 2001; Chao & Martin, 2000; Decety et al., 1994; Decety et al., 1997; Grardin et al., 2000; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Hanakawa, et al., 2003; Rizzolatti et al., 1996). The outcome of these studies is twofold. First, there exists a cortical network common to all conditions. As shown in the preceding section, the motor cortex is part of this network, which also includes cortical areas located in the superior and inferior parietal lobules, the ventral premotor cortex, and the SMA. Second, motor representations for each individual condition are clearly specified by the activation of cortical zones which do not overlap between conditions (Grardin et al., 1999; Grzes & Decety, 2001; Jeannerod, 2001).

THE PROBLEM OF ACTION INHIBITION DURING THE REPRESENTATION OF ACTIONS

The comparison between the autonomic and the motor systems during action representation reveals that, whereas activation of the former leads to changes at the level of peripheral effectors, this is not the case for the latter, hence suggesting the existence of a specific inhibition opposing muscular contraction. Classical authors, within the framework of the Ideomotor Action Theory (see above), have speculated that an idea of action was not always transformed into action because an active suppression process opposed the spontaneous tendency to move. Considering the body of data about the activity of the motor system during covert actions, there are two possible explanations for this absence of motor output. The first interpretation postulates that the transfer of the motor engrams elaborated within premotor or supra-motor cortical areas (e.g., dorsal and ventral premotor cortex, parietal cortex) to motor cortex would be blocked by a central inhibitory mechanism. The prefrontal cortical areas, which are found to be active during motor imagery (e.g., Decety et al., 1994), could represent a possible locus for this behavioral inhibition. An observation by Marshall, Halligan, Fink, Wade, and Frackowiak (1997) of a patient with a hysterical paralysis of the left side of the body lends support to this possibility. Although in this patient a normal activation (mapped with PET) of the left sensorimotor cortex was observed during movements of the right "good" leg, no such activation was observed on the right side during unsuccessful attempts to move the left "bad" leg. Instead, the right anterior cingulate and orbitofrontal cortices were significantly activated. This result suggests that these prefrontal areas exerted a state-dependent inhibition on the motor system when the intention to move the left leg was formed. This point was specifically investigated by Brass, Zysset and von Cramon (2001a) in a neuroimaging experiment in normal subjects. Subjects were instructed to perform finger movements while they were observing another person executing either congruent or incongruent movements. When the observed movements were incongruent with respect to the pre-instructed ones, the subjects had to inhibit their spontaneous tendency to imitate the movements of the other person. This task resulted in a strong activation of the dorsolateral and frontopolar areas of prefrontal cortex. This finding seems to be in line with the earlier clinical observations in patients with prefrontal lesions, who compulsively imitate actions performed in front of them (Lhermitte, 1983). This hypothesis of a cortico-cortical "disconnection," however, is not compatible with the simple fact that motor cortex remains activated during action representation. A possible interpretation for the data could be that prefrontal cortex is involved, not in inhibiting the execution of represented actions, but rather in a process of selecting the appropriate representation. While executing a pre-instructed action incompatible with an observed one, one has to select the endogenous representation and to ignore the one arising from the outside, or in other words, to prevent oneself from being distracted by an external event. This is indeed what frontal patients cannot do.

To account for the empirical data showing the involvement of motor cortex, the inhibitory mechanism must therefore be localized downstream to motor cortex, possibly at the spinal cord or brainstem level. A tentative hypothesis could be that a dual mechanism operates at the spinal level. The sub-threshold preparation to move reflected by the increased corticospinal tract activity would be paralleled by an inhibitory influence for suppressing the overt movement. The posterior cerebellum may play an important role in this inhibitory process (Lotze et al., 1999). Whereas during action execution, the activated cerebellar areas are

Marc Jeannerod

located in anterior and lateral regions, those activated during imagery and action observation are located in the posterior cerebellum (Grafton et al., 1996; Parsons et al., 1995). A similar explanation, but suggesting a different site for inhibition, was put forward by Prut and Fetz (1999) to explain motor inhibition in the monkey while the animal is waiting for execution of a learned action. They showed that, during the waiting period where the monkey is ready to move, spinal interneurons are activated, hence indicating that the spinal motor network is being primed by the descending cortico-motoneuronal input. Because the overt movement was suppressed during this period, Prut and Fetz hypothesized a superimposed global inhibition possibly originating in premotor cortex, and propagating to the spinal cord in parallel to the excitatory input. This hypothesis would account for both the increased motoneuron excitability and the block of muscular activity which are observed during action representation.

THE SIMULATION HYPOTHESIS AND ITS IMPLICATIONS

WHAT IS IMPLIED BY THE CONCEPT OF SIMULATION?

The simulation hypothesis is a rather broad framework accounting for the relationship of mental phenomena to the activity of the neural substrate. Its empirical basis accumulated from experiments in cognitive neuroscience in the last two decades. One of the most influential results was that visual mental images were found to rely on activation of the early stages of information processing of the visual system. Primary visual cortex is consistently involved in visual mental imagery (Kosslyn et al., 1993; Le Bihan et al., 1993), with an additional selective involvement of inferotemporal cortex during imagery of visual objects and occipitoparietal cortex in visual spatial imagery (see Farah, 1994). The explanation put forward for an activation of low-level processing areas during a high-level cognitive activity like mental imagery is that activation of topographically organized areas, like V1, is needed for replacing the image within a spatial frame of reference. Higher order areas, because they lack topographical organization, would not be able, by themselves, to achieve this task. In other words, the process of visual imagery would have to follow the same processing track as visual perception for giving an image its spatial layout, a process which requires the participation of V1.

This reasoning can be extended to the domain of action representations. If the assumption that represented actions correspond to covert, quasi-executed actions, is correct, then represented actions should involve the mechanisms that normally participate in motor execution. In the above sections, a number of data which satisfy this proposition have been reviewed. Motor images involve neural structures like motor cortex, premotor cortex, basal ganglia, and cerebellum, because this is where the aspects of action related to execution are normally processed. In other words, the mental content of motor images is what it is because the neural correlates include the structures required for execution. But this reasoning leads to another point, which can be set as a question: If motor images are non-executed actions, why should they involve the activation of executive neural structures? This question can only be answered partially, because the precise function of neural structures activated during action representation is incompletely known. However, because primary motor cortex is the final link

to the motoneuron level, its activity must reflect the content of the motor commands. During execution, these motor commands encode the muscular addresses for producing the action, the muscular force to be applied, the biomechanical limitations of the movements to be taken into account for reaching the final endpoint postures and for optimizing the trajectory dynamics, etc. Thus, by analogy with activation of primary visual areas in visual mental imagery, which is thought to restore the topographical layout of the image, it could be proposed that activation of motor areas (including M1) in motor representation is needed for providing the represented action with a "motor" format. In other words, in order for a represented action to be felt as a real action, it needs to be framed into the constraints which are those of a real action.

This proposition seems even easier to fulfill for action representations originating from observed actions. In that case, the simulation must provide a frame to the perception of the action: the observer understands the action he sees to the extent he can simulate it. In order for the perception to be veridical, the simulation must be complete and must involve all the aspects of the observed action. A mere visual perception, without involvement of the motor system, would only provide a description of the visible aspects of the movements of the agent; but it would not give precise information about the intrinsic components of the observed action which are critical for understanding what the action is about, what is its goal, and how to reproduce it.

Thus, the present simulation theory departs from other versions where the simulation process is conceived as a conscious reactivation of previously executed actions stored in memory (e.g., Decety & Ingvar, 1990). According to our view, motor representations, like executed actions, are automatically assembled in response to immediate task requirements and do not depend on memory (Jeannerod, 1994, 1997, 2001). Even though this process may have a conscious counterpart (one can consciously generate a motor mental image), most of its generation is opaque to the subject. As shown in the previous sections, many aspects of the content of motor images are only known by the experimenter (e.g., through measurements of response times), but not by the subject.

A final point concerning the simulation theory deserves discussion, namely, the need to draw a clear boundary between the simulation theory as exposed here and other hypotheses using the same terminology. The notion of simulation has already been used in a different framework, that of the Theory of Mind. The Theory of Mind is said to be an attribute of normal human subjects aged more than 3-4 years, which they use to understand each other's minds. This mind-reading ability has been conceptualized in two different ways. First, a subject may use a set of rules to attribute mental states to others, and to judge what these states are (the "theory-theory" version of the Theory of Mind). Alternatively, a subject can simulate within his own mind the mental states he deciphers from others and experience these mental states by himself. In the present context, the observed action would activate, in the observer's brain, the same mechanisms that would be activated, were that action intended or imagined by the observer (e.g., Gallese & Goldman, 1998). This simulation version of the Theory of Mind is distinct from the simulation theory that is being described here. First, the simulation version of the Theory of Mind is limited to understanding mental states observed from other people. Second, within this category, it has a much broader scope than the present simulation theory:

Marc Jeannerod

It includes the understanding of others emotions, desires, expectations (i.e., mental states that are not necessarily related to action per se). The type of action simulation that we are dealing with here is not limited to communication between individuals (e.g., to understanding actions performed or intended by others), it is also and mainly supposed to account for the broad phenomenon of action representation, including one's own actions. The complete set of arguments for disentangling the present simulation theory from that used in the field of agency and self-identification can be found in Jeannerod and Pacherie (2004).

IMPLICATIONS OF THE SIMULATION THEORY

MENTAL TRAINING

The strong relationships of motor imagery to the neural substrate lead to the logical expectation that the central changes produced in the motor system during imagery should affect subsequent motor performance. The sport psychology literature in the early 1960s offers a large number of studies reporting measurable effects of mental imagery on subsequent motor performance (for review and meta-analysis, see Driskell, Cooper, & Moran, 1994; Feltz & Landers, 1983). The so-called "mental training" has been shown to affect several aspects of motor performance normally thought to be specific outcomes of training, such as the increase in strength of muscular contraction (Yue & Cole, 1992), improvement in movement speed (Pascual-Leone et al., 1995), reduction of variability and increase in temporal consistency of movements (Vogt, 1995).

Among the explanations proposed for these phenomena, several have favored the role of cognitive factors. For example, mental training could modify perceptual organization and provide a new insight of the action to be performed (for a review of these explanations, see Johnson, 1982). However, the present simulation theory of action representation seems to provide a more accurate explanation for the effects of mental training. Accordingly, it can be postulated that the efferent discharges generated during mental training by the simulation process, by rehearsing the motor pathways, represent the substrate for subsequent facilitation of motor performance. This explanation is strongly supported by experimental data. Pascual-Leone et al. (1995) used TMS to evaluate the changes in cortical excitability during mental training of finger movements. They found that the size of the excitable area devoted to finger increased as movements were repeated over training periods. The increase in the size of the excitable area produced by imaging training was similar to that obtained during physical training. More recently, Lafleur et al. (2002) showed that learning a motor task by using motor imagery induces a pattern of dynamic changes in cortical activation similar to that occurring during physical practice. In both conditions, a first phase is observed with increase in activity in the premotor cortex and the cerebellum. Subsequently, this activation tends to disappear and to be replaced by activation in the basal ganglia and prefrontal cortex (in the orbitofrontal and anterior cingular regions).

The simulation interpretation of the effects of mental training is confirmed by recent experimental evidence showing that subjects can learn to voluntarily increase the degree of activation of their motor cortex during an imagined manual action (DeCharms et al.,

2004). During the training period, subjects first receive ongoing information about the level of activation of their motor cortex, via a continuously updated fMRI signal taken from the cortical motor area. Subsequently, they are able to increase this level of activation without recourse to the feedback signal. According to DeCharms et al., this procedure yields a level of activity in the sensorimotor cortex similar to, or higher than, during actual manual action. Obviously, this type of result showing the possibility to increase at will the activity in a specific brain area, opens a number of potential applications for designing new training techniques, not only in the domain of action, but also in the realm of the control of behavior in general. Rehabilitation procedures for motor impairments should greatly benefit from this possibility.

COUPLING MOTOR REPRESENTATIONS WITH NEURO-PROSTHETIC DEVICES

We have shown evidence that represented actions simulated real actions. More specifically, represented actions involve the orderly activation of the same neural structures that would be involved if the actions were actually executed (the definition of action simulation). Following this line of thought, it seems logical to assume that, if neural activity in the motor areas of a subject imagining a movement could be properly monitored and coupled to an appropriate device, the imagined movement would become visible. This conjecture is the basis for building hybrid brain-machine interfaces that could be used to control artificial devices, with the ambition to substitute deficient motor function in patients with severe motor disabilities or paralysis (e.g., Cincotti, et al., 2003; Mehring et al., 2003; Nicolelis, 2001). Recent work has shown that a monkey can be trained to move a spot on a computer screen just by "thinking" on the displacement of the spot. In the experiment (Serruya, Hatsopoulos, Paninski, Fellows, & Donoghue, 2002), the monkey was implanted with an electrode for recording the activity of a small neuronal population in area M1 controlling the animal's arm movement. The monkey first used a manipulandum for displacing a spot on the computer screen. Then the connection between the manipulandum and the computer was replaced by a connection between the output of the microelectrode and the spot: the monkey immediately used the neural-activity-based signal to carry out the task without any further training. During this time, the animal made intermittent arm movements, or no arm movements. The importance of this finding is twofold. Not only does it show that non-human primates, like humans, can generate motor representations that have properties similar to real actions; it is also of a high potential value for designing rehabilitation procedures. The fact that human subjects can learn to increase their cortical activity at will (DeCharms et al., 2004) indicates that it will become possible to train patients to learn to operate neuro-prosthetic devices and to recover by this way part of their motor autonomy.

LEARNING BY OBSERVATION AND IMITATION

There is a wealth of data in the literature, showing that observing a movement facilitates the execution of that movement by the observer. Brass, Bekkering and Prinz (2001b), for example, noticed that the execution of pre-instructed finger movements is influenced by the observation of another person performing compatible or incompatible finger movements. If the

Marc Jeannerod

movements performed by the observer are compatible with those performed by the other person, they are clearly facilitated (e.g., their reaction time is shorter). Conversely, incompatibility of the movements of the observer with those of the other person yields to degraded performance (see also Kilner, Paulignan, & Blakemore, 2003). Craighero, Bello, Fadiga, and Rizzolatti (2002) also found that observing pictures showing hand postures facilitates the execution of a grasping hand movement when the observed posture is congruent with the executed movement. The facilitation effect is not obtained if the observed movement is performed by a robotic hand instead of a human hand (Tai, Scherfler, Brooks, Sawamoto, & Castiello, 2004). These data stress the point that observing the performance of another person facilitates the formation of effector-specific motor representations. According to Sebanz, Knoblich, and Prinz (2003), simply observing the action at the disposal of another person creates in the observer a representation of that action: this representation facilitates the execution of the action by the observer. As for the action representation created during motor imagery, those which result from action observation seem to include information related to action execution. This is suggested by a series of experiments by Knoblich and his coworkers. Knoblich and Flach (2002) presented subjects with videos of an action (throwing darts) that these subjects had previously performed, and videos of the same action performed by other subjects. The subjects' task consisted in predicting the accuracy of the observed actions. Prediction was better when subjects observed their own actions than when they observed another person's actions. Thus, the observation of self-generated actions is more informative, because the mechanism that simulates the observed action is the same as that which produced it. These data represent a basis for the widespread phenomenon of learning by observation. Heyes and Foster (2002), for example, found that subjects watching an experimenter performing a sequence of movements can learn the sequence as efficiently as when practicing the task themselves.

These findings may have interesting implications in the domain of pathology. In patients with limb amputation or denervation, the activity of the corresponding part of motor cortex tends to decrease over time. At the same time, the patients may experience subjective phenomena such as phantom limb or phantom pain. Giraux and Sirigu (2003), in two such patients with a unilateral brachial plexus avulsion, showed that a normal activity can be restored in their motor cortex by observational training. These patients were trained in a situation where the image of their valid hand was visually transposed (by way of mirrors, see Ramachandran & Rogers-Ramachandran, 1996) at the location of their impaired hand. They were instructed to move their valid hand that they could see at the place of their impaired arm. Following a series of 24 such daily "visuomotor" training sessions, the activity of their M1 area contralateral to their impaired (paralyzed) arm, monitored by fMRI, was greatly increased. This result shows that observation of a normally moving limb can activate the motor area controlling the homologous limb in the observer. A possible explanation for this phenomenon is that mirror neurons similar to those found in monkey premotor cortex are activated by observation of the moving hand and trigger the activity of M1 neurons innervating the impaired hand. In these two patients, this visuomotor training procedure had a beneficial effect, not in improving their hand movements, which remained impaired due to the plexus brachial lesion, but in decreasing their phantom limb pain. This effect suggests that motor cortex, in addition to its role in controlling movements, may also influence the processing of sensory input arising from the effector it controls.

The ability of human subjects to imitate each other derives from the possibility of forming action representations from the observation of other people. It has been suggested that mirror neurons, which are one of the key elements of the action representation and simulation theory, might subserve imitation. It is controversial, however, whether monkeys where these neurons were first identified, can imitate at all (e.g., Hauser, 2000; Tomasello, 2000). Imitation requires more than simply perceiving and understanding an action. It requires some grasp of the intention involved in the duplicated action. At variance with monkeys, humans perceive actions as having goals and being guided by an actor's intention to achieve those goals. Thus, when we imitate, we are copying not only the physical action, but also the intentions underlying those actions. Although mirror neurons found in the premotor cortex of macaque monkeys respond both when the monkey performs a specific action and when he sees another performing a different token of the same action, nonetheless it seems as if the presence of mirror neurons is not sufficient to ensure the ability to engage in genuine imitation.

Neuroimaging studies of imitation in humans tend to favor what Iacoboni et al. (1999) call the Direct Matching Hypothesis. According to this hypothesis, brain areas that become active during execution of a movement should become more active when that movement is elicited by the observation of an identical movement made by another person. Areas in the left inferior frontal cortex and in parietal cortex seem to fulfill this requirement. This result, showing that brain areas for execution and observation of a movement are matched, is compatible with the simulation theory. Furthermore, it raises the point again (already raised in the section about shared representations) of how two different representations of the same action are disentangled from one another.

CONCLUSION: THE ROLE OF SIMULATION IN MOTOR COGNITION

The above pattern of results on the mechanisms of covert action corresponds to the central stages of action organization, uncontaminated by the effects of execution. As such, it represents a possible framework for motor cognition.

First, because all aspects of action appear to be involved during action representation, it seems a logical consequence of this rehearsal of the corresponding brain structures, and specifically the motor structures, that the subsequent execution will be facilitated. The presence of activity in the motor system during covert action puts the action representation in a true motor format, so that it can be regarded by the motor system as a real action. This facilitation explains various forms of training (e.g., mental training) and learning (e.g., observational learning) which occur as a consequence of self-representing an action. In addition, imitation seems to be based on directly matching the observed action onto an internal simulation of that action. Second, activation of the motor cortex and of the descending motor pathway seems to fulfill several critical functions. First, this activation contributes to generating corollary signals that propagate upstream to parietal and premotor cortex. This mechanism allows evaluating the potential consequences of the future action (see Wolpert, Ghahramani, & Jordan, 1995 for description of a control model which accounts for this function). It could also provide the subject with information for consciously monitoring his motor representations and realizing that he is the agent of this covert activity, in spite of absence of overt behavior.

Marc Jeannerod

REFERENCES

- Adams, L., Guz, A., Innes, J. A., & Murphy, K. (1987). The early circulatory and ventilatory response to voluntary and electrically induced exercise in man. *Journal of Physiology*, 383, 19-30.
- Arbib, M. A. (1981). Perceptual structures and distributed motor control. In V. B. Brooks (Ed.), *Handbook of Physiology, Section I: The nervous system, Vol.2: Motor control* (pp. 1449-1480). Baltimore: Williams et Wilkins.
- Baldissera, F., Cavallari, P., Craighero, L., & Fadiga, L. (2001). Modulation of spinal excitability during observation of hand action in humans. *European Journal of Neuroscience*, 13, 190-194.
- Bartlett, F. C. (1926). Review of Aphasia and kindred disorders of speech, by Henry Head. *Brain*, 49, 581-587.
- Beyer, L., Weiss, T., Hansen, E., Wolf, A., & Siebel, A. (1990). Dynamics of central nervous activation during motor imagination. *International Journal of Psychophysiology*, 9, 75-80.
- Binet, A. (1886). *La psychologie du raisonnement. Recherches expérimentales par l'hypnotisme*. Paris, Alcan.
- Bizzi, E., Kalil, R. E., & Tagliasco, V. (1971). Eye-head coordination in monkeys. Evidence for centrally patterned organization. *Science*, 173, 452-454.
- Bonnet, M., Decety, J., Requin, J., & Jeannerod, M. (1997). Mental simulation of an action modulates the excitability of spinal reflex pathways in man. *Cognitive Brain Research*, 5, 221-228.
- Boring, E. G. (1957). *A history of experimental psychology*. Englewood Cliffs, CA: Prentice Hall.
- Brass, M., Bekkering, H., & Prinz, W. (2001b). Movement observation affects movement execution in a simple response task. *Acta Psychologica*, 106, 3-22.
- Brass, M., Zysset, S., & von Cramon, Y. (2001a). The inhibition of imitative response tendencies. *NeuroImage*, 14, 1416-1423.
- Brugger, P., Kolias, S. S., Müri, R. M., Creliez, G., Hepp-Reymond, M. C., & Regard, M. (2000). Beyond re-membering: Phantom sensations of congenitally absent limbs. *Proceedings of the National Academy of Sciences*, 97, 6167-6172.
- Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Fogassi, L., Gallese, V., et al. (2001). Action observation activates premotor and parietal areas in a somatotopic manner: An fMRI study. *European Journal of Neuroscience*, 13, 400-404.
- Cerritelli, B., Maruff, P., Wilson, P., & Currie, J. (2000). The effect of an external load on the force and timing components of mentally represented actions. *Behavioral Brain Research*, 18, 91-96.
- Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *NeuroImage*, 12, 478-494.
- Cincotti, F., Mattia, D., Babiloni, C., Carducci, F., Salinari, S., Bianchi, L., et al. (2003). The use of EEG modifications due to motor imagery for brain-computer interfaces. *IEEE Transactions in Neural Systems and rehabilitation Engineering*, 11, 131-133.

- Clark, S., Tremblay, F., & Ste-Marie, D. (2004). Differential modulation of corticospinal excitability during observation, mental imagery and imitation of hand actions. *Neuropsychologia* (in press).
- Cochin, S., Barthelemy, C., Roux, S., & Martineau, J. (1999). Observation and execution of movement: Similarities demonstrated by quantified electroencephalography. *European Journal of Neuroscience*, 11, 1839-1842.
- Craighero, L., Bello, A., Fadiga, L., & Rizzolatti, G. (2002). Hand action preparation influences the responses to hand pictures. *Neuropsychologia*, 40, 492-502.
- Decety, J., Grezes, J., Costes, N., Perani, D., Jeannerod, M., Procyk, E., et al. (1997). Brain activity during observation of action. Influence of action content and subject's strategy. *Brain*, 120, 1763-1777.
- Decety, J., & Ingvar, D. H. (1990). Brain structures participating in mental simulation of motor behavior: A neuropsychological interpretation. *Acta Psychologica*, 73, 13-24.
- Decety, J., & Jeannerod, M. (1996). Fitts' law in mentally simulated movements. *Behavioral Brain Research*, 72, 127-134.
- Decety, J., Jeannerod, M., Durozard, D., & Baverel, G. (1993). Central activation of autonomic effectors during mental simulation of motor actions in man. *Journal of Physiology*, 461, 549-563.
- Decety, J., Jeannerod, M., Germain, M., & Pastene, J. (1991). Vegetative response during imagined movement is proportional to mental effort. *Behavioural Brain Research*, 42, 1-5.
- Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. *Behavioural Brain Research*, 34, 35-42.
- Decety, J., Perani, D., Jeannerod, M., Bettinardi, V., Tadary, B., Woods, R., et al. (1994). Mapping motor representations with PET. *Nature*, 371, 600-602.
- DeCharms, R. C., Christoff, K., Glover, G. H., Pauly, J. M., Whitfield, S., & Gabrieli, J. D. E. (2004). Learned regulation of spatially localized brain activation during real-time fMRI. *NeuroImage*, In press.
- De Sperati, C., & Stucchi, N. (1997). Recognizing the motion of a graspable object is guided by handedness. *NeuroReport*, 8, 2761-2765.
- Driskell, J. E., Cooper, C., & Moran, A. (1994). Does mental practice enhance performance? *Journal of Applied Psychology*, 79, 481-492.
- Ersland, L., Rosen, G., Lundervold, A., Smievoll, A.I., Tillung, T., Sundberg, H. & Hugdahl, K. (1996). Phantom limb imaginary finger tapping causes primary motor cortex activation: An fMRI study. *Neuroreport*, 8, 207-210.
- Fadiga, L., Buccino, G., Craighero, L., Fogassi, L., Gallese, V., & Pavesi, G. (1999). Corticospinal excitability is specifically modulated by motor imagery: A magnetic stimulation study. *Neuropsychologia*, 37, 147-158.
- Fadiga, L., Craighero, L., Buccino, G. & Rizzolatti, G. (2002) Speech listening specifically modulates the excitability of tongue muscles: a TMS study. *European Journal of Neuroscience*, 15, 399-402.
- Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation. A magnetic stimulation study. *Journal of Neurophysiology*, 73, 2608-2611.

Marc Jeannerod

- Farah, M. (1994). The neurological basis of mental imagery. A componential approach. *Cognition*, 18, 245-272.
- Feldman, A.G. (1966). Functional tuning of the nervous system during control of movement or maintenance of a steady posture. II. Controllable parameters of the muscle. *Biophysics*, 11, 565-578.
- Feltz, D. L., & Landers, D. M. (1983). The effects of mental practice on motor skill learning and performance: A meta-analysis. *Journal of Sport Psychology*, 5, 25-57.
- Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47, 381-391.
- Fogassi, L., Gallese, V., Buccino, G., Craighero, L., & Rizzolatti, G. (2001). Cortical mechanisms for the visual guidance of hand grasping movements in the monkey: a reversible inactivation study. *Brain*, 124, 571-586.
- Frak, V. G., Paulignan, Y., & Jeannerod, M. (2001). Orientation of the opposition axis in mentally simulated grasping. *Experimental Brain Research*, 136, 120-127.
- Gallese V., & Goldman, A. (1998). Mirror neurons and the simulation theory of mind reading. *Trends in Cognitive Science*, 2, 493-501.
- Gallese, V., Murata, A., Kaseda, M., Niki, N., & Sakata, H. (1994). Deficit of hand preshaping after muscimol injection in monkey parietal cortex. *Neuroreport*, 5, 1525-1529.
- Gandevia, S. C., Killian, K., McKenzie, D. K., Crawford, M., Allen, G. M., Gorman, R. B., et al. (1993). Respiratory sensations, cardiovascular control, kinesthesia and transcranial stimulation during paralysis in humans. *Journal of Physiology*, 470, 85-107.
- Gandevia, S. C., Wilson, L. R., Inglis, J. T., & Burke, D. (1997). Mental rehearsal of motor tasks recruits alpha motoneurons but fails to recruit human fusimotor neurones selectively. *Journal of Physiology*, 505, 259-266.
- Georgopoulos, A. P., & Massey, J. T. (1987). Cognitive spatial-motor processes. *Experimental Brain Research*, 65, 361-370.
- Gérardin, E., Sirigu, A., Lehericy, S., Poline, J-B., Gaymard, B., Marsault, C., et al. (2000). Partially overlapping neural networks for real and imagined hand movements. *Cerebral Cortex*, 10, 1093-1104.
- Gibson, J. J. (1979). The ecological approach to visual perception. Boston: Houghton-Mifflin.
- Giraux, P., & Sirigu, A. (2003). Illusory movements of the paralyzed limb restore motor cortex activity. *NeuroImage*, 20, 107-111.
- Goodwin, G. M., McCloskey, D. I., & Mitchell, J. H. (1972). Cardiovascular and respiratory responses to changes in central command during isometric exercise at constant muscle tension. *Journal of Physiology*, 226, 173-190.
- Gottlieb, G. L., Corcos, D. M., & Argawal, G. C. (1989). Strategies for the control of voluntary movements with one mechanical degree of freedom. *Behavioral and Brain Sciences*, 12, 189-250.
- Grafton, S. T., Arbib, M. A., Fadiga, L., & Rizzolatti, G. (1996). Localization of grasp representations in humans by positron emission tomography. 2. Observation compared with imagination. *Experimental Brain Research*, 112, 103-111.
- Grèzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation and verg generation of actions: A meta-analysis. *Human Brain Mapping*, 12, 1-19.

- Hanakawa, T., Immisch, I., Toma, K., Dimyan, M.A., Van Gelderen, P., & Hallett, M. (2003). Functional properties of brain areas associated with motor execution and imagery. *Journal of Neurophysiology*, 89, 989-1002.
- Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., & Rizzolatti, G. (1998). Activation of human primary motor cortex during action observation: A neuromagnetic study. *Proceedings of the National Academy of Sciences*, 95, 15061-15065.
- Hashimoto, R., & Rothwell, J. C. (1999). Dynamic changes in corticospinal excitability during motor imagery. *Experimental Brain Research*, 125, 75-81.
- Hauser, M. (2000). *Wild minds*. New York: Penguin Books.
- Heyes, C. M., & Foster, C. L. (2002). Motor learning by observation : Evidence from a serial reaction time task. *Quarterly Journal of Experimental Psychology*, 55A, 593-607.
- Iacoboni, M., Woods, R. P., Brass, M., Bekkering, H., Mazziotta, J. C., & Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science*, 286, 2526-2528.
- Ingvar, D., & Philipsson, L. (1977). Distribution of the cerebral blood flow in the dominant hemisphere during motor ideation and motor performance. *Annals of Neurology*, 2, 230-237.
- Jacobson, E. (1930). Electrical measurements of neuro-muscular states during mental activities. III. Visual imagination and recollection. *American Journal of Physiology*, 95, 694-702.
- Jeannerod, M. (1994). The representing brain. Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences*, 17, 187-245.
- Jeannerod, M. (1997). *The cognitive neuroscience of action*. Oxford: Blackwell.
- Jeannerod, M. (1999). To act or not to act: Perspectives on the representation of actions. *Quarterly Journal of Experimental Psychology*, 52A, 1-29.
- Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *NeuroImage*, 14, 103-109.
- Jeannerod, M., & Pacherie, E. (2004). Agency, simulation and self-identification. *Mind and Language*, 19, 113-146.
- Johnson, P. (1982). The functional equivalence of imagery and movement. *Quarterly Journal of Experimental Psychology*, 34A, 349-365.
- Johnson, S. H. (2000). Thinking ahead : The case for motor imagery in prospective judgements of prehension. *Cognition*, 74, 33-70.
- Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An interference effect of observed biological movement on action. *Current Biology*, 13, 522-525.
- Kim, S.-G., Jennings, J. E., Strupp, J. P., Andersen, P., & Ugurbil, K. (1995). Functional MRI of human motor cortices during overt and imagined finger movements. *International Journal of Imaging Systems and Technology*, 6, 271-279.
- Knoblich, G., & Flach, R. (2002). Predicting action effects: Interactions between perception and action. *Psychological Science*, 12, 467-472, 2001.
- Kosslyn, S. M., Alpert, N. M., Thompson, W. L., Maljkovic, V., Weise, S. B., Chabris, C. F., et al. (1993). Visual mental imagery activates topographically organized visual cortex: PET investigations. *Journal of Cognitive Neuroscience*, 5, 263-287.

Marc Jeannerod

- Krogh, A., & Lindhard, J. (1913). The regulation of respiration and circulation during the initial stages of muscular work. *Journal of Physiology*, 47, 112-136.
- Lafleur, M. F., Jackson, P. L., Malouin, F., Richards, C. L., Evans, A.C., & Doyon, J. (2002). Motor learning produces parallel dynamic functional changes during the execution and imagination of sequential foot movements. *NeuroImage*, 16, 142-157.
- Landauer, T. K. (1962). Rate of implicit speech. *Perceptual and Motor Skills*, 15, 646.
- Lashley, K. S. (1917). The accuracy of movement in the absence of excitation from the moving organ. *American Journal of Physiology*, 43, 169-194.
- Lashley, K. S. (1951). The problem of serial order in behavior. In L.A. Jeffress (Ed.), *Cerebral mechanisms and behavior* (pp. 112-136). New York: Wiley.
- Le Bihan, D., Turner, R., Zeffiro, T. A., Cuénod, C. A., Jezard, P., & Bonnerot, V. (1993). Activation of human primary visual cortex during visual recall: A magnetic resonance imaging study. *Proceedings of the National Academy of Sciences*, 90, 11802-11805.
- Leonardo, M., Fieldman, J., Sadato, N., Campbell, G., Ibanez, V., Cohen, L., et al. (1995). A functional magnetic resonance imaging study of cortical regions associated with motor task execution and motor ideation in humans. *Human Brain Mapping*, 3, 83-92.
- Lhermitte, F. (1983) Utilisation behaviour and its relation to lesions of the frontal lobes. *Brain*, 106, 237-255.
- Liepmann, H. (1900). Das Krankheitsbild die Apraxie (motorischen Asymbolie). *Monatschrift für Psychiatrie und Neurologie*, 8, 15-44.
- Lotze, M., Flor, H., Grodd, W., Larbig, W., & Birbaumer, N. (2001). Phantom movement and pain. An fMRI study in upper limb amputees. *Brain*, 124, 2268-2277.
- Lotze, M., Montoya, P., Erb, M., Hülsmann, E., Flor, H., Klose, U., et al. (1999). Activation of cortical and cerebellar motor areas during executed and imagined hand movements : an fMRI study. *Journal of Cognitive Neuroscience*, 11, 491-501 .
- Marshall, J. C., Halligan, P. W., Fink, G. R., Wade, D. T., & Frackowiak, R. S. J. (1997). The functional anatomy of a hysterical paralysis. *Cognition*, 64, B1-B8.
- Mehring, C., Rickert, J., Vaadia, E., Cardoso de Olivera, S., Aersten, A., & Rotter, S. (2003) Inference of hand movements from local field potentials in monkey motor cortex. *Nature Neuroscience*, 6, 1253-1254.
- Neisser, U. (1993). The self perceived. In U. Neisser (Ed.), *The perceived self. Ecological and interpersonal sources of self-knowledge* (pp. 3-21). Cambridge: Cambridge University Press.
- Nicolelis, M. A. L. (2001). Actions from thoughts. *Nature*, 409, 403-407.
- Paccalin, C., & Jeannerod, M. (2000). Changes in breathing during observation of effortful actions. *Brain Research*, 862, 194-200.
- Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 709-730.
- Parsons, L. M., Fox, P. T., Downs, J. H., Glass, T., Hirsch, T. B., Martin, C. C., et al. (1995). Use of implicit motor imagery for visual shape discrimination as revealed by PET. *Nature*, 375, 54-58.

- Pascual-Leone, A., Dang, N., Cohen, L. G., Brasil-Neto, J., Cammarota, A., & Hallett, M. (1995). Modulation of motor responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *Journal of Neurophysiology*, 74, 1037-1045.
- Porro, C. A., Francescato, M. P., Cettolo, V., Diamond, M. E., Baraldi, P., Zuiani, C., et al. (1996). Primary motor and sensory cortex activation during motor performance and motor imagery: A functional magnetic resonance study. *Journal of Neuroscience*, 16, 7688-7698.
- Prinz, W. (1990). A common coding approach to action and perception. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167-201). Berlin: Springer.
- Prut, Y., & Fetz, E. E. (1999). Primate spinal interneurons show premovement instructed delay activity. *Nature*, 401, 590-594.
- Ramachandran, V. S., & Rogers-Ramachandran, D. (1996). Synaesthesia in phantom limbs induced with mirrors. *Proceedings of the Royal Society, London, B* 263, 377-386.
- Requin, J., Brener, J., & Ring, C. (1991). Preparation for action. In J. R. Jennings & M. G. H. Coles (Eds.), *Handbook of Cognitive Psychophysiology. Central and Autonomic Nervous System Approaches*. New York: John Wiley & Sons Ltd.
- Rizzolatti, G., Camarda, R., Fogassi, L., Gentilucci, M., Luppino, G., & Matelli, M. (1988). Functional organization of area 6 in the macaque monkey. II. Area F5 and the control of distal movements. *Experimental Brain Research*, 71, 491-507.
- Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1995). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research*, 3, 131-141.
- Rizzolatti, G., Fadiga, L., Matelli, M., Bettinardi, V., Paulesu, E., Perani, D., et al. (1996). Localization of grasp representations in humans by PET: 1. Observation versus execution, *Experimental Brain Research*, 111, 246-252.
- Roland, P. E., Skinhoj, E., Lassen, N. A., & Larsen, B. (1980). Different cortical areas in man in organization of voluntary movements in extrapersonal space. *Journal of Neurophysiology*, 43, 137-150.
- Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection. Overhand versus underhand grips. In M. Jeannerod (Ed.), *Motor representation and control, attention and performance XIII* (pp. 321-342). Hillsdale: Erlbaum.
- Rossini, P. M., Rossi, S., Pasqualetti, P., & Tecchio, F. (1999). Corticospinal excitability modulation to hand muscles during movement imagery. *Cerebral Cortex*, 9, 161-167.
- Roth, M., Decety, J., Raybaudi, M., Massarelli, R., Delon-Martin, C., Segebarth, C., et al. (1996). Possible involvement of primary -motor cortex in mentally simulated movement. A functional magnetic resonance imaging study. *Neuroreport*, 7, 1280-1284.
- Schnitzler, A., Selenius, S., Salmelin, R., Jousmäki, V., & Hari, R. (1997). Involvement of primary motor cortex in motor imagery : A neuromagnetic study. *NeuroImage*, 6, 201-208.
- Schott, N., & Munzert, J. (2002). Mental chronometry in the elderly. *Journal of Sport and Exercise Psychology*, 24, 109.
- Sebanz, N., Knoblich, G., & Prinz, W. (2003). Representing other's actions: Just like one's own? *Cognition*, 88, B11-B21.

Marc Jeannerod

- Serruya, M. D., Hatsopoulos, N. G., Paninski, L., Fellows, M. R., & Donoghue, J. P. (2002). Instant neural control of a movement signal. *Nature*, 416, 141-142.
- Shallice, T. (1988). *From neuropsychology to mental structure*. Cambridge: Cambridge University Press.
- Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, 17, 701-703.
- Shiffrar, M., & Freyd, J. J. (1990). Apparent motion of the human body. *Psychological Science*, 1, 257-264.
- Sirigu, A., Duhamel, J.-R., Cohen, L., Pillon, B., Dubois, B., & Agid, Y. (1996). The mental representation of hand movements after parietal cortex damage. *Science*, 273, 1564-1568.
- Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Reviews*, 99, 605-632.
- Stelmach, G. E., Castiello, U., & Jeannerod, M. (1994). Orienting the finger opposition space during prehension movements. *Journal of Motor Behavior*, 26, 178-186.
- Stevens, J. A. (in press). Interference effects demonstrate distinct roles for visual and motor imagery during the mental representation of human action. *Cognition*.
- Tai, Y. F., Scherfler, C., Brooks, D. J., Sawamoto, N., & Castiello, U. (2004). The human premotor cortex is 'mirror' only for biological actions. *Current Biology*, 14, 117-120.
- Tomasello, M. (2000). *The cultural origins of human cognition*. Cambridge, MA: Harvard University Press.
- Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 830-846.
- Viviani, P. (1990). Common factors in the control of free and constrained movements. In M. Jeannerod (Ed.), *Motor representation and control, Attention and Performance XIII*. (pp. 345-373). Hillsdale, NJ: Erlbaum.
- Vogt, S. (1995). On relations between perceiving, imagining, and performing in the learning of cyclical movement sequences. *British Journal of Psychology*, 86, 191-216.
- Wang Y., & Morgan, W. P. (1992). The effects of imagery perspectives on the physiological responses to imagined exercise. *Behavioural Brain Research*, 52, 167-174.
- Wegner, D. (2002). *The illusion of conscious will*. Cambridge, MA: MIT Press.
- Wehner, T., Vogt, S., & Stadler, M. (1984). Task-specific EMG characteristics during mental training. *Psychological research*, 46, 389-401.
- Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, 269, 1880-1882.
- Wuyam, B., Moosavi, S. H., Decety, J., Adams, L., Lansing, R. W., & Guz, A. (1995). Imagination of dynamic exercise produced ventilatory responses which were more apparent in competitive sportsmen. *Journal of Physiology*, 482, 713-724.
- Yue, G., & Cole, K. J. (1992). Strength increases from the motor program: Comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology*, 67, 1114-1123.

THE COGNITIVE ARCHITECTURE OF COMPLEX MOVEMENT

THOMAS SCHACK

German Sport University, Cologne & Martin Luther University, Halle-Wittenberg, Germany

ABSTRACT

This article examines the cognitive architecture of complex movements, how it is organized over several levels and is built on specific building blocks. Basic Action Concepts (BACs) are identified as the major building blocks on the level of mental representations. These BACs are cognitive tools for mastering the functional demands of movement tasks. New experimental methods are introduced and applied in studies addressing the functional link between representation structures and human performance. Results from two different lines of research showed that not only is the structure formation of mental representations in long-term memory built upon BACs, but so is chunk formation in working memory and systematically relates systematically to movement structures. Further lines of experimental research in various fields of sport showed that cognitive subsystems work together functionally with different levels of movement architecture in order to solve movement tasks. These results support the hypothesis that voluntary movements are planned, executed, and stored in memory directly through representations of their anticipated perceptual effects. Conclusions are drawn for new forms of mental training as well as new ways of carrying out technical preparation.

Key Words: cognitive psychology, mental representation, chunking, performance, expertise, mental training, evolution, biomechanics

THE COGNITIVE ARCHITECTURE OF COMPLEX MOVEMENT

THE SEARCH FOR STRUCTURES OF MOVEMENT

There is a well-known phenomenon in sport training: Once athletes have attained a certain stage of learning, trainers and athletes tend to "talk at cross purposes." The athlete has developed a new feeling with regard to, for example, water, the ball, or skis. This leads to a new "movement feeling," and there is no longer an optimal fit between earlier form of instructions and the athlete's cognitive representations. Such divergences in trainer-athlete interaction prompted this closer look at the construction, stabilization, and modification of the cognitive structures involved in motor-learning processes.

Correspondence concerning this article should be sent to: Thomas Schack PhD, Institute of Psychology, German Sport University Cologne, Carl-Diem-Weg 6, D-50933 Cologne, Germany, Phone: (+) 49 (0) 221-4982-553, Fax: (+) 49 (0) 221-4982-817, E-mail: schack@dshs-koeln.de

Thomas Schack

New and interesting perspectives have emerged on how such perceptual-cognitive structures develop in movement control. These include the ideomotor approach (IM; see Knuf, Aschersleben, & Prinz, 2001; Koch, Keller, & Prinz, this issue), the theory of event coding (TEC; see Hommel, Müsseler, Aschersleben, & Prinz, 2001), and the anticipative behavioral control approach (ABC; see Hoffmann, 1993; Hoffmann, Stoecker, & Kunde, this issue). These perspectives emphasize the goal-directedness of actions and the importance of anticipated perceptual effects in action control. Through various experiments, they have shown that sensory information and effect representations play a major role in the mental control of movements. For example, Kunde (2003, 2004) has shown that presenting optical or acoustic response-affording targets can speed up motor responses. What these perspectives have in common is the basic idea that voluntary movements may be planned, performed, and stored in memory by representations of anticipated effects. In this respect these theories differ from theories that conceive motor programs as a prestructured set of muscle-oriented commands and assume that movements are initiated without regard to sensory information (see Schmidt & Lee, 1999). However, they also differ specifically from the dynamic system approach (Kelso, 1995). For example, Mechsner, Kerzel, Knoblich, and Prinz (2001) have shown that the spontaneous tendency toward symmetry that sets in with bimanual finger movements is not due to the coactivation of homologous muscles (see Kelso, 1984) but to a spatiotemporal symmetry tendency based on perceptual information. The authors view this result as support for the assumption that human movements are organized on the basis of sensory effect representations.

Interestingly however, the above-mentioned approaches (TEC, IM, and ABC) can be related not only to early work in psychology such as James (1890) or Herbart (1825) but also in a remarkable way to the pioneering work on movement science carried out by Bernstein (1947, 1967, 1975) and colleagues. Way back in 1935, Bernstein had already pointed out that movements should be understood as goal-directed acts. This is why his additional work (e.g., Bernstein, 1947, 1967, 1975) assigns a decisive role to the model of the *needed* future in the organization of movement. Bernstein has also emphasized the major role of sensory (re-afferent) feedback in controlling the motor system. He assumed that performing movement tasks requires a continuous processing of sensory feedback over the result attained so far, as well as comparisons with the coded final effect.¹ Therefore, according to Bernstein, feedback on the sensory effects of a movement plays a substantial role in the control of complex movements, because the movement system possesses a great number of degrees of freedom. This combined with the specific features of muscles makes it impossible to build an unequivocal relation between an efferent command and the effects of a movement. As a result, coordination means overcoming superfluous degrees of freedom, or, in other words, transforming the degrees of freedom of the movement system into targeted movement effects (see Bernstein, 1971). Such a transformation requires specific means, including cognitive ones (e.g., representations), and it requires a functional mediation between the different building blocks of the movement system.

¹Hence, it can be seen that these works contain basic principles that were later linked predominantly to work on the refferance principle (see Holst & Mittelstaedt, 1950) and the cybernetic control of systems (Wiener, 1948).

In his classic work *O postrojenii dvizenij* (On the construction of movement),² Bernstein (1947) presented the most comprehensive compilation of descriptive and experimental data on the functional mediation of the building blocks of the movement system available at that time. His detailed model of the interplay between, for example, movement goals, motor representations, and perceptual feedback is composed of several interdependent levels in a hierarchy headed by an object-related action organization level. He even claimed that there should be a superordinate cognitive level of symbolic or conceptual organization for complex movements, but he did not work out this idea in detail.

It now seems opportune to pick up Bernstein's idea on the construction of movement and expand it by analyzing cognitive components and structures. This basic idea not only fits nicely with work on cognitive knowledge architectures (e.g., Anderson & Lebiere, 1998; Newell, 1990) but also with the above-mentioned findings and analyses on TEC, IM, and ABC as well as current work in neurophysiology (Jeannerod, 1997: Jeannerod, in this issue).

After presenting ideas on theoretical models for the cognitive architecture of movement, this article will focus particularly on the construction and stabilization of mental representations within the context of sport. One issue is whether representation structures reveal a pattern that can be related in some specific way to action structure. In other words, is it possible to confirm a reciprocal overlap between action and representation structures? According to Bernstein (1935, 1947, 1967) and TEC (Hommel et al., 2001), such representations would have a distal focus, and should therefore contain the spatiotemporal structure of the movement effects and not that of a pattern of muscles or joints. Sport movements provide a particularly good field for studying such issues. They are integrated into an ecological context; they are sometimes extremely rapid, but they are nonetheless easy to observe and have controllable effects.

Therefore, it can be seen that the issues raised here are also relevant for the practical problem discussed at the beginning of this article. If coaches know how representation structures develop as a function of practice and task requirements, then they will know more about how to talk to athletes, and they will be able to reach them through specific instructions.

FUNDAMENTAL PRINCIPLES OF AN ARCHITECTURE OF MOVEMENT

A number of studies have addressed the architecture of cognition (see, e.g., Anderson, 1983; Anderson & Lebiere, 1998). However, based on an evolutionary and functional view, (Bernstein, 1947; Schack, 2004a) it seems appropriate to examine the cognitive architecture of action as well. This would relate to how cognitive components are built into action organization in humans, and which functional role they correspondingly take in the performance of the action system.

²This book has still not been translated into English. The only available translation is a German version of chapter VIII (see Bernstein, 1996).

Thomas Schack

THE MODEL OF THE NEEDED FUTURE

One major property of human actions is that they are volitional (see e.g., Ach, 1921; Hoffmann, 1993; Vygotsky, 1978, 1992). Human volition (or will) can be analyzed functionally and broken down into its main components. From our functional perspective we shall call this ability (volition) *mental control*. One major functional component of mental control is the coding of intended effects into an action goal. Such a coding is needed before an action goal can adopt the function of a cognitive benchmark for further processing.

Ever since Wilhelm Wundt (1893) and William James (1890), a variety of studies dealt with mental goal coding and different theoretical models have been proposed.³ Particularly during the last two decades, it has become clear that functional processes mediate between the anticipated effect of a movement and current activity. Only in recent studies, these have been mapped out step-by-step (see, e.g. Hoffmann et al. in this issue; Knuf, Aschersleben, & Prinz, 2001; Koch et al. in this issue; Kunde & Weigelt, in press).⁴ However, anticipating the outcome of a movement is also viewed as a central factor of movement organization in the domain of movement physiology. Bernstein (1957/1975) writes:

If we consider the program of the movement act macroscopically as a whole, then the only determining factor we are able to find for it is the image or idea of that effect of the ... action toward which this act is directed through comprehension of the given movement task. (p. 155, translated)

Several of Bernstein's (1947, 1975) studies reveal that he considered the *anticipation of the effect of the movement* to be the first and decisive step in its organization. This effect anticipation is followed by the generation of a *model of the needed future* to which all control and monitoring processes can be related (Bernstein, 1967, 1975).

Kunde and Weigelt (2004), for example, have examined the topic of goal coding. They used several experiments to study whether the performance advantage for mirror-symmetrical versus asymmetric movements in bimanual-object manipulations was due to the activation of homologous muscles or due to the symmetry of sensory-goal representations. Participants had to place two objects on a table in either a parallel or an opposing arrangement, using either mirror-symmetrical or mirror-asymmetrical movements. Results showed that bimanual coordination performance is determined by the symmetry of the effect-code and not by the symmetry of the muscle activation. Movement-related symmetry effects emerged only when the movements themselves become the goal representation.

The fact that something like a "model of the needed future" can be derived from goal coding can be seen clearly in a set of studies addressing the *end-state comfort effect* (e.g., Rosenbaum & Jorgensen, 1992; Rosenbaum, Meulenbreuk, & Vaughan, this issue; Weigelt, Kunde, &

³This was a much neglected topic from the 1930s to the 1980s. Internationally, this was due to the dominance of behaviorist perspectives, whereas, in Germany, this followed the Ach-Lewin controversy (see, e.g., Lewin, 1926). In Russia, however, there was a continual interest in the volitional control of actions in psychology (e.g., Vygotsky, 1929/1992) and movement science (Bernstein, 1975).

⁴Action theory has worked out that the anticipation itself becomes a major means of goal attainment (Hacker, 1998; Nitsch, 2000).

Prinz, 2004). This research has shown that individuals are prepared to adopt uncomfortable positions with their hands or arms when initiating and executing object manipulations (movement constellations) as long as this leads to a comfortable position for the final state of the movement. For example, to pick up a pencil that is pointing to the light, one uses an awkward underhand grip to ultimately hold the pencil in a comfortable writing posture. Such observations clearly show that movements are planned, controlled, and performed with reference to the anticipated final position of the movement. Hence, they indicate the existence of a *mental model* (of the needed future) to which all control processes can be related.

Instructions are a further important component of mental control. These are applied, for example, to direct attention (e.g. Temprado, Zanone, Monno, & Laurent, 1999; Wulf & Prinz, 2001) or to stabilize performance when difficulties emerge in action organization. Inner speech appears to be a particularly important component of strategies in action control (see, e.g. Luria, 1958, Luria & Subbotski, 1978; Munzert, 1997; Vygotsky, 1978).⁵

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 different kinds of representations are integrated into the motor control of complex movements.

THE VERTICAL DIMENSION OF COGNITIVE CONTROL

From an evolutionary perspective, conscious mental functions can be assumed to emerge from more elementary functions. As the discussion on the evolution of the human action system (e.g. Bernstein, 1996b; Schack, 2004a; Vygotsky, 1978) has shown, symbols (as specific cognitive tools) convey higher, mentally controlled functions. Hence, whereas elementary functions (e.g., reflexes) are influenced directly by stimulus constellations, mental control functions are guided intentionally; they are regulated by the self. For example, it is not possible for a mentally controlled action to emerge from the grasp reflex in humans. In fact, this reflex has to be inhibited actively before verbal or other cognitive means can be applied and a goal-directed action can be formed. Should, at this point, children fail to develop any inhibitory activity; they cannot manipulate objects at all. All they will do is grasp. The same applies to 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 (automated and) purposeless. This points to the vertical dimension (hierarchical organization) of cognitive control. As the organization of the organism-environment interaction becomes increasingly effective, various levels of functional organization also seem to have formed.

Alongside Bernstein's (1947) approach to the construction of action mentioned above, there have been several formulations of the idea that movement control is constructed hierarchically. One set of studies has focused on a hierarchy of different levels of representation (see, e.g., Keele, 1986; Perrig & Hofer, 1989; Saltzman, 1979). Other studies,⁶ in contrast, have focused

⁵Experimental series concerning the function of inner speech in action control was carried out predominantly in Russian laboratories from beginning until the middle of the last century.

⁶Support for different levels of movement control can be derived from findings indicating that neurophysiological structures are also constructed hierarchically (Bernstein, 1947, 1975; Jeannerod, 1995; Luria, 1992). Moreover, multilevel models have also been proposed for the organization of perception (e.g., Powers, 1990) and the interdependencies between perception and behavior (e.g., Marken, 2002).

Thomas Schack

more strongly on the aspect of a hierarchic execution regulation (e.g., Greene, 1972; Hacker, 1998; Keele, Cohen, & Ivry, 1990; Rosenbaum, 1987). In contrast, the model proposed here views the functional construction of actions⁷ (Schack, 2002, 2004) on the basis of a reciprocal assignment of performance-oriented regulation levels and representational levels (see Table 1). These levels differ according to their central tasks on the regulation and representation levels. Each level is assumed to be functionally autonomous.

Table 1
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

The function of the mental control level (Level IV) has already been sketched for voluntary movement regulation and the coding of the anticipated outcome of movement. The level of mental representations (Level III) predominantly forms a cognitive benchmark for Level IV. It is organized conceptually, and is responsible for transferring the anticipated action outcome into a movement program sufficient to bring about the desired outcome. Since an action is "no chain of details, but a structure subdivided into details" (Bernstein, 1988, p. 27, translated), action organization has to possess a working model of this structure.⁸

The corresponding abilities to use such targets and representations have been acquired stepwise during evolution (Schack, 2004a). As a result, the current level of human development can draw on hierarchically organized representations of either states in the environment, objects, or goal-directed movements.

Basic Action Concepts (BACs) have been identified as major representation units for complex movements (Schack, 2002). They tie together their functional and sensory features. The functional features are derived from movement goals. This link connects BACs to Level IV.

⁷The relation between this and other architecture models (e.g., Bernstein, 1947) has been discussed elsewhere (see Schack, 2002).

⁸This makes it necessary to represent the topology and thereby the spatiotemporal effect structure of the movement on a functionally autonomous level. For complex movements, this occurs on the level of mental representations. As a result, this level also forms the background for processes of sensorimotor control, particularly for the spatial and temporal integration of the elements making up a complex movement.

However, BACs also integrate sensory features of submovements for example through chunking. As a result, they also refer to the perceptual effects of the movement. This connects BACs with Level II. Finally, the connection between BACs and sensory-effect representations permits the intentional manipulation of the cognitive framing conditions of sensorimotor coordination. These mental representations (BACs) are the subject of the next section and the experimental analyses reported below. They contain a kind of 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.

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.⁹ The level of sensorimotor control is built on functional units composed of perceptual effect representations, afferent feedback, and effectors. The essential invariant (set value) of such functional units¹⁰ is the representation of 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.

The need for a level of sensorimotor representation is obvious 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 now become associated with kinesthetic, tactile, optical, and, in part, 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 on how these two lower levels function comes from studies in the field of the physiology of movement. An *action acceptor* (see Anochin, 1967, 1978) has been identified as an important functional component in these goal-directed movements. This translates the intended action outcome into a sensory (perceptive) model of the action effects, thus providing criteria to guide 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 to 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 to formulate an intention and even control the

⁹Experiments on ideomotor action (Knuf et al., 2001) have confirmed the differentiation between perceptual versus intentional induction in human movement control.

¹⁰Interesting proposals on how these functional units work are to be found in the physiology of movements (e.g., Anochin, 1967; Bernstein, 1967, 1975), neurophysiology (Jeannerod, 1997), and biocybernetics (e.g., Kalveram, 2002, 2004).

Thomas Schack

enactment of this task by third persons (recognizing any errors they make), but they either no longer possess control over their own actions, or are able to evaluate errors in their own action performance (see Luria, 1992; Luria, Pribram, & Chomskaja, 1964).

What is interesting for complex movements in sport is that routines, like pre-performance routines in golf (Whitmarsh & Schack, 2004), 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 become embedded within the action and thus in a functional interaction with Levels III and IV (Schack, 2002). Increasing automatization is accompanied by increasingly adequate correction mechanisms between Levels I and II and "tacit knowledge" (see, e.g., Sternberg, 1995) emerges. The routines that develop here are direct components of 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 makes it possible to assess this knowledge base of performance experimentally.

BUILDING BLOCKS OF THE ARCHITECTURE

Much debate exists over what may be the relevant units of human movement control. In recent years, the main focus has been on both motor programs (e.g. Schmidt & Lee, 1999) and attractor-formed muscular connections (e.g. Kelso, 1995). The perspective proposed here differs in a specific way. For this purpose, it is first necessary to establish a functional classification of the building blocks in the architecture.

Phylogenetically speaking, the level of mental control is superimposed on the level of sensorimotor control (see Bernstein, 1996b). As a result of this evolution, one can assume that, functionally speaking, this level of mental control "enslaves" the level of sensorimotor control, or exploits its functions in order to achieve action goals (see Greene, 1988; Turvey, 1977). The architecture model assumes that these execution or regulation levels communicate over the levels of representation. Hence, each of these levels requires its own adequate representation units, that is, *cognitive units* that are able to cope with the task on each level of regulation (action vs. movement organization).

Hence, in principle, the building blocks in this architecture have to possess a compatible format. The building blocks presented here code sensory starting conditions or sensory effects and, thus, events (see TEC, Hommel et al., 2001). Therefore, they are directed continuously toward (re)afferent information, and integrate distally focused feature codes.¹¹ This perspective simplifies quite a few things: For example, Swinnen and Wenderoth's (2004, p. 22) distinction between *higher-level abstract* and *lower-level muscle- or effector-specific* codes raises some questions; it is not clear through which steps abstract codes should be translated into muscle or effector codes. In principle, abstract codes and (muscle) effector codes are incompatible

¹¹This is the reason these representation units (building blocks) are also compatible with the effect-related goal codes on the level of mental control.

(see Hommel, et al; Prinz, 1992). In the present architecture model, such translation problems do not emerge, because muscle codes are superfluous.¹² Support for such a position can be found in neurophysiology,¹³ for example, Jeannerod (1997) writes:

An alternative mechanism for the comparison between efferent and reafferent signals is that the representation encodes, not joint rotations or kinematic parameters, but final configurations (of the body, of the moving segments, etc.) as they should arise at the end of the action. In other words, the goal of the action, rather than the action itself, would be represented. This idea of the representation of a final state of the system (a representation of the state of the organism when the goal has been reached) is appealing, because the difference between the present state (before the action) and the final state (after the action has been completed) is the action. (p. 179)

For units on the level of mental representations, further properties should play a role alongside the sensory features of building blocks on the level of sensorimotor representations. Because these units tend to be superimposed on the units of sensorimotor representation, they inherit their properties (also in genetic terms). This enables them to retain the relation to the movement effects that always remain sensory effects for the entire system. Moreover, the units of mental movement representations have to exhibit properties corresponding to the functional goal settings on the level of mental control. To do this, they also need to be able to influence elementary sensorimotor control operations within the architecture framework (conveyed through sensorimotor representations). This approach permits the assumption that the units on the level of mental representations need to possess functional feature links or properties in addition to sensory ones. As a result of these delimitations, we view concepts as major units or building blocks in the organization of movement on a level of mental representations. Because they can possess not only functional but also sensory properties, they are highly classifiable in the functional space of the architecture model.¹⁴

According to Narziß Ach (1905, 1921), concept formation makes a major contribution to volitional actions. Objects are being grouped together by means of functional equivalence (see Ach, 1921; Hoffmann, 1986). For instance, both a pencil and a ballpoint pen are useful for writing down an important message; therefore, they are 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, it will very probably be stored under the concept "cup" or "glass." Hence, object concepts are cognitive groupings of objects according to the functions they share in the attainment of action goals (see Hoffmann, 1986, p. 11).

¹²This does not contradict the presence of effectors or the functional significance of activating muscles for human movements. However, the functionally necessary elements of movement do not necessarily require an analogue code. For example, there is also no such thing as a bone code.

¹³In the architecture model, effect codes (efference syntheses) form the guiding invariant of movement organization or of motor control structures. The movement itself may vary strongly. This simultaneously suggests the hypothesis of reafferently triggered, variable motor innervations as the fundamental condition for attaining goal-directed, stable movement effects (see Bernstein, 1996b; Luria, 1992).

¹⁴Various approaches support the assumption that concepts should be assigned a major function in action control or movement organization (see, e.g., Hoffmann, 1986, 1993a; MacKay, 1985; Prinz, 1983). In a broader sense, research emphasizing chunking as a major process in the compilation of movement programs (see, e.g., MacKay, 1982; Newell & Rosenbloom, 1981) also relates to the assumptions on the building blocks of human movement control formulated here.

Thomas Schack

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 actions 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, 1993). *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 they are assessed through these attributes.

Action concepts, in contrast, serve to classify movements that lead to certain effects. Hence, they are involved in the spatiotemporal control of actions. Drawing on experimental studies, these concepts have been labeled *basic action concepts*.¹⁵ 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. They are cognitive tools for overcoming superfluous degrees of freedom. In this way, they finally serve to maximize the control of actions with the lowest possible cognitive and energetic effort. This serves to transform the movement system into a *controllable system*.

The function of such action 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, thereby reducing 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, 1947; Vereijken, van Emmerik, Whiting, & Newell, 1992). One can observe similar strategies in adults when forced to write with the nondominant hand (Newell & 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 a person can substitute one for the other within the context of a behavior without this threatening the behavioral goal. This is the case, for example, when performing the attack hit in volleyball. Here the movement concept "extending legs" summarizes all movements that complete the 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, the BAC "extending legs" summarizes all movements that *functionally* fulfill the same purpose when generating the hit.

¹⁵BACs correspond to the basic concepts characterized for object concepts by, among others, Rosch (1978) and Hoffmann (1986, 1993). Basic concepts are the most general concepts that are still characterized by mostly sensory and visible features within a concept hierarchy ranging from sensory to categorical concepts. In allocation experiments, this representation type is defined by the shortest decision times.

As mentioned above, each individual BAC is characterized by a set of closely interconnected sensory and functional features. For example, a BAC like "whole body stretch motion" in tennis 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 a monitoring of the initial conditions are kinesthetic and tactile information coming from bended 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, for instance, proprioceptive and, finally, perhaps visual perceptions of the swinging arm and ball in view.

An essential aspect within the framework of the total architecture is that the building blocks on the level of mental representations are laid functionally on top of building blocks on the level of sensorimotor representations. This means that they have to be able to integrate and organize the "lower-level" building blocks or codes (see, also, Perrig & Hofer, 1989; Viviani, 1986). Distinguishing building blocks (BACs) on the level of mental representations in this way make an effective functional control of the total system conceivable. Within this system, learning could be a product of modifying the mediating conceptual (BAC) structures. These modifications would then impact the total system, so that new constellations are also generated between a level of mental and a level of sensorimotor control through the integration or rearrangement of sensorimotor representation units (perceptual effect-codes). This enables the system to perform an effect-related optimization of relations between intentions and elementary operations depending on the starting conditions.

BACs and object concepts are generally not represented in isolation. They are part of hierarchical concept systems. It is very likely that the two types of concepts are also 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).

According to the model presented here, the structure of mental representations must have a distal focus. Because BACs are based on sensory effect codes, it can be anticipated that the representation structure is formed by essential (topological) properties of the movement. Bernstein (1935/1975) already formulated such an assumption:

The constant ease and the retention of the handwriting immediately suggest that the skill of writing is not the skill of a set of muscles, and, as a result, that the part of the central nervous system acquiring it is located close to the topology of handwriting and far from the topology of the joints and muscles. (p. 94, translated)

Thomas Schack

This leads us to ask how we can conceive the mental structures responsible for complex movements. Is it possible to confirm mutual overlaps between representation structures and movement structures? To answer such questions in the development of the paper, we will move along different lines of empirical research.

STRUCTURE FORMATION IN LONG-TERM MEMORY

Simplification in the domain of cognitive operations and structures is accompanied by order formation. Such order formation in action knowledge reduces the cognitive effort required to activate relevant information. In general, cognitive structures improve when more problem-solving related classifications (concepts) are formed.

In the present perspective, we have to solve movement tasks purposefully and step-by-step within the framework of a voluntary organization of movement. So it is of interest to learn about the task-related order formation of action knowledge.

Anglo-American research on the relation between expertise and representations in sport (see, e.g., Huber, 1997; Starkes, Deakin, Lindley, & Crisp, 1987) borrowed most of its models and methods from the expertise research in physics, mathematics, and other problem-solving fields of the 1970s and 1980s (see e.g. Chi, 1979; Garner, 1987). For example, specific sorting techniques and interview methods have been used to confirm expertise-dependent differences in the classification and representation of context-specific problem states in springboard divers, judoists, triathletes, and weight lifters (Huber, 1997; Russell, 1990). Research on springboard diving has revealed that the nodes of the representation structures in experts possess far more features than those of novices. This replicates findings in the problem-solving domain (Chi & Glaser, 1980). Likewise, expert springboard divers reveal a greater number of connections between nodes, just like experts in problem-solving research (see Huber). Studies using sorting methods have shown that experts classify problems according to underlying functional principles, whereas novices operate more strongly with superficial features (Allard & Burnett, 1985; Russell & Salmela, 1992). Furthermore, questionnaire methods and interviews have revealed the structure and organization of movement knowledge in, for example, tennis (McPherson & Thomas, 1989; McPherson & Kernodle, 2003), Volleyball (McPherson & Vickers, in the part I of this special issue) and basketball (French & Thomas, 1987).

It can be seen that most previous studies of knowledge components in long-term memory in sport-specific domains have used interviews, paper-and-pencil tests, and specific forms of protocol analysis. However, using such methods leads to problems with objectivity and reliability (see Thomas & Thomas, 1994). Moreover, it is worth distinguishing between knowledge that is functionally relevant for the control and organization of actions and knowledge that merely accompanies actions or justifies them in retrospective. We cannot assume that the knowledge reported by top performers (experts) is the same as the knowledge responsible for their actual performance. The goal of our studies is not only to examine the relation between movement structure and representation structure in complex sport movements, but also to use an experimental approach to determine representations.

Concrete research questions can be derived from the architecture model presented here. We shall focus on two of these: (a) is it possible to use experimental methods to confirm specific expertise-dependent (and, hence, learning-level-dependent) structures in long-term memory (LTM)?, and (b) is the structure of mental representations in LTM formed more by the spatiotemporal effect structure of the movement or by muscle and joint constraints?

One of our studies (Schack, 2004b) addresses the representation of the attack hit in volleyball. This technique was chosen because of its central importance, as the whole game is organized around implementing attack hits. The technique is also highly observable and its effect can be judged unequivocally.

Performing an 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 BACs were determined with the help of biomechanical methods (functional movement analysis), interviews, and experimental methods:¹⁶ (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.

The biomechanical analyses showed that the attack hit consists of four distinct phases, each fulfilling distinct functional demands: run-up, takeoff, hit preparation, and main-phase hit. One can assume that specific problems have to be solved in each phase. For example, the hit phase involves the goal-directed application of the energy generated in the previous movement phases. BACs 1-3 are relevant for the run-up movement phase; BACs 4 and 5, for the takeoff; BACs 6-8, for the hit preparation; and BACs 10-11/12, for the attack hit itself. BAC 9, *glance toward opponent's block*, refers to an environmental constellation that is of central importance for the success of the hit. Due to a modified technique of the attack hit, the German national team removed the formerly used node (12) *drawthrough of hitting arm* from their training scheme half a year before this study took place. The coaches instructed their players to dispose of this node, which had been practiced as part of their movement execution for more than 3.5 years previously. Still, we incorporated the corresponding BAC in the list of units to be studied in order to find out whether this modification of technical preparation could be detected in the mental representations and had thus already reached a functional status. Because the rating and sorting methods described above do not allow a psychometric analysis of the representational structure, we used an experimental method to measure the structure of mental movement representation in LTM. This method is called Structure Dimensional Analysis-Motorics (SDA-M; Schack, 2002) and proceeds in four steps.

The SDA-M method starts by trying to uncover information on the distance between selected BACs (Step 1) through the application of a special splitting technique in an experimental setting. Participants are asked to judge the functional relationship between two BACs

¹⁶Reaction-time experiments were used to test whether the concepts really were basic in character.

Thomas Schack

respectively (see, for more detail, Schack, 2002, 2004a, b; Schack & Mechsner, in press).¹⁷ Hence, SDA-M does not ask the subjects to give explicit statements regarding their representation structures but rather reveals this structure by means of knowledge-based decisions in an experimental setting.

The second step is to obtain the structured relations between the BACs by compiling a distance matrix through the scaling procedure presented above and subjecting this to hierarchic cluster analysis (Step 2). The next step ascertains the feature dimensions of the representation structure through factor analysis and a special cluster-oriented rotation procedure (Step 3). This factor analysis delivers the features (factors) and their weights (factor loadings) for the predominant cluster formation (structuring) in each case. Because cluster solutions can differ both between and within individuals, the next step is an invariance analysis (Step 4) based on a specially defined structural invariance measure (Lander, 1991; Schack, 2002). In the present analysis, two structures were declared invariant if they possessed a higher value than the invariance measure $\lambda_0 = .68$.¹⁸

In 2001 and 2002, Schack (2004b) studied 19 female players from the German adult and junior national volleyball teams (mean age: 18.7 years), 15 top-rank Cuban players (mean age: 23.6 years) who were top performers in carrying out hits, 17 German regional-division players with a much lower level of performance (mean age: 22.4 years), and 6 persons with no volleyball experience (mean age: 25.5 years).¹⁹ Results showed clear and significant between-group differences in the representation structures (Schack, 2002, 2004a, 2004b). In top-level experts, these representational frameworks were organized in a distinctive hierarchical tree-like structure. Evidently, the classification of these representation structures follows functional principles that are derived from the movement. They were well matched with the functional and biomechanical demands of the task. Interestingly, experts' representation structures were remarkably similar across individuals. In comparison, the action representations in low-level regional-division players and nonplayers showed more variability between persons, were organized less hierarchically, and did not match functional and biomechanical demands.

An example may clarify these results. Figure 1 presents the results of a hierarchical cluster analysis for the group of quick spikers from the German national team.

¹⁷ One selected BAC was displayed constantly on a computer screen as a standard unit in red-colored writing. The rest of the BACs were presented in yellow-colored writing as a randomly ordered list. For each of these yellow-colored BACs, the participant had to judge whether or not it was „functionally close while performing the movement“ to the standard red-colored BAC. This produced two subsets that were then submitted repeatedly to the same procedure until the referee decided no further splits were needed. Because this anchor role of standard was assigned to each BAC in succession, we ended up with a total of 12 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.

¹⁸ Special computer programs were developed to apply this method so that such experiments could be carried out within a reasonable time (10-15 min; the programs are available from the author by request).

¹⁹ These studies were funded through grants from the Federal Institute of Sport Science, Project Number VF 0407/10/07/01.

Figure 1. Results of hierarchic cluster analysis for experts (German women's national volleyball team) in the player position quick spiker ($n = 6$, $\alpha = 1\%$, $d_{crit} = 4.55$). The lower the value of a link between two items (see the scale of Euclidean distances on the right), the lower the distance between the BACs in long-term memory. The value for d_{crit} is displayed as a bar splitting the scale of Euclidean distances; it separates the relevant structural links from less relevant ones (above d_{crit}) for a given α probability.

They reveal a hierarchical representation structure containing four clusters. The mental movement representation is structured in exactly the same way as the movement organization. The categories determined by the clusters (run-up, takeoff, hit preparation, hit) are spatially distinct and ordered in a temporal sequence. The specific BAC structures are evidently used to solve specific subproblems in the movement. Interestingly, BAC 12 does not prove to be represented as a single unit. As mentioned, training instructions have been directed towards a modified execution of the athletes' technique and they have been advised to dispose of this sub-movement for an extensive period of time. The fact that at least for the group of quick spikers this BAC can still be found in the mental representation structure suggests that the corresponding movement is being executed as it has been in the past. Systematic observations (e.g. via 3D- video-analysis) of the movement support this finding.

Thomas Schack

Figure 2. Results of hierarchical cluster analysis for low-level players (regional division) in the player position quick spiker ($n = 7$, $\alpha = 1\%$, $d_{crit} = 4.55$).

Figure 2 presents the results of the hierarchic cluster analysis of data obtained from regional division players. The representation structure revealed clear differences compared with that of experts (see Figure 1). Unlike experts, their BACs were not separated into functionally conceivable clusters.

A biomechanical function analysis of the movement was used to determine an ideal structure for performing the attack hit. This structure is composed of the movement phases run-up, takeoff, hit preparation, and the attack hit itself. By classifying these phases to the relevant BACs, a biomechanically based reference structure could be derived for the movement (1-3; 4-5; 6-8; 10-11). The invariance comparison of the representation structure ascertained for the experts (Figure 1) with the biomechanically based reference structure produced an invariance measure (λ score) of .71. Hence, both structures were invariant. Results on the low-level regional-league players failed to confirm an invariance to either the reference structure ($\lambda = .49$) or the experts' structure ($\lambda = .38$).

A closer look at topological characteristics of representation structures can be obtained by inspecting the dependence of the mental representation of the hit itself on the player's position. First, some particular features of each position have to be considered: Hits in volleyball are made from the quick-spiker and ace-spiker positions. According to Papageorgiou and Spitzley (2000, p. 117), players on the national women's level face specific differences in the demands imposed by 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 24.6s for quick spikers. The number of takeoffs in competitions is 49.4 for ace spikers and 76.7 for quick spikers. Therefore, 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 means that they have to make their technique available more rapidly than other players.

One interesting feature in the structure of quick spikers (Figure 1) is that the play-related node *glance toward opponent's block* is linked to the total cluster of run up and takeoff. Hence, this idiosyncrasy of representation structure is linked clearly 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. For these players, the node *glance toward opponent's block* is integrated into the hit preparation phase (see Schack, 2002, 2004b). 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, takeoff, hit preparation, and hit indicate a functional and differentially confirmable relation between the performance of athletes and representation structures.

A number of our studies on order formation in LTM focused on rotational movements for example in gymnastics, wind-surfing, sky-surfing, alpine freestyle skiing (e.g. Schack, 2002). These movements demand highly defined movement coordination. The essence of motor control is to eliminate the redundant degrees of freedom. However, our test findings reveal that athletes can do this only when they form adequate concepts (BACs) and use them purposefully to solve the movement task. Because rotation movements additionally impose very well-defined and biomechanically reconstructable demands on movement coordination, the functionally relevant concepts are limited in terms of quantity. This advantage is enhanced even more by the fact that athletes generally have already attained a certain expertise level before exercising the rotational movements of their sport (e.g. alpine skiing, gymnastics, windsurfing, sky surfing, snowboarding). Thus, well-defined concepts for the solution of the movement problems nearly always exist already at the beginning of the learning process.

Here, we want to focus on rotational movements in jumping (aerials) in alpine/free style skiing. Alpine skiing involves several notable movements. The helicopter jump or aerial 360° requires a 360° rotation around the stretched longitudinal axis.

Thomas Schack

We shall use a small example to demonstrate what we can find out about the relation between representation structure and performance in specific movement problems. From a total sample of 32 athletes with differing levels of expertise, we shall concentrate on one top-level athlete and one with intermediate expertise who had special movement problems.

Figure 3. An individual expert's dendrogram (subject 11) for a BAC quantity concerning the helicopter movement in ski alpine freestyle ($d_{\max}=3,5$; $d_{\text{krit}} = 3,0$; $\alpha = 5\%$). The lower the value of a diagonal connection between BACs (compare the value scale of Euclidian distances on the right), the lower the distance between concepts.

The test resulted in 14 concepts (mental key points of the movement activity) for solving the movement problems. These are: (1) gliding; (2) going low; (3) backswing movement; (4) swinging arm toward opposite shoulder; (5) rotation initiation head-arms-trunk (HAT); (6) jump; (7) stretched body axis/twisting HAT; (8) inner arm toward the body; (9) head steering; (10) legs follow rotation; (11) view toward direction of motion; (12) opening the arms; (13) landing; and (14) bending knees, hips.

The representation structure of the expert given in Figure 1 shows a remarkable similarity to the biomechanical functional structure of the movement. The higher concepts (start/introduce movement, preparing rotation, rotation, landing) are spatially distinct and ordered chronologically. They seem to solve specific partial problems (getting energy, introducing the impulse, rotation). Furthermore, it is interesting to see that athletes with a high expert level

demonstrate an invariant memory structure (as confirmed by the structural invariance measure). The mental representations of novices and experts also differ significantly in terms of their structure. At the same time, novices' mental representations demonstrate a high variance in the distribution and composition of cognitive substructures.

Figure 4. A dendrogram of an novice (subject 21) with specific movement problems in performing the helicopter movement in alpine freestyle skiing ($d_{\max}=3,5$; $d_{\text{krit}} = 3,0$; $\alpha = 5\%$).

Figure 4 presents the representation structure of the novice with special movement problems. The first thing to be noted is that the representation structures emerge from the central phases (preparing rotation and rotation) and thus from the effect of the movement. The substructures of these two phases are already very clear, whereas the movement phases of "introduce moving" and "landing" are less well structured. At the time of the study, this novice (Participant 7) was finding it particularly difficult to perform the central rotation movement. Most jumps failed because he was unable to introduce and complete the rotation movement in a controlled way. Our results show where the problems may lie. For example, BAC 9 (head steering) is not located in the main phase of the movement but in the phase of preparing rotation. This BAC is linked to sensory (visual) effect representations such as BAC 11 (view toward direction of motion), so that the athlete knows when to prepare for the landing. Its location in the preparing rotation phase can be taken as dysfunctional for optimal performance of the helicopter movement. Later we will show that such experimental analyses can be used to optimize the movement execution through, for example, new forms of mental training.

Thomas Schack

Numerous experimental studies are now available on the structure of mental representations in LTM for complex sport movements. They have examined golf, tennis (e.g., Schack & Mechsner, in press), windsurfing (Schack, 2002; Schack & Mechsner, 2004), sky surfing, gymnastics (Heinen, Schwaiger, & Schack, 2002), freestyle alpine skiing, track and field techniques, or team sports (techniques in soccer, basketball, handball, volleyball). There is also one special group of studies addressing cyclic movements such as walking (Engel & Schack, 2004), riding unicycles, or aqua jogging.

All these studies show that the mental representation structures found relate clearly to performance. As the volleyball study has shown, they are also position- and thereby task-dependent. These representation structures are the outcome of an increasing and effort-reducing formation of order in LTM. This order formation reveals a clear relation to the structure of the movement. With increasing expertise, the representation of the movement corresponds increasingly more exactly to its topological (spatiotemporal) structure. On this level, it has nothing to do with a muscle-oriented effector code. Evidently, the representation structures form through the sensory movement effects of distinctive node points of the movement. The spatiotemporal coupling of these represented movement effects becomes particularly clear when we imagine the representation structures as presented in three dimensions of space and one dimension of time. For instance, looking at Figure 1, imagine the movement of an athlete executing the three nodes of the takeoff within the three dimensions of space. This structure is overlapped by the dimension of time.²⁰ Evidently, the representation structure itself possesses spatiotemporal properties. It corresponds with the structure of the movement. Accordingly, movement control becomes possible by representing the anticipated intermediate effects of the movement and comparing them with incoming effects. This permits a distal focusing on the needed future on the level of mental representations. It also means that no special translation mechanism is required between perception, representation, and movement. From this perspective, voluntary actions are planned, executed, and stored in memory directly through representations of their anticipated perceptual effects.²¹

MOVEMENT-BASED CHUNKING IN WORKING MEMORY

In principle, there are two methodological approaches to the experimental study of representation structures: to determine them from response behavior or to determine them from reaction times. Whereas the first approach has been used for the study of order formation in LTM, the second approach should be used only to ascertain chunk structures in working memory. The architecture model (Schack, 2002) proposes that not only does the LTM structure of mental representations serve as notable function in the organization of movement acts, but also as the exploitation of working-memory *capacity*. It assumes that working memory forms a unit that is structurally and functionally distinct from LTM.

²⁰These analyses were performed on the basis of Euclidean distances in n-dimensional space. This makes the structures n-dimensional. However, this complexity was reduced drastically through the two-dimensional graphic presentation.

²¹At this point, relations to other approaches that explicitly deal with representations become apparent. Examples in this context are TEC (Hommel, et al. 2001), works regarding common coding (e.g. Prinz, 1997), or the perceptual-cognitive approach (Mechsner, 2004).

Donders (1868) introduced the *decomposition of reaction times* as an experimental method for analyzing psychophysiological subprocesses. About 100 years later, Sternberg (1969) adopted this method as a basis to develop a highly influential paradigm for studying high-speed scanning in working memory. Even though Sternberg himself viewed his *additive factor method* (AFM) as an extension of Donders' subtraction method, it actually provides a qualitatively new procedure for decomposing reaction times (see Sternberg, 1998, 2001).

To analyze memory processes, Sternberg (1969) developed a specific experimental paradigm based on his AFM. This approach, now known as the Sternberg Paradigm, confronts participants with a recognition task. A collection of stimuli (N) contains elements (e.g., numbers) that are identical in terms of their physical and semantic features. A subset (S) from this stimulus collection, labeled the positive set, is selected for each trial. The remaining elements (N - S) form the so-called negative set. This set is presented to participants for a short time (circa 3 s), and they have to remember it. After a short break (circa 2 s), a test number is displayed that may belong to either the positive (S) or the negative (N - S) set from the stimulus collection (N). Participants have to decide as quickly as possible whether the test number belongs to the previously displayed positive set or not. Dependent variables are errors and the time interval between test stimulus presentation and reaction.

Sternberg's (1969) studies revealed a *linear dependence* between the reaction time function for positive (hits) or negative answers (misses) and the size of the positive set. One particularly interesting finding proved to be the parallels between the functions for yes and no responses. Sternberg used these to support his assumption of a *serial* and *exhaustive* search process in working memory. He proposed that participants store the list of positive stimuli ($S = 1$ up to $S = 6$) as a reference list in memory and compare each test stimulus presented in the experiment successively with this list. As a result, successively increasing the size of the set will change the total time for the reaction, but not the slope of the reaction-time function. Modifying the optical quality of the presented stimuli changes only the total time and not the slope. Reducing stimulus quality impacts only the stage of stimulus perception.

Our approach (Cognition and Movement Chronometry, CMC) represents a specific further development of the Sternberg Paradigm (Schack, 2002). We shall sketch a few selected points. To obtain appropriate stimuli for the analysis planned here, the movement is broken down into the nodes (BACs) necessary for solving the movement task. These BACs can be presented as, for example, photographs. The relation between the stimuli presented was manipulated systematically to ascertain the development of movement-specific chunks. The memory set in the CMC method displays movement sequences. A complete movement sequence can be viewed as a category. In addition, movement sequences can be presented from different movement acts (multicategorical). Because of the functional structure of the movement, this picture material is simultaneously structured internally (e.g., in terms of functional units or phases). This internal structure should only be accessible when functionally ordered, movement-based mental representations are available to the participant in LTM.

Generally, this approach is applied to three groups: nonathletes, novices, and experts. Although all participants are principally able to solve the task, it can be assumed that groups will differ as a function of their expert status in the way they draw on a specific knowledge of

Thomas Schack

movement. Persons with no experience in solving movement tasks (nonathletes) should also lack the corresponding knowledge components. They are assumed to extract other features from the stimuli than experts.

Table 2

Comparison between the Classic Sternberg Paradigm and the Current Approach (CMC)

	Sternberg (1966, 1969)	Schack (2000)
Stimulus material	Homogeneous/Symbolic Uni-categorical Identical sets of features	Movement-specific pictures Multi-categorical Superficial vs. functional sets of features
Experimental groups	Completely homogeneous	3 separate homogeneous groups: - Nonathletes - Novices - Experts

The example presented here studied freestyle alpine skiing. There were three groups of 15 participants: nonathletes, novices, and experts (Schack, 2000). The stimulus material consisted of pictures of freestyle alpine skiing under the following three conditions:

Non-categorical: Pictures from within a certain sport, but with no direct relation to a special technique.

One-categorical: Pictures of only one movement technique (helicopter).

Two-categorical: Pictures of two different movement techniques (e.g. full twist, helicopter).

This article reports only comparisons of reaction-time functions for the non-categorical versus one-categorical sets in experts versus non-athletes. Because the proportion of decision-making errors (misses) was below 5% for all sets and groups, it was assumed to be low. Hence, further results were based on the reaction times. An alpha level of 5% was used to test hypotheses statistically.

Figure 5 presents the results on the non-categorical set for freestyle alpine skiing experts. The reaction time curves revealed a good fit with a linear function (straight line) for both negative and positive sets.

Figure 5. Experts' mean reaction times for the *non-categorical* set. Coordinates for positive (o) and negative (Δ) responses are based on 120 measurements per set.

Nonathletes also produced linear reaction-time curves (not presented here). The slopes of the reaction-time functions did not differ across groups, and did not reveal any significant differences between positive and negative responses. These results support the idea of a serial and exhaustive memory search for non-categorical picture sets as suggested by Sternberg's (1969, 1975) experiments with letters and numbers. However, experts' absolute reaction times were significantly faster than those of nonathletes on both positive and negative responses. Following the logic of the additive factors method (Sternberg, 1975, 2001), this indicates that experts encoded relevant features of the non-categorical material more quickly than nonathletes. Nonetheless, what is important here is that the memory search did not differ between the two groups.

This is what makes the results on one-categorical item sets so interesting. Randomly ordered pictures of a specific movement (helicopter movement) are viewed as one category. Because of the functional structure of the movement, this picture material is simultaneously structured internally (e.g., in terms of functional units or phases). However, this internal structure should be accessible only when participants possess a higher level of movement knowledge in their LTM. Whereas non-athletes revealed a linear reaction-time function in the one-categorical items sets (results not presented here), athletes produced one corresponding roughly to a logarithmic function (see Figure 6).

Thomas Schack

Figure 6. Experts' mean reaction times for the one-categorical set. Coordinates for positive (o) and negative (Δ) responses are based on 120 measurements per set.

Hence, the reaction-time function no longer increased in a linear relation to the set of given items. This constitutes a fundamental difference in comparison to previous results gained in Sternberg's experiments. Thus, these results point to higher-level memory structures and decision-making processes. They suggest a movement-based chunking. Further experiments, including ones on professional volleyball, free climbing, and gymnastics, varied the set structures in a number of ways and related them specifically to the structure of the selected movement (Schack, 2002, 2004a; Schack & Mechsner, 2004). These studies revealed a plausible relation between chunking processes in working memory and the structure of human movements.

HORIZONTAL COOPERATION BETWEEN COGNITIVE SYSTEMS ON THE LEVEL OF MENTAL REPRESENTATIONS

The architecture model assumes that both systems (LTM and working memory) interact when solving movement tasks. In line with this interaction assumption, the repeatedly confirmed chunking in working memory (Chase & Simon, 1973; Schack, 2000) must possess a functional relationship to the units and the structure of mental representations in LTM. Experiments were designed to assess both the structure of mental representations in LTM (determined with the SDA-M) and chunking in working memory (determined with CMC). If the interaction assumption is true, identifying functional modules of the movement architecture with both groups of experiments should make it possible to match indications of structure in LTM with those in working memory. Results confirmed this (see Schack, 2002; Schack & Mechsner, 2004), demonstrating that cognitive systems interact to produce complex movements.

However, what is crucial is that the previous experiments have shown that both the order formation in LTM and the chunking in working memory build on the topological (spatiotemporal) structure of the movement. This provides experimental evidence that structures in movement and memory mutually overlap.

VERTICAL COOPERATION BETWEEN LEVELS OF REPRESENTATION

If we want to gain a closer understanding of the cognitive architecture of complex movements, it is not only interesting to know whether LTM and working memory cooperate horizontally, for example, on one level of mental representations; it is also crucial to know whether there is a vertical cooperation between the level of mental representations and the level of sensorimotor control.

According to the present architecture model, such a vertical cooperation almost has to posit a coordination of the levels of representation. Because the level of sensorimotor control is directed toward effect representations, it must be possible to confirm relations between the structures of the BACs on the level of mental representations and the structure of sensory effect representations on the level of sensory representations. This hypothesis was tested in two experiments with top international windsurfers (Schack, 2002). Within an indirect scaling procedure using the SDA-M presented above, participants did not classify BACs to further BACs (the BAC x BAC procedure), but BACs to sensory features (BAC x feature procedure). For a number of BACs necessary to generate the end-over (frontal loop) in windsurfing (e.g., takeoff, head turning), participants had to judge whether not only functional features (e.g., stay stable) but also visual or kinesthetic effect representations such as "seeing the horizon," "seeing aft over the shoulder," or "board and body turn" were close together or not. We then examined whether the experimentally ascertained structures for the sensory effect representations were identical to the mental representation structures formed by the attendant BACs. Results confirmed a systematic coupling of BAC features on functional and sensory feature dimensions. Hence, a pattern of functional and perceptual effect representations could be ascertained for every BAC. Finally, the majority of experts revealed a structural invariance between sensory effect representations on the level of sensorimotor representations and attendant BACs on the level of mental representations. Evidently effect-related feature aspects generate the structure of mental movement representations. These findings point to a distal- and effect-related focusing of representation levels. At the same time, they provide indications for structure-functional interactions between the levels of representation.

VERTICAL COOPERATION BETWEEN THE LEVEL OF MENTAL REPRESENTATION AND THE LEVEL OF SENSORIMOTOR CONTROL

The experiments on the structure of mental representations and the structure of chunks have shown a mutual overlap between representation structures and movement structures. The architecture model leads to a further major question in this context: Are there functional relations between the level of mental representations and the level of sensorimotor control? One could also ask whether biomechanically relevant features can be found in the structure

Thomas Schack

of mental representations. Such questions fit into a long discussion over the missing link between biomechanics and other fields of motor research. Therefore, one important step for further research in movement science could be to perform a systematic search for paths between biomechanical aspects and functional units of movement organization.

Some of our studies have been designed to start a systematic search for paths between biomechanical aspects and mental movement representation (Heinen & Schack, 2004; Schack & Mechsner, 2004). This required us to develop methodological approaches to measure kinematic parameters and the structure of mental representations.

To determine such relations, we carried out several studies in gymnastics and volleyball (Heinen & Schack, 2004; Schack & Mechsner, 2004). For example, we investigated how well 36 female gymnasts could perform a special kind of rotational movement: a twisting somersault. Movements were recorded with two cameras, and the movement kinematics were analysed with a computer-based 3D-analysis software (AViP System; Heinen & Schack, 2004). Participants had to perform trampoline somersaults. The number of twists (0.5, 1.0, 1.5, 2.0, and 2.5) increased every sixth jump until participants reached their individual ceiling. Only successful jumps were analyzed with the AViP method. Parallel to this, the structure of mental representations for somersaults was determined with the SDA-M method.

The experimental analysis showed that representational frameworks were organized in a hierarchical tree-like structure and revealed a good match with the biomechanical demands of the task. After measuring kinematic parameters, we investigated the relationship between the structure of motor representation and the kinematic parameters of the twisting somersault movement. We found significant correlations between kinematic parameters (time structure, angles according to the takeoff phase, tilt angle, angular velocities, etc.) of the movement and the corresponding parts of mental representations. For instance, the Euclidian distance between the takeoff and touchdown BACs within the structure of mental representation revealed a significant correlation of $r = .96$ ($p < .001$) with the time of flight. Hence, even the time of flight seems to be mapped (implicitly) in the structure of mental-movement representations. Thus timing may well be only a byproduct of control (see Zelashnik, 2004). However, these empirical findings also apply for parameters such as twisting angular velocity. They provide further indications that the representation of movement possesses a spatiotemporal structure.

These results also suggest that there is a level in the organization of movement from which representations are translated directly into movement. According to this perspective, the representation structure can access all the topological properties that support the movement. This also means that no special translation mechanism is required between perception, representation, muscle control, and movement performance. Because movement effects always appear only within the context of one's own movement system, the pattern of sensory effects, just like the BAC structure imposed on them, has to contain information on them implicitly. This perspective links up with ideas already suggested by Bernstein (1935, 1947). It is not just supported by the present experimental findings, but also by a series of further theoretical and experimental studies (see, e.g., Jeannerod, this issue; Koch et al. this issue).

APPLIED FIELDS IN SPORT

MENTAL TRAINING

Studies carried out during the first half of the 20th century already revealed indications that performing tasks mentally leads to improvements in subsequent test performance (e.g., Sackett, 1935). Various fields of sport psychology have continued such research systematically, particularly since the 1960s (see, e.g., the meta-analysis of Driskell, Copper, & Moran, 1994). The use of mental training in top-level sport has become particularly prominent.

Various theories have been used to explain the effects of mental training (see, e.g., Heuer, 1985; Driskell et al. 1994). The major explanatory models based on current scientific findings can be differentiated according to whether they consider effects to be due to physically peripheral (neuromuscular) processes or central mechanisms (e.g., symbolic codes or programs). Our findings on the cognitive architecture of complex movement extend the work on ideomotor action (Knuf et al., 2001, Koch et al., this issue) and current neurophysiological findings (Jeannerod, 1995; Jeannerod, this issue) and open up a new explanation for the effects of mental training: the *perceptual-cognitive hypothesis*. This posits a representation system in which more strongly cognitive representation units (nodes) are linked to perceptual representations (e.g., kinesthetic-, optical-, or acoustic-effect codes). Because they possess a spatiotemporal structure, these representations can be translated directly into movement. This makes additional motor, spatial-pictorial, or other representations (see, for the symbolic hypothesis, Heuer, 1985) unnecessary for movement control. A further basic assumption of this model is that imagining a movement and performing it are based on the same representations (Jeannerod, 1995; Schack, 2002). This hypothesis would explain the impact of mental training by proposing that it activates and stabilizes the representation system internally. Mental simulations of movement may forge or strengthen links between cognitive representation of intermediate states of the movement and the accompanying perceptual effect codes. At the same time, interfering perceptual inputs will be inhibited. Because these representations are also conceived as being located on a hierarchy of levels, mental training also initiates feedback processes between various representation levels (see Jeannerod).

This grants the methods developed here (e.g., SDA-M) direct significance for the development of new forms of mental training. The main disadvantage of traditional procedures is that they try to optimize the performance through repeated imagination of the movement without taking the athlete's mental technique representation into account (i.e., they are representation blind). However, if the movement's cognitive reference structure has structural gaps or errors, these will tend to be stabilized rather than overcome by repeated practice. The alternative developed here is to measure the mental representation of the movement before mental training and then integrate these results into the training. This Mental Training Based on Mental Representations (MTMR) has now been applied successfully for several years in professional sports such as golf, volleyball (Schack, 2004b), gymnastics (Schack & Heinen, 2000; Heinen, Schwaiger, & Schack, 2002) and windsurfing (Schack & Heinen, 2000).

Thomas Schack

TECHNICAL PREPARATION

Technical preparation is an important field of training in performance sport. How the structure of movements is shaped and how stable modes of coordination for the solution of movement tasks evolve are particularly central themes in research on technical preparation. Assessing mental movement representations opens up specific opportunities to develop new technologies in this field.

This can be illustrated with a practical example from the German national women's volleyball team. Both a trainer survey and movement observation revealed that this player had persistent problems in performing the attack hit in volleyball. Trainers were unable to report any specific causes for this. As a result, she also received very unspecific technique training. The player herself suspected that the reason for her problem was that she was not performing the hit phase correctly. However, the representation structures obtained through the SDA-M method suggested another explanation (Figure 7).

To explain this in detail, one can compare findings from quick-spikers with good movement performance (Figure 1) with those from this quick-spiker with specific movement problems. In quick-spikers with a good movement performance, four different clusters can be identified in the mental representation of the attack hit: run-up (1-3), takeoff (4-5), hit preparation (6-8), and hit (10-12). These substructures are spatially distinct and ordered in a chronological sequence.

Figure 7. Individual representation structure of a German national team player (subject 9) displaying specific movement problems in regard to the quick-spike, shown as a result of cluster analysis ($\alpha = 5\%$; $d_{krit} = 3.98$). The highlighted positions are explained in the text.

The representation structure for this player with specific movement problems had a less functionally well-arranged relation in mental representation (see Figure 7). It differed from the ideal structure (Figure 1) particularly in Items 1-5, which are essential for run-up and takeoff. They were located in three different clusters, with BACs 2-5 falling into two less plausible clusters, whereas Element 1 was in the hit preparation phase. These results indicated that her problems related particularly to an inappropriate movement structure within the run-up and takeoff phases. This led not only to an insufficient generation of kinetic energy but also to an inappropriate distance from the net. Such analyses might be used to work out approaches for mentally supported technique training. However, it would also be possible to derive direct consequences for a technical preparation. For example, it has been suggested that technical preparation should focus more strongly on building a functional rhythm into the first two phases (run-up, takeoff), instead of repeating the entire movement with all its movement errors. This kind of technical preparation led to a demonstrative improvement in performance (Schack, 2004 b).

CONCLUSION

The lines of research presented here have specific consequences for both further research and practical work with athletes. The main concern in the current approach has been to identify the cognitive framing conditions for the organization of complex movements. The present model of the cognitive architecture of complex movements permits a cumulative integration of empirical findings from various fields of research. For example, we are currently carrying out further studies on sensorimotor adaptation, the neurophysiological correlates of mental (BAC) structures, or the modeling of sensorimotor processes. Moreover, relations are becoming clear between various fields of cognitive psychology (e.g., the TEC, IM, and ABC approaches mentioned above), to neurophysiology, and also to biomechanics and biocybernetics. It can be seen how the model formulated here makes it possible to overcome the disadvantages of research focusing solely on specific single theories of limited breadth.

The main idea in the present model is that major interfaces in the architecture of movement are cognitive in nature. Such a perspective does not view the motor system as being distinct from cognition. Instead, it considers both mental and automatized processes of movement organization to be based functionally on cognitive structures and processes that can be described with precision. This does not ignore the significance of emotional or motivational processes; it simply puts them on one side so that we can focus on the architecture of movement. Until now, the line of research reported here represents the first ever attempt to investigate the cognitive representations of complex movement skills in high-level competitive sport settings on the basis of a number of different experimental methods. It has made it possible to transfer established findings from the field of experimental psychology to the fields of sport psychology and movement sciences. This can serve as a specific incentive to carry out further integrative research along the common borders between cognitive psychology, sport psychology, biomechanics, neurophysiology, and other disciplines. In particular, these approaches may be viewed as a new step toward establishing an experimentally oriented cognitive sport psychology (see, already, Straub & Williams, 1984; Zani & Rossi, 1991).

Thomas Schack

The present coupling of basic research with practical problems in various sport domains has clear consequences for applied fields: It contributes to professionalizing the application of sport psychology in various fields of competitive, rehabilitative, and leisure-time sport. Once trainers, teachers, or therapists know how the action system changes step-by-step as a function of an athlete's learning phase or a patient's progress in rehabilitation, they are in a far better position to initiate learning processes, to fine-tune practical interventions, and to reach athletes by matching instructions to their current representation structures.

REFERENCES

- Ach, N. (1905). *Über die Willenstätigkeit und das Denken*. Göttingen: Vandenhoeck und Ruprecht.
- Ach, N. (Hrsg.). (1921). *Untersuchungen zur Psychologie und Philosophie, Bd.3. Über die Begriffsbildung. Eine experimentelle Untersuchung*. Bamberg: C. C. Buchners Verlag.
- Allard, F., & Burnett, N. (1985). Skill in sport. *Canadian Journal of Psychology*, 39, 294-312.
- Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University Press.
- Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought*. Hillsdale, NJ: Erlbaum.
- Anochin, P. K. (1967). *Das funktionelle System der physiologischen Architektur des Verhaltensaktes* (Bd. 1). Jena: Gustav Fischer Verlag.
- Anochin, P. K. (1978). *Beiträge zur Allgemeinen Theorie des funktionellen Systems*. Jena: Fischer.
- Bernstein, N. A. (1935/1967). The problem of the interrelation of co-ordination and localization, (orig. archiv biologiceskich nauk, 38, T. 1, 1-34). In N. A. Bernstein (1967). *The coordination and regulation of movement* (pp. 15-59). London: Pergamon Press.
- Bernstein (Bernstejn), N. A. (1947). *O postrojenii dvizenij* (Über den Aufbau der Bewegungen). Moskva: Medgiz.
- Bernstein, N. A. (1967). *The coordination and regulation of movement*. London: Pergamon Press.
- Bernstein (Bernstejn), N. A. (1971). Bewegungskontrolle. In T. Kussmann & H. Kölling (Hrsg.), *Biologie und Verhalten* (S. 146-172). Bern: Huber.
- Bernstein, N. A. (1975). *Bewegungsphysiologie*. Leipzig: Barth.
- Bernstein, N. A. (1988). *Bewegungsphysiologie* (2.Aufl.). Leipzig: Barth.
- Bernstein, N. A. (1996a). *Die Entwicklung der Bewegungsfertigkeiten*. Leipzig: IAT Eigenverlag.
- Bernstein, N. A. (1996b). On dexterity and its development. In M. L. Latash & M. T. Turvey (Eds.), *Dexterity and its Development* (pp. 3-237). Mahwah: Erlbaum.
- Chase, W. G., & Simon, H. (1973). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215-281). New York: Academic Press.
- Chi, M. T. H. (1979). Knowledge development and memory performance. In M. P. Friedman, J. P. Das, & N. O'Connor (Eds.), *Intelligence and learning* (pp. 221-229). New York: Plenum Press.
- Chi, M. T. H., & Glaser, R. (1980). The measurement of expertise: Analysis of the development of knowledge and skill as a basic for assessing achievement. In E. L. Baker & E. S. Quellmalz (Eds.), *Educational testing and evaluation* (pp. 37-47). Beverly Hills, CA: SAGE.
- Donders, F. C. (1868). Die Schnelligkeit psychischer Processe. *Reichert's & Dubois-Reymond's Archiv für Anatomie, Physiologie und Wissenschaftliche Medizin*, 657-681.
- Driskell, J. E., Copper, C., & Moran, A. (1994). Does mental practise enhance performance? *Journal of Applied Psychology*, 79(4), 481-492.

Thomas Schack

- Engel, F., & Schack, T. (2004). *Motor control of gait movement in elderly*. Manuscript submitted for publication.
- French, K. E., & Thomas, J. R. (1987). The relation of knowledge development to children's basketball performance. *Journal of Sport Psychology*, 9, 15-32.
- Garner, R. (1987). Strategies for reading and studying expository text. *Educational Psychologist*, 22, 299-312.
- Greene, P. H. (1972). Problems of organization of motor systems. In R. Rosen & F. M. Snell (Eds.), *Progress in theoretical biology* (Vol. 2, pp. 123-145). New York: Academic Press.
- Greene, P. H. (1988). The organization of natural movement. *Journal of Motor Behavior*, 20, 180-185.
- Hacker, W. (1998). *Allgemeine Arbeitspsychologie*. Bern: Huber.
- Heinen, T., & Schack, T. (2004). *Mental representation and kinematics - approaches to the functional structure of motor actions*. Manuscript submitted for publication.
- Heinen, T., Schwaiger, J., & Schack, T. (2002). Optimising gymnastics training with cognitive methods. *Proceedings of 7th Annual Congress of the European College of Sport Science* (p. 608). Athen: ECSS.
- Herbart, J. F. (1825). *Psychologie als Wissenschaft neu gegründet auf Erfahrung, Metaphysik und Mathematik*. Zweiter analytischer Teil. [Psychology newly established on experience, metaphysics, and mathematics]. Königsberg: August Wilhelm Unzer.
- Heuer, H. (1985). Wie wirkt mentale Übung? *Psychologische Rundschau*, 4, 191-200.
- Heuer, H. (1994). Koordination. In H. Heuer & S. W. Keele (Hrsg.), *Psychomotorik* (Enzyklopädie der Psychologie: Themenbereich C. Theorie und Forschung: Serie 2. Kognition: Bd. 3, S. 147-222). Göttingen: Hogrefe.
- Hoffmann, J. (1986). *Die Welt der Begriffe*. Berlin: Verlag der Wissenschaften.
- Hoffmann, J. (1993). *Vorhersage und Erkenntnis*. Göttingen: Hogrefe.
- Holst, E. von, & Mittelstaedt, H. (1950). Das Reafferenzprinzip. *Naturwissenschaften*, 37, 464-476.
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24(5), 849-878.
- Huber, J. (1997). Differences in problem representation and procedural knowledge between elite and nonelite springboard divers. *The Sport Psychologist*, 11, 142-159.
- James, W. (1890). *The principles of psychology* (Vol. 1). New York: Holt.
- Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia*, 33(11), 1419-1432.
- Jeannerod, M. (1997). *The cognitive neuroscience of action*. Oxford, UK: Blackwell Publishers Ltd.
- Kalveram, K. T. (2002, Januar). *Regelung und Steuerung bei menschlichen Bewegungen*. Vortrag gehalten auf dem Workshop "Prinzipien der menschlichen Bewegungssteuerung" des Max-Planck-Institut für Psychologische Forschung, München.
- Kalveram, D. T. (2004). The inverse problem in cognitive, perceptual and proprioceptive control of sensorimotor behavior. *International Journal of Sport and Exercise Psychology*, 2(3).

- Keele, S. W. (1986). Motor control. In L. Kaufmann, J. Thomas, & K. R. Boff (Eds.), *Handbook of perception and performance*. New York: Wiley.
- Keele, S. W., Cohen, A., & Ivry, R. (1990). Motor programs: Concepts and issues. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 77-110). Hillsdale, NJ: Erlbaum.
- Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology: Regulatory, Integrative and Comparative*, 15, R1000-R1004.
- Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: Bradford Book, MIT Press.
- Knuf, L., Aschersleben, G., & Prinz, W. (2001). An analysis of ideomotor action. *Journal of Experimental Psychology: General*, 130(4), 779-798.
- Kunde, W. (2003). Temporal response-effect compatibility. *Psychological Research*, 67, 153-159.
- Kunde, W. (2004). Response priming by supraliminal and subliminal action effects. *Psychological Research*, 68, 91-96.
- Kunde, W., & Weigelt, M. (in press). Goal-congruency in bimanual object manipulation. *Journal of Experimental Psychology: Human Perception and Performance*.
- Lander, H.-J. (1991). Ein methodischer Ansatz zur Ermittlung der Struktur und der Dimensionierung einer intern-repräsentierten Begriffsmenge. *Zeitschrift für Psychologie*, 199, 167-176.
- Leontjew, A. N. (1979). *Tätigkeit, Bewusstsein, Persönlichkeit*. Berlin: Volk und Wissen.
- Lewin, K. (1926). *Vorsatz, Wille und Bedürfnis mit Vorbemerkungen über die psychischen Kräfte und Energien und die Strukturen der Seele*. [Intention, volition, and need with preliminary remarks about the psychic forces and energies and the structures of the soul]. Berlin: Springer.
- Luria (Lurija), A. R. (1958). Rol'reci v reguljacii normnal'nogo i anomal'nogo povedenija. V sb: *Problemy vysšej nervnoj dejatel'nosti normal'nogi i anomal'nogo rebenka. Tom 2* (ci. 5-46). Moskva.
- Luria (Lurija), A. R. (1992). *Das Gehirn in Aktion*. Reinbek: Rowohlt.
- Luria, A. R., Pribram, K. H., & Chomskaja, E. D. (1964). An experimental analysis of the behavior disturbances produced by a left frontal arachnoidal endothelioma (meningioma). *Neuropsychologia*, 2, 257-280.
- Luria, A. R., & Subbotski, E. V. (1978). Zur frühen Ontogenese der steuernden Funktion der Sprache. In G. Steiner (Hrsg.), *Die Psychologie des 20. Jahrhunderts* (Bd. VII, S. 1033-1048). München: Kindler.
- MacKay, D. G. (1982). The problem of flexibility and fluency in skilled behavior. *Psychological Review*, 89, 483-506.
- MacKay, D. G. (1985). A theory of representation, organization, and timing of action with implications for sequencing disorder. In E. Roy (Ed.), *Neuropsychological studies of apraxia and related disorders. Advances in Psychology*, 23 (pp. 267-308). New York: Academic Press.
- Marken, R. S. (2002). The hierarchical behaviour of perception. In R. S. Marken (Ed.), *More mind readings: Methods and models in the study of purpose* (pp. 84-116). Chapel Hill, NC: New View Publications.

Thomas Schack

- McPherson, S. L., & Kernodle, M. W. (2003). Tactics, the neglected attribute of expertise: Problem representations and performance skills in tennis. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise* (pp. 137-167). Champaign, IL: Human Kinetics.
- McPherson, S. L., & Thomas, J. R. (1989). Relation of knowledge and performance in boy's tennis: Age and expertise. *Journal of Experimental Child Psychology*, 48, 190-211.
- Mechsner, F. (2004, in press). *A psychological approach for human voluntary movements*.
- Mechsner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature*, 414, 69-72.
- Munzert, J. (1997). *Sprache und Bewegungsorganisation*. Schorndorf: Hofmann.
- Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.
- Newell, K. M., & van Emmerik, R. E. A. (1989). The acquisition of coordination: preliminary analysis of learning to write. *Human Movement Science*, 8, 17-32.
- Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practise. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1-55). Hillsdale, NJ: Erlbaum.
- Nitsch, J. R. (2000). Handlungstheoretische Grundlagen der Sportpsychologie. In H. Gabler, J. R. Nitsch, & R. Singer (Hrsg.), *Einführung in die Sportpsychologie. Teil 1: Grundthemen* (Bd. 2, 3. Aufl., S. 43-164). Schorndorf: Hofmann.
- Papageorgiou, A., & Spitzley, W. (2000). *Handbuch für Leistungsvolleyball* (3. Aufl.). Aachen: Meyer & Meyer.
- Perrig, W. J., & Hofer, D. (1989). Sensory and conceptual representations in memory: Motor images that cannot be imaged. *Psychological Research*, 51, 201-207.
- Powers, W. T. (1990). A hierarchy of control. In R. J. Robertson & W. T. Powers (Eds.), *Introduction to modern psychology: The control-theory view*. Gravel Switch: CSG Publishing.
- Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology*, 4, 1-20.
- Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, 9, 129-154.
- Rosch, E. (1978). Principles of categorization. In E. Rosch & B. B. Loyd (Eds.), *Cognition and categorization* (pp. 27-48). Hillsdale, NJ: Erlbaum.
- Rosenbaum, D. A. (1987). Successive approximations to a model of human motor programming. *Psychology of Learning and Motivation*, 21, 153-182.
- Rosenbaum, D. A., & Jorgensen, M. J. (1992). Planning macroscopic aspects of manual control. *Human Movement Science*, 11, 61-69.
- Russell, S. J. (1990). Athletes' knowledge in task perception, definition and classification. *International Journal of Psychology*, 21, 85-101.
- Russell, S. J., & Salmela, J. H. (1992). Quantifying expert athlete knowledge. *Journal of Applied Sport Psychology*, 4, 10-26.
- Sackett, R. S. (1935). The relationship between amount of symbolic rehearsal and retention of a maze habit. *Journal of General Psychology*, 13, 113-128.

- Saltzman, E. (1979). Levels of sensorimotor representation. *Journal of Mathematical Psychology*, 20, 91-163.
- Schack, T. (2000). Experimental Studies on the speed of information processing in sports related memory. *Journal of Sport & Exercise Psychology*, 22, 94.
- Schack, T. (2002). *Zur kognitiven Architektur von Bewegungshandlungen - modelltheoretischer Zugang und experimentelle Untersuchungen*. Unveröff. Habil., Psychologisches Institut, Deutsche Sporthochschule, Köln.
- Schack, T. (2004a). Knowledge and performance in action. *Journal of Knowledge Management*, 8(4), 38-53.
- Schack, T. (2004b). *Mental representation and performance in volleyball*. Manuscript submitted for publication.
- Schack, T., & Heinen, T. (2000). Mental Training based on Mental Representation. In B. A. Carlsson, U. Johnson, & F. Wetterstrand (Eds.), *Sport Psychology Conference in the New Millennium - a dynamic research-practise perspective* (pp. 333-337). Sweden: Halmstadt University.
- Schack, T., & Mechsner, F. (in press). *Representation of motor skills in human long-term-memory*. *Neuro Science Letters*.
- Schack, T., & Mechsner, F. (2004). *Perceptual-cognitive basis of movement control - direct links between movement, perception and representation*. Manuscript submitted for publication.
- Schmidt, R. A., & Lee, T. D. (1999). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics.
- Starkes, J. L., Deakin, J. M., Lindley, S., & Crisp, F. (1987). Motor versus verbal recall of ballet sequences by young expert dancers. *Journal of Sport Psychology*, 9, 222-230.
- Sternberg, S. (1969). The discovery of processing stages: Extension of Donders' method. *Acta Psychologica*, 30, 276-315.
- Sternberg, S. (1975). Memory scanning: New findings and current controversies. *Quarterly Journal of Experimental Psychology*, 27, 1-32.
- Sternberg, R. J. (1995). Theory and measurement of tacit knowledge as a part of practical intelligence. *Zeitschrift für Psychologie*, 203, 319-334.
- Sternberg, S. (1998). Discovering mental processing stages: the method of additive factors. In D. Scarborough & S. Sternberg (Eds.), *Methods, models, and conceptual issues. an invitation to cognitive science* (Vol. 4, pp. 703-865). Cambridge, Massachusetts: MIT Press.
- Sternberg, S. (2001). Separate modifiability, mental modules, and the use of pure and composite measures to reveal them. *Acta Psychologica*, 106, 147-246.
- Straub, W. F., & Williams, J. M. (1984). *Cognitive sport psychology*. New York: Sport Science Associates.
- Swinnen, S. P., & Wenderoth, N. (2004). Two hands, one brain: cognitive neuroscience of bimanual skill. *Trends in Cognitive Sciences*, 8, 18-25.
- Tembrado, J. J., Zanone, P., Monno, A., & Laurent, M. (1999). Attentional load to the intentional stabilization of preferred coordination patterns. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 1579-1594.
- Thomas, K. T., & Thomas, J. R. (1994). Developing expertise in sport: The relation of knowledge and performance. *International Journal of Sport Psychology*, 25, 295-312.

Thomas Schack

- Turvey, M. T. (1977). Preliminaries of a theory of action with reference to vision. In R. Shaw & J. Balfour (Eds.), *Perceiving, acting and knowing* (pp. 211-265). Hillsdale, NJ: Erlbaum.
- Vereijken, B., Van Emmerik, R. E. A., Whiting, H. T. A., & Newell, K. M. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behaviour*, 24, 133-142.
- Viviani, P. (1986). Do units of motor action really exist? *Experimental Brain Research*, 15, 201-215.
- Vygotsky, L. S. (1978). *Mind in society - The development of higher psychological processes*. Cambridge, MA: Harvard University Press.
- Vygotsky (Vygotskij), L. S. (1992; orig. 1929). *Geschichte der höheren psychischen Funktionen*. Münster: Lit.
- Weigelt, M., Kunde, W., & Prinz, W. (2004). *End-state comfort in bimanual object manipulation*. Manuscript submitted for publication.
- Whitmarsh, B., & Schack, T. (2004). Movement-routines. In J. Taylor (Ed.), *Comprehensive perspectives on applied sport psychology: From researcher and consultant to coach and athlete*. Champaign, IL: Human Kinetics.
- Wiener, N. (1948). *Cybernetics or control and communication in the animal and the machine*. New York: Wiley.
- Wulf, G., & Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychonomic Bulletin & Review*, 8(4), 648-660.
- Wundt, W. (1893). **Grundzüge der Physiologischen Psychologie** (Bd. II, 4. Aufl.). Leipzig: Engelmann.
- Zani, A. & Rossi, B. (1991). Cognitive psychophysiology as an interface between cognitive and sport psychology. *International Journal of Sport Psychology*, 22, 376-398.
- Zelaznik, H. (2004, June). Timing with and without a representation of time. *Journal of Sport and Exercise Psychology, Supplement*, 26, 6.

Author Note

I would like to thank Wilfried Kunde, Franz Mechsner, Matthias Weigelt and Thomas Heinen for helpful comments on an earlier draft of this paper.

WHAT IS THE POINT OF MOTOR PLANNING?

DAVID A. ROSENBAUM¹, RUUD G. J. MEULENBROEK², AND JONATHAN VAUGHAN³

¹Pennsylvania State University, USA

²University of Nijmegen, The Netherlands

³Hamilton College, Clinton, NY, USA

ABSTRACT

In this paper we review our theory of posture-based motion planning, which emphasizes the fact that a single action may be governed by a number of simultaneous constraints and that motion planning is hierarchical with initial emphasis on the determination of goal postures. We critically review the development of the theory and summarize the sources of evidence for its assumptions. We then relate the theory to other recent developments in cognitive neuroscience – such as the growing importance of ideomotor theory – and discuss possible applications of our theory to sport and exercise science.

Key Words: motor planning, degrees of freedom, reaching, manual control, computational model

WHAT IS THE POINT OF MOTOR PLANNING?

What is the point of motor planning? The question is deceptively simple. The point, one is tempted to say, is simply to plan motor activities. The problem with this answer is that the nature of what is planned is not obvious. Moreover, the premise of the question – that motor planning has a single point – may itself be suspect. Motor planning, we argue, has multiple points or purposes, and this is true not just for sequences of movements but also for individual motor acts. Whether one reaches for a glass of water, throws a baseball, swings a golf club, or performs an arabesque, the act is planned to satisfy many constraints. This idea – that motor planning does not have a single point or purpose but instead has many – lies at the core of the theory of motor planning we have developed over the past several years.

In this article, we first review the theory and the sources of evidence for it. We do so by tracing the stages we went through in developing the theory. Such an historical account helps one see that reaching conclusions that may seem obvious in hindsight were not so obvious before they were conceived. By the same token, if the theory seems correct now, we would be remiss in

Correspondence concerning this article should be addressed to David A. Rosenbaum, Department of Psychology, Moore Building, Pennsylvania State University, University Park, PA 16802. E-mail: dar12@psu.edu

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

accepting it uncritically for many questions arise from the theory and many of its assumptions still need to be confirmed. Taking these remarks into account, we offer this review as a report of work in progress rather than a statement of a *fait accompli*. After reviewing the theory, we compare it to other recent developments in cognitive neuroscience and discuss its possible applications to sport and exercise science.

OPTIMAL MOVEMENT SELECTION

In the 1980s, two developments in the field of motor control were especially important. One was the emergence of dynamical systems analysis and the view that movements exploit rather than resist mechanical properties of the environment (Kugler & Turvey, 1987). The other was the suggestion that movements tend to obey a simple optimization criterion, such as minimizing mean-squared jerk (Flash & Hogan, 1985), or mean-squared torque change (Uno, Kawato, & Suzuki, 1989). These two developments challenged researchers who were committed to a purely symbolic view of motion planning as a special case of human information processing. A more biologically and physically realistic view of motor control and planning was necessary.

Figure 1. Illustrations of the degrees of freedom problem for a single positioning movement, which has (A) different speed profiles, (B) different spatial trajectories, (C) different final postures.

Both of the developments alluded to above enabled, or compelled, researchers to address the problem made famous by Bernstein (1967) in his now-classic volume, *The Coordination and Regulation of Movement*. This was the degrees of freedom (*df*) problem. Expressed most generally, the *df* problem inheres in the mapping of many elements to a fewer number elements such that the mapping is indeterminate. The *df* problem can be observed at many levels. In movement control, for example, innumerable combinations of neurons' action potentials can result in the same net contraction pattern of the innervated muscle. Overt movement has a similar *df* problem. For a simple gesture such as moving the fingertip from

one location to another, there are an infinite number of potential speed profiles (see Figure 1A). At a higher level of description there is also a *df* problem: The spatial trajectory followed by the finger need not be the most direct path to the target (see Figure 1B). Rather, an infinite number of spatial paths can be pursued. Furthermore, for each of those spatial paths, there is a plethora of possible speed profiles. The multiplicity of options does not stop there, for when the fingertip reaches a target location in the workspace, the finger, hand, and arm to which it is connected need not be in a unique posture (see Figure 1C). An infinite number of limb configurations may bring the fingertip to a given location in the workspace. The number of options, therefore, is staggering. If we suppose that there are p possible final postures, s possible spatial paths to each posture, and v possible speed (or tangential velocity) profiles for each path, the number, n , of possible movements is

$$n = s \cdot v \cdot p, \quad (1)$$

and this is true even for a task as simple as moving the fingertip from one location to another. Clearly, there has to be a mechanism for choosing one of these many possibilities.

Flash and Hogan's (1985) hypothesis that the hand follows an optimal "minimum jerk" trajectory was one of the first attempts to grapple with this difficult problem (see Nelson, 1983, for an earlier attempt). It did so with respect to v . Considering the idealized speed profiles shown in Figure 1A, Flash and Hogan noted that the speed profiles that are normally seen rise smoothly and then descend smoothly, suggesting the observed profiles had the mathematical property of minimizing the sum over movement time of the mean-squared jerk (the third time derivative of position).

A minimum jerk trajectory defines a speed profile, but it does not define the time over which the profile is defined. Hence, minimizing jerk or other costs such as minimum torque change (Uno et al., 1989), does not reduce v to 1. How can the movement time be specified? Here the other important line of work in 1980s – the emergence of dynamical systems analysis with its incorporation of Bernstein's views – comes into play. Any object has a natural or "resonant" frequency of vibration. The resonant frequency of a hummingbird's wing is much higher than the resonant frequency of an eagle's wing. Limb segments are no different. A short, light segment such as a finger has a higher resonant frequency than does a long, massive segment such as the forearm. Kugler and Turvey (1987) helped psychologists appreciate the importance of resonant frequencies. They studied the simple task of swinging pendulums at preferred frequencies and found that the frequencies that subjects spontaneously adopt while swinging the pendula agree with classical mechanics: As the length of the pendulum increases, the frequency at which it is swung decreases. Subsequent investigations have replicated and extended this outcome.

Rosenbaum, Slotta, Vaughan, and Plamondon (1991) pursued the hypothesis that different resonant frequencies for limb segments of different length might provide a basis for the specification of movement times. They also asked whether the relative contributions of different limb segments to simple limb displacements might be predicted by the limbs' optimal combinations of frequency and amplitude. As is well known in classical mechanics, a mass-spring system not only has a resonant frequency; it also has characteristic amplitudes for

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

different frequencies of vibration (French, 1971). Typically, for a given spring stiffness, the maximal amplitude of vibration is easiest to sustain at some optimal amplitude-frequency combination. Assuming that this principle applies to limb segments, Rosenbaum et al. (1991) hypothesized that during simple positioning movements the relative contributions of different limb segments might depend on the extent to which their optimal amplitude-frequency combinations approximate the amplitude-frequency combinations required of the end effector (e.g., the fingertip in the case of a hand movement from one place to another).

To test this hypothesis, Rosenbaum et al. (1991) conducted two experiments with the same subjects (see Figure 2). In the first experiment, the subjects were asked to carry out back-and-forth manual displacements in the horizontal plane. The participants were asked to oscillate either the index finger alone (rotating about the metacarpophalangeal joint), the hand alone (rotating about the wrist, keeping the index finger rigidly extended), or the forearm alone (rotating about the elbow, keeping the wrist and index finger rigidly extended). In the amplitude-driven condition, they were asked to move the fingertip back and forth between two targets at whatever frequency they preferred; the distance between the targets was varied. In the frequency-driven conditions, they were asked to move the fingertip back and forth in time with a metronome whose frequency was varied, covering whatever distance they preferred. The question was what frequencies subjects would spontaneously generate with each limb segment in the amplitude-driven condition and what amplitudes they would spontaneously generate with each limb segment in the frequency-driven condition.

Figure 2. Finger, wrist, and forearm solutions to the problem of moving the fingertip between two points in space. Reprinted from Vaughan, J., Rosenbaum, D. A., Diedrich, F., & Moore, C. M. (1995). Cooperative selection of movements: The optimal selection model. *Psychological Research/Psychologische Forschung*, 58, 254-273.

The results, shown in Figure 3, indicate that for each limb segment there was an inverse linear relation between frequency and amplitude. Furthermore, there were small differences in slope for the amplitude-driven and frequency-driven conditions. At a higher-than-optimal frequency

the preferred amplitude was smaller, and vice-versa. These differences allowed Rosenbaum et al. (1991) to identify the intersection of the two functions for each limb segment as the optimal amplitude-frequency combination for that limb segment. As expected from classical mechanics, the longer and heavier the limb segment, the lower its optimal frequency and the larger its optimal angular amplitude. Thus, much as a hummingbird's wings flutter at a high frequency over a small amplitude, the finger oscillates most efficiently at a high frequency over a small angular amplitude. Similarly, much as an eagle's wings flap at a low frequency over a large amplitude, the forearm oscillates most efficiently at a low frequency over a large angular amplitude. The wrist can be regarded as the "robin" of the group, having an optimal frequency and angular amplitude that are intermediate.

Figure 3. Amplitude-frequency relations for the finger, wrist, and forearm. Rosenbaum, D. A., Slotka, J. D., Vaughan, J., & Plamondon, R. J. (1991). Optimal movement selection. *Psychological Science*, 2, 86-91.

In the second experiment that Rosenbaum et al. (1991) conducted, they asked the same subjects to move the fingertip back and forth such that there was a prescribed amplitude and frequency in each condition. Now the subjects were free to use whatever limb combination they preferred. The results, shown in Figure 4, indicated that the relative contributions of the limb segments to the net displacement of the fingertip was related to the similarity of the required fingertip amplitude and frequency to the limb segments' optimal amplitude-frequency combinations. When a large-amplitude, low-frequency oscillation was required, the forearm contributed the most, but when a small-amplitude, high-frequency oscillation was required, the finger contributed the most. The wrist contributed the most for intermediate combinations. Similar results were obtained by Vaughan, Rosenbaum, Diedrich, and Moore (1995) in a rhythmic tapping task.

David A. Rosenbaum, Ruud G. J. Meulenbroek, & Jonathan Vaughan

Figure 4. Relative contributions of the finger, wrist, and forearm to tasks requiring displacement of the fingertip over prescribed amplitudes at prescribed frequencies. Reprinted from Rosenbaum, D. A., Slotka, J. D., Vaughan, J., & Plamondon, R. J. (1991). Optimal movement selection. *Psychological Science*, 2, 86-91.

These results are consistent with the hypothesis that limb segments contribute in proportion to their ability to perform the task at hand. Said another, more general way, motor planning that is informed by dynamic considerations allows limb segments to move optimally, or as close to optimally as possible. Using this idea, it is possible to fit the data shown in Figure 4 with a simple weighting scheme in which each limb segment's contribution is weighted according to how close the fingertip's required amplitude and frequency come to the limb segment's optimal amplitude-frequency combination. Details can be found in Rosenbaum et al. (1991), and Vaughan et al. (1995).

POSTURE-BASED MOTION PLANNING

As simple as the optimal selection model is, it runs into a problem that was not apparent when the model was proposed. The problem can be understood by considering the stick figure in Figure 5. The stick figure can bend at the hip, shoulder, and elbow, permitting movement of the torso, upper arm, and forearm in the sagittal plane. Nonetheless, there is no way for the stick figure to rely on the optimal movement method to bring its hand from the starting position to the target. The reason is that neither hip rotation by itself, nor shoulder rotation by itself, nor

elbow rotation by itself permits the hand to reach the target. By contrast, in the experiments of Rosenbaum et al. (1991) and Vaughan et al. (1995) it was always possible for each effector to achieve the required displacement on its own. When such self-sufficiency is not met, the model breaks down. This is because each effector's potential contribution is defined with respect to the amplitudes and frequencies it can generate on its own given where the limb is situated at the start of the task.

Figure 5. Different postures that allow the finger to reach the same location in space. Reprinted from Rosenbaum, D. A., Engelbrecht, S. E., Bushe, M. M., & Loukopoulos, L. D. (1993b). Knowledge model for selecting and producing reaching movements. *Journal of Motor Behavior*, 25, 217-227 (Special issue edited by T. Flash & A. Wing: Modeling the control of upper limb movement).

How can this problem be solved? There is no simple way to solve it through a modification of the optimal selection model, so in response to this impasse, Rosenbaum, Engelbrecht, Bushe, and Loukopoulos (1993a, 1993b) proposed that there is a stage of motor planning that occurs before movements are planned. This stage involves specification of a limb configuration or goal posture. According to the emergent *posture-based motion planning* perspective, movements are planned to goal postures and goal postures must be planned first. After a target location is chosen in external space, a goal posture is found and then a movement to the goal posture is specified. Only then is the physical movement actually performed according to the model.

Several results in the literature on motor control and motor learning led to this idea, and newer results have since lent more credence to it. We list those results below and then turn to more details about the way the model functions.

SUPPORT FOR GOAL POSTURE PLANNING

Six lines of evidence provide support for the notion that goal postures are planned before movements are specified. It is noteworthy that these findings come from disparate approaches to the study of motor control and motor learning. Moreover, to the best of our knowledge, there are no findings that contradict the hypothesis, which is not to say that the hypothesis cannot be disconfirmed.

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

MOVEMENT SMOOTHNESS

One source of evidence for the goal-posture-first idea has already been presented here. As already noted, movements tend to be smooth, as emphasized by Flash and Hogan (1985). To generate a smooth movement, one must know in advance how long the movement will take and how far it will go, at least if the generation of smooth movements relies on computations analogous to those outlined by Flash and Hogan. Insofar as these values imply knowledge of final limb configurations, such knowledge must be present in advance. The criterion for movement smoothness need not be minimum mean-squared jerk, as suggested by Flash and Hogan, but other criteria such as minimum mean-squared torque change (Uno et al., 1989) or peak work (Soechting, Buneo, Herrmann, & Flanders, 1995) also require knowledge of final position and of total movement time.

ANTICIPATORY EFFECTS

If end states are known before movements begin, one should observe that very early phases of overt movements differ depending on how the movements will terminate. There are many sources of support for this prediction.

One is linked to the evidence for movement smoothness, discussed above. If speed profiles for discrete positioning movements are bell-shaped, then one should find scaling of the basic speed profile according to the amplitude and duration of movement, including in its earliest phases. Evidence consistent with this prediction has been obtained in a number of studies. For example, Gordon, Ghilardi, and Ghez (1997) found that initial speed is scaled to subsequent amplitude, as shown in Figure 6 (see next page).

It has also been shown that the orientation of the hand, or of a hand-held tool, varies in the first 120 ms for movements in accordance with the hand orientation that will be adopted at the end of the movement (Brown, Moore, & Rosenbaum, 2002). Similar effects have been obtained for reaction times to initiate hand movements that end with different orientations (Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992). In the latter study, the ending orientations were determined by the subjects and were not due to differences in what the subjects saw prior to acting.

Anticipatory effects of a different sort, which also support the view that goal postures are represented in advance, take the form of the *end-state comfort* effect. This is a tendency to place the hand and arm in an uncomfortable position when taking hold of an object for the sake of comfort (or good control) later, when the object is brought to its final position. The end-state comfort effect was discovered when a waiter was observed picking up inverted glasses and filling each glass with water. The waiter took hold of each glass with his thumb down close to the table and with his little finger up. This was an uncomfortable position, but by adopting it, the waiter was able to be in a comfortable or easily controlled posture later, when the glass was upright and water was poured into it. Evidently, the waiter tolerated initial discomfort for the sake of end-state comfort. The broader implication was that later postural states are represented before they are adopted.

Figure 6. Bell-shaped tangential velocity profiles for movements in different directions and distances. Reprinted from Gordon, J., Ghilardi, M.F., & Ghez, C. (1997). Accuracy of planar reaching movements .1. Independence of direction and extent variability. *Experimental Brain Research*, 99, 97-111.

A series of laboratory experiments confirmed that the end-state comfort effect is a robust phenomenon (Hermsdörfer, Buchner, Kerkhoff, Mai, & Goldenberg, 1999; Rosenbaum & Jorgensen, 1992; Rosenbaum, Marchak, Barnes, Vaughan, Slotta, & Jorgensen, 1990; Rosenbaum et al., 1992; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993; Short & Cauraugh, 1997, 1999; Steenbergen, Meulenbroek, & Rosenbaum, in press). For example, as seen in Figure 7, when subjects reached out and took hold of a handle to rotate a turntable 180°, they took hold of the handle in such a way that the final posture at the end of the rotation would bring the forearm close to the middle of the pronation-supination range. Oscillations of the forearm near the middle of the pronation-supination range are also faster than oscillations of the forearm near the extremes of this range (Rosenbaum, Heugten, & Caldwell, 1996). Similarly, the torques that can be generated are greater at midrange (Winters & Klewen, 1993), and so is proprioceptive sensitivity (Rossetti, Meckler, & Prablanc, 1994). The latter findings provide a good functional rationale for ending movements at or near the middle of the pronation-supination range, especially when precision is required for the ending phase.

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

Figure 7. The end-state comfort effect. Reprinted from Rosenbaum, D. A., Vaughan, J., Jorgensen, M. J., Barnes, H. J., Stewart, E. (1993). Plans for object manipulation. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV — A silver jubilee: Synergies in experimental psychology, artificial intelligence and cognitive neuroscience* (pp. 803-820). Cambridge: MIT Press, Bradford Books.

Anticipatory effects in general provide the basis for behavioral evidence of planning, a point first enunciated by Lashley (1951) and picked up by many others afterward (e.g., Klapp, 1977; Sternberg, Monsell, Knoll, & Wright, 1978). Lashley argued that if a person commits a slip of the tongue that can be interpreted as an intrusion from something he or she is likely to say later (e.g., saying “flow snurries” instead of the intended “snow flurries”), it is reasonable to infer that a plan exists both for the immediate and subsequent parts of the utterance. Detailed analyses of slips of the tongue have permitted detailed models of plans for language production (Dell, 1986; Levelt, 1989). The data reviewed above provide complementary evidence for behaviors at a smaller scale – for individual gestures rather than for sequences of gestures or language acts (cf. Norman, 1981; Reason, 1990).

DISTINCT SYSTEMS FOR MOVEMENT AND FOR POSITION

A third source of evidence for the hypothesis that there are distinct stages of planning for end states and for movements is that distinct systems exist for coding position and for coding movement. Different receptors in the muscles and joints respond to static position and to motion. Moreover, recent behavioral studies support a dissociation between the control of position and the control of movement. As seen in Figure 8, when the hand is moved back and forth repeatedly without visual feedback and the subject’s aim is to cover the same distance and axis of motion in every movement cycle, the hand’s position drifts but its distance and axis of motion remain remarkably invariant over movement cycles (Brown, Rosenbaum, & Sainburg, 2003a, b). This outcome suggests that there are distinct levels of control of positioning and for moving the hand.

Figure 8. Relative invariance in movement direction and distance despite drift in hand position. Reprinted from Brown, L. E., Rosenbaum, D. A., & Sainburg, R. L. (2003a). Limb position drift: Implications for control of posture and movement. *Journal of Neurophysiology*, 90, 3105-3118.

MEMORY FOR POSITION VERSUS MEMORY FOR AMPLITUDE

A dissociation between position and movement is also apparent in research on memory. As shown in classic work by Marteniuk and Roy (1972), memory for final hand position is superior to memory for movements to those same final positions. Thus, if participants are asked to return the hand to the place it last occupied, they can do so very well even if the starting position is changed and even if the movement is momentarily interrupted. By contrast, covering the same distance that was last covered from a different starting point is much less accurate. This finding has been replicated and extended in subsequent studies (see Smyth, 1984, for review). Finding that position is better remembered than movement suggests that position is represented at a higher functional level than is movement, at least by analogy to the classic finding that memory for sentence meaning occupies a higher level than memory for exact sentence wording given that sentence meanings are remembered longer than are exact sentence wordings (Sachs, 1967).

NEURONS FOR MOVEMENT AND NEURONS FOR POSTURES

If positions and movements have distinct functional representations, they might also have distinct neural representations. Many studies have provided evidence for neurons whose activity is related to forthcoming movements. The firing of such neurons correlates with forthcoming directions of eye movements and hand movements as well as other features of forthcoming motions of the eyes, hands, and other effectors. For a review of classic work on this topic, see Georgopoulos (1991).

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

Figure 9. Postures evoked by stimulation of neural pools in primary motor cortex and premotor cortex. Reprinted from Graziano, M. S., Taylor, C. S. R., & Moore, T. (2002). Complex movements evoked by microstimulation of precentral cortex. *Neuron*, 34, 841-851.

Recently, it has been shown that neurons in the primary motor cortex and premotor cortex of the monkey code body postures rather than relative movements (Graziano, Taylor, & Moore, 2002). Electrically stimulating these neurons for behaviorally relevant periods of time (e.g., 500 ms rather than the 20-50 ms used in the classical evoked-movements studies of Penfield and Rasmussen, 1950) elicits characteristic postures of the hand, arm, and face (see Figure 9) regardless of the posture the monkey happens to be in prior to stimulation. To bring the monkey to the same posture, stimulating these brain regions must produce different muscle activation patterns depending on the animal's initial posture, suggesting that lower regions in the nervous system – most probably the spinal cord and cerebellum – generate the necessary muscle activations. That the generation of muscle commands comes from a lower center is further supported by the finding that when the limb is prevented from moving to the goal posture, the muscle activity is approximately the same as when the limb can move freely to the goal posture.

REFERENCE CONDITIONS FOR POSITION

Although the foregoing results, like the others described above, support the hypothesis that there is a dissociation between control of position and movement, only the last set of results needs to be taken to suggest that goal postures are represented *before* movements. There is another reason to believe that representations of goal postures are formed before representations of movements. This reason harks back to why positioning movements occur at all. The point of positioning movements is to bring the hand (or other part of the body) to a desired position. When positioning movements are made, corrections are made if the

movements do not bring the end-effector to its desired position. This capacity for error-correction could exist only if there were a representation of the end-effector's goal position. Seeing the hand make a corrective movement allows for the inference that the hand's incorrect goal position must have been represented in advance. By the same token, the very first movement toward a target site can likewise be viewed as an instance of error correction, albeit on a larger scale. When one decides to bring one's hand to a position, one finds oneself immediately in error, for the hand is not where it belongs. Thus, saying that a representation of a goal position exists before the very first movement is made is no more controversial than saying that a representation of the goal position exists before subsequent corrective movements are performed.

COMPUTATIONAL METHODS

The previous section offered six reasons for the proposition that goal postures are represented independently of, and prior to, movements. In this section we provide more information about the computational methods that our posture-based model uses to generate movements. These computational methods have undergone some changes in the years since 1993, when the model was first introduced (Jax, Rosenbaum, Vaughan, & Meulenbroek, 2003; Rosenbaum et al., 1993a, b; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). We refrain from reviewing the succession of methods used because these are matters of implementation which are of no particular significance for present purposes. What is important, however, is that the core claims of the model have remained the same since its inception. Indeed, the computational method has become simpler and more powerful as we have continued to work with and better understand the model.

Why have we prepared our model in computational form? The main reason is that implementing a model computationally requires one to fully specify all the assumptions needed to get the model to work. Furthermore, a computational model of movement lets one render the model's output as an artificial, moving creature. The performance of such an animated figure allows one to view the animation much as one views actual behavior and thus judge informally as well as formally how its performance compares to what people (and animals) do in the everyday environment.

ELIMINATION BY ASPECTS

To organize the presentation of the computational methods of the posture-based model, it is useful to recall the three levels of indeterminacy discussed earlier in this article.

The model first resolves the indeterminacy of p . It does so by identifying a goal posture that is best suited for the positioning task to be performed. The way it identifies the goal posture relies on the principle expressed in the opening of this article, namely that motor planning has multiple points or purposes, not just one. In the case of specifying a goal posture, the goal posture needs to satisfy many constraints. If the only constraint that had to be satisfied was that

David A. Rosenbaum, Ruud G. J. Meulenbroek, & Jonathan Vaughan

the end-effector had to be in contact with the spatial target, this would not uniquely specify a goal posture for every point within the workspace, for, by definition, every such point can be contacted with infinitely many postures. Thus, the constraint that the end-effector be in contact with the target does not, under normal circumstances, uniquely imply a single posture. More constraints are needed. These added constraints can be viewed as occupying lower levels of a hierarchy of constraints.

The successive application of constraints at a number of levels, from highest to lowest, is known as *elimination by aspects* (Tversky, 1972). When a choice is made via elimination by aspects, some candidates are eliminated if they do not satisfy the highest-level constraint, then other candidates are eliminated if they do not satisfy the constraint at the next, lower level, and so on. If, after the lowest level constraint has been applied, more than one candidate is still viable, the "winner" can be chosen at random. Defining such a constraint hierarchy is one way of defining a task to be performed. Different tasks can be defined by different constraints, or the order of the same constraints may vary (depending, for example, on whether grace, speed, or accuracy is most important). The way performers define tasks has received scant attention in psychology, although task switching and its time costs have recently become the target of much investigation (Monsell, 2003). Insofar as skilled performance is marked by its flexibility, it is vital to understand how actors recognize which tasks should be performed in which circumstances. It is equally important that there be a formalism by which tasks can be represented. The constraint hierarchy is one such formalism, and elimination by aspects is one means by which the constraint hierarchy can be used to good effect.

SPECIFICATION OF GOAL POSTURES, MOVEMENT PATHS, AND SPEEDS

Once one allows for the constraint hierarchy, one has a way of resolving all the indeterminacies outlined earlier. The plethora of options for goal postures, p , can be resolved by having enough constraints to define the goal posture to be adopted. Likewise, the plethora of options for spatial movement paths, s , and for tangential velocities, v , can be resolved if adequate constraints are assumed to exist for these two parameters. More details are given below, and a full account is given in Rosenbaum et al. (2001).

Because our model is rendered as a stick figure that reaches within a plane, the constraints in the model allow the stick figure to carry out movements within that plane. The constraints related to goal-posture specification let the stick figure bring a desired point along its rigid limb segment chain to a specified point within its planar workspace. Such a point may be on a tool (e.g., the end of a hand-held rod). If the tool is rigid and is attached to a single point along the limb segment chain with a known angle of attachment, its location in external space can be computed using forward kinematics (trigonometry). The same method can be used to find the extrinsic spatial location of any other point along the limb segment chain. If there is a part of the workspace that should or should not be contacted when the stick figure is in its goal posture, that constraint can also be added when a goal posture is sought. Similarly, if it is important for multiple parts of the stick figure to be in contact with a target, that constraint can be added as well (e.g., in placing the fingers around an object to be grasped). Finally, if one cares about the cost of moving to a possible goal posture from a starting posture, that

constraint can likewise be taken into account in choosing a goal posture. Which of these multiple constraints is brought to bear in goal-posture specification depends, by definition, on the task to be performed, as does the relative importance of the constraints. Both the identities of the constraints for goal-posture selection and the relative priority of the constraints are needed to define the constraint hierarchy. The point of goal-posture selection is, according to this view, to satisfy the constraints of the current constraint hierarchy.

Movement selection works in much the same way in our theory. The point of movement selection is to satisfy whatever constraints define the nature of the movement to be performed. One such constraint, which is used by default (i.e., not necessarily in all conditions) is that the movement be smooth in the sense that its tangential velocity profile be bell-shaped and the duration of the movement be matched to the preferred amplitude-period combinations of the effectors used to bridge the gap between the starting posture and just-selected goal posture. This constraint addresses the indeterminacy denoted by v .

Figure 10. Superposition of movements for movement shaping. The main movement from a starting posture to a goal posture is performed at the same time as a sequence of movements from a starting posture to a bounce posture and then back to the starting posture.

The indeterminacy concerning spatial path, s , is likewise addressed by invoking appropriate constraints. By default, the movement path is defined by a straight line through posture space between the starting posture and goal posture. Such a movement is more economical than one that requires staggering or reversing the direction of joint rotation. If the anticipated movement path is not acceptable (e.g., it would result in a collision with an obstacle or violate some other constraint) the shape of the movement path may need to be further constrained. Through forward modeling (i.e., internally simulating the possible movement) an acceptable movement path can be found before a movement is actually performed physically. The means of shaping the movement path, according to the theory, is reminiscent of the means of selecting goal postures: When a movement must have a shape other than the one it has by

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

default, one must govern that shape by selecting a bounce posture in addition to a goal posture. The idea behind the bounce posture is that a movement may be made from the starting posture to the bounce posture and then back to the starting posture. This back-and-forth movement sequence is performed at the same time that a movement is made from the starting posture to the goal posture (see Figure 10). The observed movement is a composite of the two. Because the movement from the starting posture to the bounce posture is followed by a movement back to the starting posture, the entire back-and-forth sequence adds no net displacement to the main movement from the starting posture to the goal posture. However, depending on where the bounce posture is located relative to the starting and goal posture, the back-and-forth movement can have a dramatic effect on the composite movement, as shown in Figure 11. In our model, the bounce posture is chosen with respect to its own constraint hierarchy which takes into account the path shape that must be followed. More details are given in Rosenbaum et al. (2001) and Vaughan, Rosenbaum, and Meulenbroek (2001).

Figure 11. The superposition of movements in the joint-velocity domain during obstacle-avoidance. Reprinted from Vaughan, J., Rosenbaum, D. A., & Meulenbroek, R. G. J. (2001). Planning reaching and grasping movements: The problem of obstacle avoidance. *Motor Control*, 5, 116-135.

SUMMARY OF COMPUTATIONAL METHOD AND SOME FURTHER POINTS ABOUT IT

The foregoing comments provide an overview of the means by which goal postures and movements are specified in the posture-based motion planning theory. To review the main

points, it is claimed that the point of motor planning is to satisfy multiple, task-dependent constraints. These constraints are assumed to be represented in a hierarchy. It is also assumed that the planning of movements proceeds in two main stage. In the first stage, a goal posture is found. In the second stage, a movement to that goal posture is established. If, during planning, the anticipated movement is found to be inadequate in one way or another (e.g., it would result in collision with an obstacle or would fail to result in contact with an object for which contact is desired), the default movement path is reshaped by selecting an appropriate bounce posture which may afford suitable superposition of back-and-forth movements to and from the bounce posture on top of the main movement to the primary goal posture. The theory does not preclude the possibility that movement planning may feed back to goal-posture planning, triggering a search for a goal posture that affords a better movement (cf. Kawato, 1996). However, for simplicity, the working computational version of the theory is uni-directional (goal postures selected before movements) rather than bi-directional (goal postures selected before or after movements). Another feature of the computational method of the theory is that it relies on a combination of generation and recall of goal postures and movements. According to the theory, a goal posture may be identified either by recalling a goal posture that was recently adopted – the theory allows that $m > 1$ such postures may be stored – or by generating a new goal posture. A new goal postures can be found by “tweaking” the retrieved goal posture that is the best candidate for the task at hand, as defined by the goal-posture constraint hierarchy. Recent behavioral work supports this hypothesis (Cohen & Rosenbaum, in press).

REPRESENTATIVE RESULTS

What can the posture-based motion-planning model achieve? The model makes it possible to simulate or explain a number of phenomena, some of which are observed in the laboratory and some of which occur in the everyday world. This section provides an overview of the main competencies and phenomena the model can explain.

COMPENSATION FOR REDUCED MOBILITY OF JOINTS

Changing the mobility of a joint does not result in paralysis. Instead, other joints typically compensate. Thus, if one walks and gets a pebble in one's shoe, walking does not come to a halt. Similarly, if one's wrist is immobilized by arthritis or accident, activities that require manual activity do not come to a crashing halt. The posture-based model provides a simple account of compensation for changes in joint mobility. For example, when one reaches for a point in external space, the hip, shoulder, and elbow normally contribute to the movement. If, however, the elbow cannot bend as easily as usual, the shoulder and hip can contribute more than usual (Rosenbaum et al., 1995). The mechanism that makes this possible in the posture-based motion-planning model is simply to favor goal postures that entail smaller elbow rotations. Similarly, if the hip cannot rotate as well as usual, goal postures can be selected that entail little bending of the hip. Representative simulations are shown in Figure 12.

David A. Rosenbaum, Ruud G. J. Meulenbroek, & Jonathan Vaughan

Figure 12. Compensation for changes in joint mobility. Reprinted from Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G. M., Vaughan, J., & Engelbrecht, S. E. (1995). Planning reaches by evaluating stored postures. *Psychological Review*, 102, 28-67.

REACHING AROUND OBSTACLES

Just as it is important to compensate for changes in joint mobility, it is important to reach around obstacles. As mentioned above, the posture-based model provides a way of explaining this competency. It does so by assuming that after a goal posture is specified, a movement to the goal postures is internally simulated and evaluated to see whether it will result in an unwanted collision with an object in the workspace. The evaluation relies on forward kinematics. If an unwanted collision is anticipated, a search is mounted for a suitable bounce posture, as discussed above. This proposal has been tested by confronting the model with obstacle-avoidance tasks analogous to ones that human subjects have been asked to perform. The model has performed much as humans do in these situations, as illustrated in Figure 13. See Rosenbaum, Meulenbroek, and Vaughan, (1999), Rosenbaum et al. (2001), and Vaughan et al. (2001).

Figure 13. Simulation of reaching around an obstacle. Reprinted from Vaughan, J., Rosenbaum, D. A., & Meulenbroek, R. G. J. (2001). Planning reaching and grasping movements: The problem of obstacle avoidance. *Motor Control*, 5, 116-135.

Coordinated Grasping and Reaching

A great deal of research has been done on the detailed kinematics of the fingers, hand, and arm during the simple task of reaching out to take hold of an object (Jeannerod, 1981; Mackenzie & Iberall, 1994; Wing, Haggard, & Flanagan, 1996). The observed data concerning the kinematics of the effectors, especially of the index finger, thumb, and wrist, provide benchmarks against which theoretical simulations can be contrasted. Rosenbaum et al. (2001) and Meulenbroek, Rosenbaum, Jansen, Vaughan, & Vogt (2001) focused on the control of grasping and checked how well the model could predict human prehension kinematics. In the behavioral experiment, human subjects reached for a cylinder placed at different distances and radial directions from a home position. The ways the upper arm, forearm, wrist, and index finger moved during the prehension task were subsequently modeled by determining the expense factors for the effectors that afforded the best fit to the human data. When these best fitting parameters were found, it was possible to conclude that the model could account for the observed kinematics of any human subject as well as the observed kinematics of any other subject could. Notwithstanding the fact that the data to be explained were, by the choice of the experimenters, only the kinematics of upper arm, forearm, wrist, and index finger, this outcome is *prima facie* evidence in favor of the general validity of the model.

MOTOR EQUIVALENCE IN HANDWRITING

Perhaps no task reflects the motor system's flexibility as well as the capacity to generate the same written output no matter what part of the body is used for writing. Writing with a pen held between one's teeth, between one's toes, with the non-preferred hand, or with the preferred hand yields comparable written output. The capacity to generate comparable written output with any part of the body has been simulated using the principles of posture-based motion planning (Meulenbroek, Rosenbaum, Thomassen, Loukopoulos, & Vaughan, 1996). To generate the simulations, some of whose results are shown in Figure 14, the pen tip was made to go to spatial target locations (defined as points of maximum curvature in the cursive letters to be produced) and *through* "via points" (defined as points of minimum curvature in the same cursive letters).

Figure 14. Comparable written output generated with different effectors in different planes. Reprinted from Meulenbroek, R. G. J., Rosenbaum D. A., Thomassen, A. J. W. M., Loukopoulos, L. D., & Vaughan, J. (1996). Adaptation of a reaching model to handwriting: How different effectors can produce the same written output, and other results. *Psychological Research/Psychologische Forschung*, 59, 64-74.

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

Noncommutativity of Joint Rotations

If one did not subscribe to the view that goal postures are planned before movements are planned, one would have to grapple with the problem of noncommutativity of joint rotations. The term "commutativity" refers to the fact that the order in which operations are performed does not matter, as in addition: Whether one adds 2 to 3 or 3 to 2, the answer is the same. Joint rotations, by contrast, are noncommutative. The order in which joints are rotated does matter. For an example, see Rosenbaum et al. (2001, p. 730). Noncommutativity of joint rotations is a problem for any theory of motor planning which says that, in an effort to reach desired end positions, the motor planning system deals first with possible movements rather than with possible goal postures. Dealing first with possible movements results in a large number of final limb positions that may not be close to the desired final limb position because the order of joint rotations gives rise to widely discrepant end states. The nonlinearity of the mapping of joint-rotation orders to end positions resulting from noncommutativity is what makes end-state planning so hard, especially in a model that realistically represents movements in three-dimensional space, where many joints have more than one potential axis of rotation. By contrast, if the motor planning system deals first with goal postures and if the considered movements all share the property that they bridge the gap between the initial posture and the goal posture, then the movements under consideration are restricted to just those that bring the limb to where it needs to go. The possible movements differ only with respect to the timing and magnitude of the joint rotations. Interestingly, it has been suggested that staggering of joint rotations (i.e., varying the timing and magnitudes of joint rotations while keeping start and end positions invariant) may prove to be an effective way of shaping limb trajectories for tasks such as obstacle avoidance, writing, and gesturing (Hollerbach, Moore, & Atkeson, 1987).

START-POSITION EFFECTS

The foregoing section appeals to the importance of start-position information as well as end-position information in motor planning. Start-position knowledge is needed to ensure that motor commands have desired effects on the limb. If the muscles pull on the bones with forces and torques that are inappropriate to the limbs' starting position, the position that the limb ultimately adopts will be far from the one that is desired. At a higher level of control – the level of movement planning rather than movement execution – the specification of goal postures may depend on start postures, though in principle they need not do so. For example, if one endorses a strong form of the equilibrium point hypothesis (see Latash, 1993), one could say that one merely needs to establish signals for the equilibrium point without regard to the starting position of the limb and the limb will move to the equilibrium point. Though this is possible a priori, our posture-based motion planning model says that goal postures are normally planned with respect to start postures. This makes it possible to choose goal postures that permit easy movements from starting positions and also allows for immediate compensation for changes in joint mobility, as discussed above. Several studies have shown that adopted goal postures do in fact depend on start postures (Elsinger & Rosenbaum, 2003; Fischer, Rosenbaum, & Vaughan, 1997; Soechting et al., 1995). Likewise, performance suffers when start-position information is reduced (Desmurget, Gréa, & Prablanc, 1998).

OTHER EFFECTS

There are other effects as well which the posture-based motion-planning model can account for. First, consistent with the model's claim that travel costs are taken into account in goal-posture planning, goal-posture selection depends on required (and produced) movement speed (Fischer et al., 1997).

Second, consistent with the model's claim that memory for position involves memory for postures and not just memory for end-effector spatial location, studies of memory for position reveal that when one hand must go to the place recently occupied by the other hand, there is a tendency for the hand and arm used for the reproduction to mirror the posture recently during the induction phase (Baud-Bovy & Viviani, 1998; Rosenbaum et al. 1999).

Third, consistent with the model's claim that limb position and limb motion are controlled at different levels, it has recently been shown that movement direction and distance are well preserved even while limb position drifts considerably (Brown et al. 2003a,b). In these experiments, subjects moved the hand back and forth on a frictionless table (with the forearm resting on an airsled) first with sight of the hand's displacement between two targets and then without sight of the still-moving hand. The hand's position drifted in successive movements, due to the accumulation of small direction and distance errors. However, as shown through inverse dynamic modeling, the commands to the muscles were modulated to take into account the limb's position. If the muscle commands had not been modulated in this way, the directions and distances moved would have deviated much more than they did from their desired constant values. This result reveals a dissociation between limb-position control and limb-movement control. Participants in these studies were unsure where their limbs were, as they reported during debriefing. Nevertheless, the system responsible for moving the limbs worked accurately, generating muscle commands that reflected relatively accurate monitoring of limb position of which the participants were not aware. This outcome accords with the hypothesis that there are separate systems for the control of limb position and for the control of limb movement (see also Rantanen & Rosenbaum, 2003).

REMAINING ISSUES AND IMPLICATIONS FOR SPORT AND EXERCISE PSYCHOLOGY

In this final section of the article we tackle two more matters. First, we address several questions that often arise in connection with our model. In this connection, we also consider some remaining issues for the model to address. Finally, we consider possible implications of our model for sport and exercise psychology.

QUESTIONS AND REMAINING ISSUES FOR THE MODEL

Several questions often arise in connection with our model. We raise them below and also provide answers to them.

David A. Rosenbaum, Ruud G. J. Meulenbroek, & Jonathan Vaughan

DOES THE MODEL ALLOW FOR SPATIAL CODING OF MOVEMENTS?

With its heavy reliance on posture coding, the posture-based motion planning model seems to deny representations of the spatial coding of end-effectors, yet there is abundant evidence for the priority of spatial coding over motor coding in human perceptual-motor tasks. For instance, stimulus-response compatibility effects are more strongly determined by the spatial congruence of response locations and stimulus locations than by which effector (e.g., the left or right hand) makes the response to a stimulus on the left or right (Wallace, 1971). Does the model include spatial coding or, according to the model, are all responses coded only in terms of postures? The answer is that the model certainly allows for spatial coding of responses and of response outcomes (Greenwald, 1970; Hommel, Musseler, Aschersleben, & Prinz, 2001). These are assumed to be represented at a higher level of planning than are the representations of postures. Posture representations come into play when the actor determines how to use the body to get to a spatial position chosen before.

That spatial coding is represented at a higher level than posture coding is supported by a study in which participants tried to adapt to artificial distortions of displayed hand positions when they had to bring the hand, without visual feedback, to a position they thought would let the hand touch a visible spatial target (Rogosky & Rosenbaum, 2000). When the distortion was spatial (e.g., when the hand cursor was shown at a higher position than the hand actually was), participants could adapt easily. By contrast, when the distortion was postural (e.g., the hand cursor was shown at a position that depended on the angle of the elbow), participants had a much harder time adapting. Insofar as the distortion was no more complicated, from a mathematical standpoint, in the posture-distortion condition than the space-distortion condition, this outcome is consistent with the hypothesis that posture planning is different from spatial planning. The greater difficulty participants encountered in the posture-distortion condition fits with the view that posture planning is "deeper down" in the system than in spatial planning. For a related experiment that also made the point that posture-learning occurs during adaptation, see Rosenbaum & Chaiken (2001).

Is the Model Consistent with Ideo-Motor or Event Coding Theories?

Much recent discussion in the human performance literature has confirmed the view that plans for movement include representations of the movements' anticipated perceptual consequences (Greenwald, 1970; Hommel et al. 2001). Such a view makes sense from a cybernetic (feedback-control) perspective. For feedback to be evaluated so corrections can be initiated if needed, the feedback must be compared to a previously established reference value. Such a reference value (or vector of values) is embodied in a representation of expected perceptual consequences of movements.

The posture-based motion-planning model is consistent with this view. As implied in the last section, we view the representation of future postural states as just one part of the plan for action. When movements are made, they are typically made for a larger purpose than just to bring the body to a new goal posture. The hand is brought to a new position to indicate one's willingness to bid more money at an auction, to press a button in a voting booth, or to provide the downbeat to an orchestra. Or more direct perceptual consequences may be anticipated, such as turning on a light. In the case of haptic consequences, the fact that

haptic results of forthcoming arm movements are represented in advance has been demonstrated in recent studies inspired by the discovery that rods felt with two hands at the same time are felt to be parallel when, at least for some rod positions, the rods have widely divergent angles (cf. Kappers, 2003; Meulenbroek, Kappers, & Mutsaerts, 2001).

DOES THE MODEL ACCOUNT FOR MOVEMENT ERROR CORRECTION?

Does the model apply to corrective movements or only to initial movements toward spatial targets? It does. Whenever a voluntary movement brings a part of the body to a target, the movement is triggered by detection of a discrepancy between where the body part is relative to the target. This is just as true for initial movements as for subsequent movements. Moreover, it is usually the case that there are just as many possible goal postures for corrective movements as for initial movements. Thus, the machinery needed to find an appropriate goal posture for corrective movements is the same as for initial movements.

HOW MANY LEVELS DO CONSTRAINT HIERARCHIES HAVE?

The theme of this article is that motor planning does not have a single purpose but instead has many purposes, as stipulated in constraint hierarchies. It is reasonable to ask, therefore, how many levels constraint hierarchies have. In the modeling work we have done, we have included as many constraints as needed to define the goal posture and corresponding movements of a stick figure moving in two spatial dimensions. Relatively few constraints were needed for this artificial creature performing these tasks. More constraints are obviously needed for real actors performing in the physical world. How many constraints are required is hard to say, but it is important to observe that more constraints are probably required for some tasks than for others. A task requiring considerable precision and grace (e.g., drinking tea with Queen Beatrix of the Netherlands) probably requires more constraints than a task that does not require as much precision or grace (e.g., drinking beer with one's buddies). More interestingly, it is likely that more constraints are used for practiced, skilled tasks than for less practiced, less skilled tasks. An accomplished musician, for example, probably has a much more elaborated description of the musical performance task he or she is about to perform than does a neophyte. This conjecture, which emerges from our posture-based motion-planning model, is worth exploring in the future.

WHAT ABOUT MOVING IN THREE SPATIAL DIMENSIONS?

All the simulations described so far have involved movements in just two spatial dimensions. Planar (two-dimensional spatial) movements are easier to model than volumetric (three-dimensional spatial) movements, but the posture-based model is extendable to movements in three spatial dimensions. We have made progress on this front (see Figure 15), suggesting that the same kind of synchronous joint movements observed in our two-dimensional modeling work are also observed in three-dimensional workspaces (Klein Breteler & Meulenbroek,

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

2003). The same obstacle-avoiding mechanisms used in 2-dimensional movement planning also work for three-dimensional movements (Vaughan, Lantz, Rosenbaum, Jax, Kurdushian, Meulenbroek, et al., 2003).

Figure 15. Front (left panel) and side views of the modeled reach of a stick-figure in three-dimensions, from a starting location (S) to a goal location (G), avoiding an obstacle in the path of direct movement. Reprinted from Vaughan, J., Lantz, K., Rosenbaum, D. A., Jax, S., Kurdushian, A., Meulenbroek, R. G. J., et al. (2003, March). Moving about obstacles: Pass the salt, but don't spill the milk. *International Workshop on Posture-Based Motion Planning*. Pennsylvania State University, University Park, PA.

WHAT ABOUT FORCES AND TORQUES?

The simulations described so far have been restricted to the control of kinematics (positions without regard to the forces or torques that affect those positions). Realistic theories of motor planning must explain how forces and torques are controlled. In the work described earlier on the dissociation of limb positions and limb movements (Brown et al., 2003a, b), inverse dynamics modeling was used to infer the dissociation. This technique lets one model the forces and torques that give rise to observed limb positions. From the observed limb positions, one works "backwards" to infer what the necessary forces and torques were. This is not the same as modeling how forces and torques are specified in advance of movement, however. Those values must be specified by the nervous system. Indeed, in much the same way that there are all the levels of indeterminacy for motor performance discussed above – the number, v , of possible speed (or tangential velocity) profiles, the number, s , of possible spatial paths, and the number, p , of possible goal postures – there is also a number, f , of possible forces and torques defining the dynamics of the positions to be adopted. Including f in an equation to define the number, n' , of possible movements for a simple positioning tasks, increases the value of n by a factor of f , that is, the indeterminacy grows still more.

How is the indeterminacy of f resolved? At this time we can only give a speculative answer: In principle, it should be possible to specify muscle forces and torques through constraint hierarchies that include requirements about dynamics. Implementing this claim in a working computer simulation is a challenge we intend to pursue in the future.

IMPLICATIONS FOR SPORT AND EXERCISE PSYCHOLOGY

What are the implications of our model for sport and exercise psychology? Apart from any implications that are obvious insofar as they bear on aspects of everyday motor performance, we think three additional implications are worth noting. These implications pertain to individual differences in motor abilities, the nature of coaching and practice, and a surprising claim about the actual goal of some athletic tasks.

With respect to individual differences in motor abilities, our model may have something to say about clumsiness in some individuals and, at the other extreme, exceptional skill as exemplified in great athletes. Our model has various parameters that allow it to run on a computer. These parameters in turn influence the nature of the simulated performance. For example, every joint in the model has a number of possible values within its range; the larger this number, the finer the postural discriminations that can be made. Extending this idea to people, someone with a small number of possible joint values for postural discriminations might not be able to adopt, at will, very different goal postures, and such a person, as a result, might be clumsy. By contrast, someone with a large number of possible joint values for postural discriminations might be able to adopt, at will, highly differentiated goal postures, and such a person might be especially adroit athletically. A possible prediction that stems from these suggestions is that people who have acute proprioceptive discrimination should be better athletes – all other things being equal – than people who have poor proprioceptive discrimination. This is just one example of a way in which a parameter of the model might shed light on, or at least raise new questions, about the nature of individual differences.

A second implication of the model pertains to coaching and the nature of practice. If a major feature of skill acquisition is the formation of increasingly detailed constraint hierarchies, then a focus of coaching and practice might be on the performer's understanding of the tasks to be achieved. Here we refer not just to the performer's awareness of the major aims of the task but instead to an ever more exacting appreciation of the detailed features of what should be aspired to. Taking a cue from what happens at music conservatories – a domain we are more familiar with than athletics because the first author is an avid amateur musician and father of a Juilliard conservatory graduate but not an athlete – the coach should work with the performer to enable him or her to say or demonstrate exactly what s/he is trying to do in every situation under study. Such a practice may help the performer form constraint hierarchies that are better suited to the tasks to be performed. This view of skill development differs from the standard view of skill acquisition (Fitts, 1964; Fitts & Posner, 1967) which asserts that skill development consists of moving from a cognitive to an associative and then to an autonomous (or automatic) stage. Developing automaticity is doubtless important, but it does the performer little good simply to become more automatic on tasks that may have been improperly encoded early in practice. Appreciation of the task itself must undergo refinement as the skill develops, for if it does not, development of the skill may falter.

The third and final implication of the model for exercise and sport psychology is that the ostensive goal of some athletic activities may not be what they seem to be at first. Initially, the goal of hitting a golf ball is to get the ball into the hole. But if one wrote a program to get a robot to hit a golf ball, telling the robot to get the ball to the hole would do little good. The

David A. Rosenbaum, Ruud G. J. Meulenbroek, & Jonathan Vaughan

details of motor execution would be left unspecified. How, then, would the robot move its arms (assuming it had arms) to achieve the goal? The robot would have to find a means of moving to get the ball to its goal position. Having found that means of movement, the robot's motoric goal would in fact be to move so as to bring its body to whatever goal position it had specified.

According to this analysis, the motoric goal of hitting a goal ball is not to get the ball into the hole. Instead, it is to bring the club over the shoulder at a particular position after having swung the club at a speed and through a path that happens to knock the ball in the direction and over the distance it needs to go. Freddie Couples, one of the world's leading golfers, known especially for the beauty of his swing, wrote something that echoes this perspective. "I learned when I was a kid," he wrote, "that the faster I get my hands on my left shoulder, the farther it goes" (Golf Digest Special Edition 1996).

Obviously, no one cares about the final position of the golfer's body if his or her shots routinely yield bogies. Our point is that good scores can only be achieved if the actual, motoric goal of golfing is effectively realized. The same can be said for throwing a baseball, for swinging a bat, or for kicking a soccer ball. What happens to the ball after it has lost contact with the athlete is what everyone cares about, including the athlete, but the motoric goal of the athlete must be, and indeed can only be, what he or she is able to do with his or her body while in contact with the ball. To the extent that this analysis is correct and to the extent that the posture-based motion-planning theory is correct, the implication is that learning to produce the most consistent goal postures possible through the most consistent strokes should be the main focus of athletes attempting to improve their skills in tasks requiring propulsion of balls to desired locations. The golf, tennis, or baseball player who is able to achieve a consistent follow-through by consistent planning of the goal posture will be rewarded by an efficient collision with the ball at an optimal point in the movement trajectory. Pursuing consistent goal postures through consistent movements might be a useful way of improving athletic performance for other tasks as well, at least according to the analysis we have provided.

REFERENCES

- Bernstein, N. (1967). *The coordination and regulation of movements*. London: Pergamon.
- Baud-Bovy, G., & Viviani, P. (1998). Pointing to kinesthetic targets in space. *The Journal of Neuroscience*, 18, 1528-1545.
- Brown, L. E., Moore, C. M., & Rosenbaum, D. A. (2002). Feature-specific processing dissociates action from recognition. *Journal of Experimental Psychology: Human Perception and Performance*, 28, 1330-1344.
- Brown, L. E., Rosenbaum, D. A., & Sainburg, R. L. (2003a). Limb position drift: Implications for control of posture and movement. *Journal of Neurophysiology*, 90, 3105-3118.
- Brown, L. E., Rosenbaum, D. A., & Sainburg, R. L. (2003b). Movement speed effects on limb position drift. *Experimental Brain Research*, 153, 266-274.
- Cohen, R. G. & Rosenbaum, D. A. (in press). Where objects are grasped reveals how grasps are planned: Generation and recall of motor plans. *Experimental Brain Research*.
- Dell, G. S. (1986). A spreading activation theory of retrieval in sentence production. *Psychological Review*, 93, 283-321.
- Desmurget, M., Gréa, H., & Prablanc, C. (1998). Final posture of the upper limb depends on the initial position of the hand during prehension movements. *Experimental Brain Research*, 119, 511-516.
- Elsinger, C. L., & Rosenbaum, D. A. (2003). End posture selection in manual positioning: Evidence for feedforward modeling based on a movement choice method. *Experimental Brain Research*, 152, 499-509.
- Fischer, M. H., Rosenbaum, D. A., & Vaughan, J. (1997). Speed and sequential effects in reaching. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 404-428.
- Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243-285). New York: Academic Press.
- Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont, CA: Brooks Cole.
- Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *The Journal of Neuroscience*, 5, 1688-1703.
- French, A. P. (1971). *Vibrations and waves*. New York: W. W. Norton & Co.
- Georgopoulos, A. P. (1991). Higher order motor control. *Annual Review of Neuroscience*, 14, 361-37
- Gordon, J., Ghilardi, M.F., & Ghez, C. (1997). Accuracy of planar reaching movements .1. Independence of direction and extent variability. *Experimental Brain Research*, 99, 97-111.
- Graziano, M. S., Taylor, C. S. R., & Moore, T. (2002). Complex movements evoked by microstimulation of precentral cortex. *Neuron*, 34, 841-851.
- Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, 77, 73-99.

David A. Rosenbaum, Ruud G. J. Meulenbroek, & Jonathan Vaughan

- Hermisdörfer, J., Buchner, K., Kerkhoff, G., Mai, N., & Goldenberg, G. (1999). Effects of unilateral brain damage on grip selection, coordination, and kinematics of prehension movements. *Experimental Brain Research*, 128, 41-51.
- Hollerbach, J. M., Moore, S. P., & Atkeson, C. G. (1987). Workspace effect in arm movement kinematics derived by joint interpolation. In G. N. Gantchev, B. Dimitrov, & P. Gatev (Eds.), *Motor control* (pp. 197-208). Plenum.
- Hommel, B., Musseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24, 849-937.
- Jax, S. A., Rosenbaum, D. A., Vaughan, J., & Meulenbroek, R. G. J. (2003). Computational motor control and human factors: Modeling movements in real and possible environments. *Human Factors*, 45, 5-27.
- Jeannerod, M. (1981). Intersegmental coordination during reaching at natural objects. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 153-169). Hillsdale, N.J: Erlbaum.
- Kappers, A. M. L. (2003). Large systematic deviations in a bimanual parallelity task: Further analysis of contributing factors. *Acta Psychologica*, 114, 131-145.
- Kawato, M. (1996). Bidirectional theory approach to integration. In T. Inui & J. L. McClelland (Eds.), *Attention and performance XVI: Information integration* (pp. 335-367). Cambridge, MA: MIT Press.
- Klapp, S. T. (1977). Reaction time analysis of programmed control. *Exercise and sport sciences reviews*, 5, 231-253.
- Klein Breteler, M. D., & Meulenbroek, R. G. J. (2003). *The timing of 3D arm-joint rotations: Independent control of geometrical degrees of freedom?* Paper presented at the Dutch Psychonomics Conference, Egmond aan Zee, The Netherlands, 19-20 December 2003.
- Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law and self-assembly of rhythmic movements: A study in the similitude of natural law*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112-131). New York: Wiley.
- Latash, M. L. (1993). *Control of human movement*. Champaign, IL: Human Kinetics.
- Levelt, W. J. M. (1989). *Speaking*. Cambridge, MA: MIT Press.
- MacKenzie, C. L., & Iberall, T. (1994). *The grasping hand*. Amsterdam: North-Holland.
- Marteniuk, R. G., & Roy, E. A. (1972). The codability of kinesthetic location and distance information. *Acta Psychologica*, 36, 471-479.
- Meulenbroek, R. G. J., Kappers, A. L., & Mutsaerts, M. (2000, March). *Does haptic space play a role in the planning and execution of grasping movements?* Poster presented at the Workshop on Neural Control of Space Coding and Action Production, Lyon, France.
- Meulenbroek, R. G. J., Rosenbaum, D. A., Jansen, C., Vaughan, J., & Vogt, S. (2001). Multijoint grasping movements: Simulated and observed effects of object location, object size, and initial aperture. *Experimental Brain Research*, 138 (2), 219-234.

- Meulenbroek, R. G. J., Rosenbaum D. A., Thomassen, A. J. W. M., Loukopoulos, L. D., & Vaughan, J. (1996). Adaptation of a reaching model to handwriting: How different effectors can produce the same written output, and other results. *Psychological Research/Psychologische Forschung*, 59, 64-74.
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, 7, 134-140.
- Nelson, W. L. (1983). Physical principles for economies of skilled movements. *Biological Cybernetics*, 46, 135-147.
- Norman, D. A. (1981). Categorization of action slips. *Psychological Review*, 88, 1-15.
- Penfield, W., & Rasmussen, T. (1950). *The cerebral cortex of man: A clinical study of localization of function*. New York: MacMillan.
- Rantanen, E., & Rosenbaum, D. A. (2003). Drift in blind reciprocal aiming movements. *Motor Control*, 7, 199-228.
- Reason, J. (1990). *Human Error*. New York: Cambridge University Press.
- Rogosky, B. J., & Rosenbaum, D. A. (2000). Frames of reference for human perceptual-motor coordination: Space-based versus joint-based adaptation. *Journal of Motor Behavior*, 32, 297-304.
- Rosenbaum, D. A., & Chaiken, S. (2001). Frames of reference in perceptual-motor learning: Evidence from a blind manual positioning task. *Psychological Research/Psychologische Forschung*, 65, 119-127.
- Rosenbaum, D. A., Engelbrecht, S. E., Bushe, M. M., & Loukopoulos, L. D. (1993a). A model for reaching control. *Acta Psychologica*, 82, 237-250.
- Rosenbaum, D. A., Engelbrecht, S. E., Bushe, M. M., & Loukopoulos, L. D. (1993b). Knowledge model for selecting and producing reaching movements. *Journal of Motor Behavior*, 25, 217-227 (Special issue edited by T. Flash & A. Wing: Modeling the control of upper limb movement).
- Rosenbaum, D. A., Heugten, C. V., & Caldwell, G. C. (1996). From cognition to biomechanics and back: The end-state comfort effect and the middle-is-faster effect. *Acta Psychologica*, 94, 59-85.
- Rosenbaum, D. A., & Jorgensen, M. J. (1992). Planning macroscopic aspects of manual control. *Human Movement Science*, 11, 61-69.
- Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G. M., Vaughan, J., & Engelbrecht, S. E. (1995). Planning reaches by evaluating stored postures. *Psychological Review*, 102, 28-67.
- Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J., & Jorgensen, M. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and performance XIII: Motor representation and control* (pp. 321-342). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Rosenbaum, D. A., Meulenbroek, R. G., & Vaughan, J. (1999). Remembered positions: Stored locations or stored postures? *Experimental Brain Research*, 124, 503-512.
- Rosenbaum, D. A., Meulenbroek, R. G., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review*, 108, 709-734.

David A. Rosenbaum, Ruud G.J. Meulenbroek, & Jonathan Vaughan

- Rosenbaum, D. A., Slotta, J. D., Vaughan, J., & Plamondon, R. J. (1991). Optimal movement selection. *Psychological Science*, 2, 86-91.
- Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992). Time course of movement planning: Selection of hand grips for object manipulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 18, 1058-1073.
- Rosenbaum, D. A., Vaughan, J., Jorgensen, M. J., Barnes, H. J., & Stewart, E. (1993). Plans for object manipulation. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV — A silver jubilee: Synergies in experimental psychology, artificial intelligence and cognitive neuroscience* (pp. 803-820). Cambridge: MIT Press, Bradford Books.
- Rossetti, Y., Meckler, C., & Prablanc, C. (1994). Is there an optimal arm posture? Deterioration of finger localization precision and comfort sensation in extreme arm-joint postures. *Experimental Brain Research*, 99, 131-136.
- Sachs, J. (1967). Recognition memory for syntactic and semantic aspects of a connected discourse. *Perception & Psychophysics*, 2, 437-442.
- Short, M. W., & Cauraugh, J. H. (1997). Planning macroscopic aspects of manual control: End state comfort and point-of-change effects. *Acta Psychologica*, 96, 133-147.
- Short, M. W., & Cauraugh, J. H. (1999). Precision hypothesis and the end state comfort effect. *Acta Psychologica*, 100, 243-252.
- Smyth, M. M. (1984). Memory for movements. In M. M. Smyth & A. M. Wing (Eds.), *The psychology of human movement* (pp. 83-117). London: Academic Press.
- Soechting, J. F., Buneo, C. A., Herrmann, U., & Flanders, M. (1995). Moving effortlessly in three dimensions: Does Donders' Law apply to arm movement? *Journal of Neuroscience*, 15, 6271-6280.
- Steenbergen, B., Meulenbroek, R. G. J., & Rosenbaum, D. A. (in press). Constraints on grip selection in hemiparetic cerebral palsy: Effects of lesional side, end-point accuracy, and context. *Cognitive Brain Research*.
- Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 117-152). New York: Academic Press.
- Tversky, A. (1972). Elimination by aspects: A theory of choice. *Psychological Review*, 79, 281-299.
- Uno, Y., Kawato, M., & Suzuki, R. (1989). Formation and control of optimal trajectory in human multijoint arm movement: Minimum torque-change model. *Biological Cybernetics*, 61, 89-101.
- Vaughan, J., Lantz, K., Rosenbaum, D. A., Jax, S., Kudurshian, A., Meulenbroek, R. G. J., et al. (2003, March). Moving about obstacles: Pass the salt, but don't spill the milk. *International Workshop on Posture-Based Motion Planning*. Pennsylvania State University, University Park, PA.
- Vaughan, J., Rosenbaum, D. A., Diedrich, F., & Moore, C. M. (1995). Cooperative selection of movements: The optimal selection model. *Psychological Research/Psychologische Forschung*, 58, 254-273.

- Vaughan, J., Rosenbaum, D. A., & Meulenbroek, R. G. J. (2001). Planning reaching and grasping movements: The problem of obstacle avoidance. *Motor Control*, 5, 116-135.
- Wallace, R. J. (1971). Stimulus-response compatibility and the idea of a response code. *Journal of Experimental Psychology*, 88, 354-360.
- Wing, A. M., Haggard, P., & Flanagan, R. (Eds.). (1996). *Hand and brain: Neurophysiology and psychology of hand movement*. San Diego: Academic Press.
- Winters, J. M., & Kleweno D. G. (1993). Effect of initial upper-limb alignment on muscle contributions to isometric strength curves. *Journal of Biomechanics*, 26, 143-153.

Author's Note

The work described here was supported by grants from the National Science Foundation, Grant 1 R15 NS41887-02 from the National Institute of Neurological Diseases and Strokes, the Research and Graduate Studies Office of the College of Liberal Arts of Pennsylvania State University, and the Dutch National Science Foundation. We thank Chip Gerfen, a linguist and amateur golfer, for telling us about the golfer Freddie Couples, and we thank Rajal Cohen, a graduate student in the first author's lab at the time this article was written for suggesting the hypothesis that people who have acute proprioceptive discrimination should be better athletes – all other things being equal – than people who have poor proprioceptive discrimination.

BULLETIN BOARD

UPCOMING EVENTS AND CONFERENCES

February 3 - 6 2005

7th Motor Control and Human Skill Conference

Fremantle, Australia. Keynote Speakers: Joseph Sergeant (Vrije Uni of Amsterdam, The Netherlands), John Rothwell (Institute of Neurology, London, UK). Further Information: Dr Natalie Gasson, Email: n.gasson@curtin.edu.au, Web site: <http://psych.curtin.edu.au/conference/motorcontrol/index.htm>

June 2-4, 2005

European workshop on movement science

Vienna, Austria. It is hosted by the Workgroup for Movement Science of the Veterinary University Vienna. Keynote speakers: Axel Cleeremans (Liege, Belgium,), Carlo J. De Luca (Boston, USA), Sten Grillner (Stockholm, Denmark), Marc Jeannerod (Bron/Paris, France), Heinz Ulbrich (Munich, Germany) More information: Email: ewoms2005@vu-wien.ac.at, Official Web site: <http://www.vu-wien.ac.at/i111/www/EWOMS-2005/welcome.html>

August 14-19, 2005

11th World Congress of Sport Psychology "Promoting health and performance for life"

Sydney Convention & Exhibition Centre, AUSTRALIA. Hosted by the International Society of Sport Psychology; the Australian Psychological Society; and by the College of Sport Psychologists. For more information contact: Sport Psychology World Congress Managers; GPO Box 128; Sydney NSW 2001; Australia; Tel: + 61 2 9248 0800; Fax: + 61 2 9248 0894; Email: WorldCongress@issp2005.com; Web site: <http://www.issp2005.com/>

HOME PAGES CONCERNING SPORT PSYCHOLOGY

International Society of Sport Psychology

www.ISSPonline.org

ISSP official journal: http://www.meyer-meyer-sports.com/verlag_english/start.cfm

11th World Congress of Sport Psychology: <http://www.issp2005.com/>

European Federation of Sport Psychology (FEPSAC)

<http://www.fepsac.org>

FEPSAC official journal: <http://www.elsevier.nl/locate/psychsport>

APA division 47 – Exercise and Sport Psychology

<http://www.psyc.unt.edu/apadiv47>

Metropolitan Association of Sport Psychology (Argentina)

www.psicodeportes.com

Online Journal of Sport Psychology

<http://www.athleticinsight.com>

CORRESPONDENT'S LIST

Belgium: Dr. Paul Wylleman, Flemish Association of Sport Psychology (VVSP), E-mail: Paul.Wylleman@vub.ac.be, crjannes@uncg.edu

Denmark: Dr. Reinhard Stelter, Department of Physical Education, Pedagogy & Psychology; Institute of Exercise and Sport Sciences; University of Copenhagen; Nørre Allé 51; DK 2200- Copenhagen N; Tel: +45 35320866; Fax: +45 35320870

Finland: Dr. Jarmo Liukkonen; Dept of Physical Education; University of Jyväskylä; SF - 40100 Jyväskylä; Fax: 358-41-602071; E-mail: liukkonen@palo.jyu.fi

France: Dr. Didier Delignières, Université de Montpellier; U.F.R.S.T. Activités; Physiques et Sportives; 700, Avenue du Pic St-Loup; 34090 Montpellier; Fax: 67 04 22 17. E-mail: delignieres@univ-montpl.fr

Germany: Dr. Jorn Munzert; Institute for Sport Science; University of Giessen; Kugelberg 62; D-35394 Giessen; Tel: +49-641 992 5220; Fax: + 49-641 992 5209, E-mail: joern.munzert@sport.uni-giessen.de

Greece: Dr. Yiannis Theodorakis, Dept of PE and Sport Science; University of Thessaly; Eleftherias str; 42 100 Trikala; Tel: + 930431 47046; Fax: +930 431 47042; E-mail: Ytheo@pe.uth.gr

Israel: Dr. Boris Blumenstein; Ribstein Center for Research and Sport Medicine Sciences; Wingate Institute; Netanya 42902; Tel: + 972 9863 9400; E-mail: psychwin@post.tau.ac.il

Italy: Dr. Alberto Cei; Scuola dello Sport, CONI, Via dei campi sportivi 48; 00197 Roma; Tel: 39 6 3685 9205, Fax: 39 6 3685 9230

Korea: Dr. Myungwoo Han; Sun Moon University, Korea; Tel: +82 – 0418 – 530 - 2293; Fax: +82 – 0418 – 41 – 7425. E-mail: mhan@omega.sunmoon.ac.kr

Mexico: Dr. Guillermo Dellamary; Florencia#2896; Providencia; Guadalajara Jalisco; C.P. 44630; Fax: 52 36 42 60 64. E-mail: Dellamar@yahoo.com

Norway: Dr. Glyn Roberts; Norges Idrettshogskole; Box 4014; N-0806 Oslo; Tel: +47 22 18 5768; Fax: +47 22 18 5718; E-mail: glynr@nih.no

Portugal: Dr. Sidónio Serpa and Duarte Araújo, Faculty of Human Movement, U.T.L., Laboratório de Psicologia do Desporto, Estrada da Costa, Cruz Quebrada, 1499 Lisboa Codex; Pho. 351 21419 6777; Fax: 351 21415 12 48. E-mail: Sserpa@fmh.utl.pt

Romania: Dr. Mihai Epuran; Academia Nationala de Educatie Fizica si Sport; Str. Stefan Furtuna 140; 76708 Bucharest; Fax: 40-1-3120400; E-mail: mepuran@anefs.kappa.ro

Bulletin Board

South-America: Dr. Benno Beker; Rua Casimiro de Abreu 755; 90420 - 001 Porto Alegre, RS.;
Tel/Fax: 55-51-315 70 36; Homepage: <http://psicoesporte.web.zaz.com.br/> E-mail.
bennoj@zaz.com.br; and benno@feevale.br

Spain: Dr. Félix Guillén García. Faculty Formación del Profesorado. University of Las Palmas
de Gran Canaria. C/. Juana de Arco, 1. 35004 Las Palmas de Gran Canaria. Telephone:
928451775; Fax: 928452880. E-Mail: fguillen@dps.ulpgc.es

Sweden: Dr. Erwin Apitzsch; Dept. of Psychology, Lund University, Box 213, S-221 00 LUND,
Sweden; Fax: + 46 46 222 4209, E-mail: erwin.apitzsch@psychology.lu.se

Switzerland: Dr. Roland Seiler; SWI-ESSM; CH-2532 Magglingen; Fax: 41 32 276 405.
E-mail: roland.seiler@mbox.essm.admin.ch

United Kingdom: Dr. Nanette Mutrie, Institute of Biomedical and Life Sciences; University of
Glasgow; Glasgow G12 8LT; Scotland, UK; Fax: +44 141 330 5079; E-mail:
n.muttrie@biomed.gla.ac.uk

N.B.: more detailed information may be requested from the country's correspondent.

GUIDELINES FOR CONTRIBUTORS

1. GENERAL

The International Journal of Sport and Exercise Psychology publishes empirical and theoretical contributions in the science of physical activity, human movement, exercise, and sport. It is aimed at enhancing the knowledge (theoretical and practical) in these fields. The Journal encourages researchers and scholars all over the world to submit their work for publication, since it emphasizes international perspective. Innovative applications and unique studies of cross cultural natures are especially encouraged.

The editors are assisted by the editorial board, section editors, external and special reviewers, all of whom are qualified in their respected fields. The first review process will be completed within 6-8 weeks once the manuscript arrives at the co-editors. However, some delays can occur due to unexpected and/or uncontrolled circumstances.

The manuscripts that are sent for publication should be original and not published elsewhere. While in reviewing process, the manuscript should not be submitted for publication to another source at the same time. When published, the article can not be published again in another book or journal.

2. HOW TO PREPARE THE MANUSCRIPT

Manuscripts should be typed and double-spaced. The manuscript should not exceed 30 pages, including references, tables, figures, and appendices with short summaries in English (250 words). On final acceptance of a manuscript the authors will be requested to submit a copy of the manuscript on a computer disk in Word Document format. The manuscript must conform to the *Publication Manual of the American Psychological Association (5th Edition)*. The manuscript should be written in appropriate English and format, otherwise it will be returned to the authors.

The IJSEP is focused on the most efficient review process possible, and as such will be utilizing E-mail attachments as a valuable resource. Authors should send a Word Document attachment of their manuscript via E-mail to the co-editor (please refer "To Whom To Send The Manuscript?", for relevant E-mail addresses). Authors telephone, facsimile, and E-mail addresses (if available) should be noted on the 1st page of the manuscript. Keywords should be included at the end of the abstract. It is advisable that authors should keep a copy of the manuscript to themselves since the original copy will not be returned. The order of the submitted manuscript is as follows:

- Title page
- Blind Title Page (without name (s) and addresses)
- Abstracts with Keywords
- Text
- References
- Notes and Footnotes

- Tables
- Figure Captions
- Figures
- Appendices

Theoretical manuscripts do not follow this format. However, a logical development of the issues discussed should be followed, and appropriate "section titles" be given. Since the review process is blind, **DO NOT** forget to attach the title page to the manuscript, excluding names and addresses after the first page.

Multiple authors should be listed in order. For each of the authors, the following information should be given: Department/Institution or Company, Full Address, Telephone/Facsimile/E-mail (if available). A special note to whom editors correspond should be clearly stated on the first page. Grants or special thanks associated with the work should also be included on the bottom of the first title page.

Any change of address (including E-mail) should be notified immediately.

3. REPRINTS

The publisher provides reprints to authors at cost. The cost depends on the number of pages in the final publication and the number of reprints asked for by the authors. An order form with a price-table is attached to the galley proofs submitted to authors for correction. Reprints should be ordered prior to publication. Post-publication orders cannot be filled at regular reprint rates.

4. LABELLING SUBJECTS & USE OF TERMS

Protection & Labelling of Research Participants

The IJSEP Editorial Board requires that all appropriate steps be taken to obtain the informed consent of all human subjects participating in the research of investigators submitting manuscripts for review and possible publication. Authors need not describe in the manuscript the specific steps taken to obtain informed consent; however, they must indicate by a phrase that "informed consent was obtained from the participants," or similar statement.

Descriptive categories such as male-female, black-white, Jewish-Christian, high achievers-low achievers, and emotionally disturbed-normals are sometimes used to label participants. Authors must be careful that the construct label selected to identify a group of human subjects is a valid, descriptive term that can be documented as accepted, current, professional terminology.

5. TABLES AND ILLUSTRATIONS (original and three copies)

The number of figures and tables is to be kept to a minimum. Each table should be typed on a separate page. Tables should be self-explanatory, supplementing but not duplicating the text. A brief title should be provided for each. Abbreviations used in tables should be defined.

Guidelines for Contributors

Illustrations should be numbered in the order in which they are first mentioned in the text. They should be marked on the back to indicate the first author's name, the figure number, and the top edge.

6. CHECKLIST

- Letter of submission
- Original and three copies of manuscript
- Title page (Title of article, full name(s), affiliation of author(s))
- Corresponding author (address and telephone number)
- Abstract (double-spaced)
- References on a separate sheet
- Tables (each on a separate sheet)
- Legends on a separate sheet
- Illustrations (original and two copies), labeled

7. DISK SUBMISSIONS

Authors must submit a computer disk of their manuscript. The disk must reflect the exact wording of the final revision of the manuscript.

Acceptable formats/diskettes: All diskettes must be submitted in "Word" file.

TO WHOM TO SEND THE MANUSCRIPT?

All correspondence concerning manuscripts should be directed to:

Africa, Europe, Asia to: Gershon Tenenbaum, Co-Editor IJSEP, Florida State University, Department of Educational Psychology and Learning Systems, 307 Stone Building, Tallahassee, Florida 32306 (USA).

Tel.: + (1) 850-644-8791; Fax: + (1) 850-644-8776

E-mail: tenenbau@coe.fsu.edu

South/North America, Australia to: Dieter Hackfort, Co-Editor IJSEP, Sports Academy, Dept. of Quality Management, Educational and Social Affairs, P.O. Box 23833, Doha, Qatar.

Tel.: +974 468 0918; Fax: +974 469 7346

E-mail: dieter.hackfort@gmx.de or dieter@qatarsports.net.

Guidelines for Contributors

Whilst every effort is made by the publishers and editorial board to see that no inaccurate or misleading data, opinion, or statement appears in this Journal, they wish to make it clear that the data and opinions appearing in the articles and advertisement herein are the responsibility of the contributor or advertiser concerned. Accordingly, the publisher, the editorial committee accept no liability whatsoever for the consequence of any such inaccurate or misleading data, opinion, or statement.

Four issues are published annually: March, June, September, and December. Further special issues may be published, containing the proceedings of national or international conferences, if requested and supported by the organizers of the meeting.

2005 Subscription Rates:

Individual US \$ 90.00 or € 90, ISSP membership US \$ 70.00 or € 70 (US \$ 120.00 or € 120 and US \$ 90.00 or € 90 by air mail).

Institutions US \$ 120.00 or € 120 (US \$ 160.00 or € 160 by air mail).

Journals and books for review must be sent to: Tony Morris, University of Victoria, Dept. of Psychology, P.O. Box 14428 MMC, Melbourne, VIC 3000, Australia

Notices of upcoming international events must be sent to: Sidonio Serpa, FMII-UTI, Estrada Da Costa – Cruz Quebrada, 1499 Lisboa Codex, Portugal

Business correspondence, subscriptions, and address changes should be mailed to verlag@m-m-sports.com

Meyer & Meyer Verlag, Von-Coels-Straße 390, 52080 Aachen (Germany)

Telephone: + 49 (0)2 41-9 58 10-0; Facsimile: + 49 (0)2 41-9 58 10-10

Copyright by Meyer & Meyer Sport, Germany – All rights reserved.

Printed by DMP Digitaldruck GmbH, Germany.

Published by Meyer & Meyer Sport, Germany.

Cover Design by Noam Y. Tenner.

ISSN 1612-197X

ISSP 11th World Congress of Sport Psychology Promoting Health and Performance for Life

Invitation

The International Society of Sport Psychology (ISSP), the Australian Psychological Society (APS) and the College of Sport Psychologists (CoSP), as hosts, and the Organising Committee have great pleasure in inviting you to the ISSP 11th World Congress of Sport Psychology to be held at the famous Sydney Convention and Exhibition Centre at Darling Harbour, Sydney, Australia. In particular, the sport and exercise psychologists of Australia and New Zealand aim to present the warmest welcome to a memorable event that befits our esteemed colleagues, who will come from all parts of the world to share their knowledge and experience of our exciting field.

Join us in Sydney 2005 for an experience we are sure you will treasure.

Professor Tony Morris
Chair, Organising Committee
ISSP 11th World Congress of Sport Psychology

Registration

Registration is now available online via the Congress website: <http://www.issp2005.com/>

Call for Papers

The Scientific Program Committee of the ISSP 11th World Congress of Sport Psychology invites the submission of papers for consideration in the scientific program.

Deadline Date: 19 November 2004

Submission information is now available online and papers are to be submitted via the Congress website: <http://www.issp2005.com/papers.asp>

Any queries in relation to the submission of papers should be directed to the Congress Managers.

Scientific Program

Following registration and the Opening Ceremony, the scientific program of the ISSP 11th World Congress of Sport Psychology spans four full days of communications relating to our important conference theme Promoting Health and Performance for Life. On each day there will be keynote presentations from two eminent colleagues, reflecting the breadth of the sport and exercise psychology field, including motor learning and control, and addressing the Congress theme.

Accommodation

Sydney has a wide range of accommodation that offers a great variety of style and atmosphere. A selection of hotels will be available to suit the budgets of all delegates.

The hotels available are all in close proximity to the Sydney Convention & Exhibition Centre.

Exhibition Opportunities

A wide range of opportunities are available for companies wishing to sponsor the Congress. Companies wishing to participate as either a sponsor or exhibitor are invited to contact the Congress Managers for details. You may register your interest online.

Social Program

A comprehensive Social Program has been developed, aiming at providing delegates with the opportunity to experience Sydney and the culture that is Australian.

Tours

Pre and Post Congress Tours will be specially arranged to enable participants to experience the contrasts of this vast southern continent.

ISSP Congress Managers
GPO Box 128 Sydney NSW 2001 Australia
Ph: +61 2 9248 0800 Fax: +61 2 9248 0894 Email: <mailto:ISSP2005@tourhosts.com.au>

<http://www.issp2005.com/>

SPORT, CULTURE & SOCIETY

Volume 1

128 pages
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-059-2
£ 12.95 UK/\$ 17.95 US
\$ 25.95 CDN/€ 18.90

Volume 2

358 pages
7 tables, 5 figures
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-093-2
£ 14.95 UK/\$ 19.95 US
\$ 29.95 CDN/€ 18.90

Volume 3

206 pages
5 photos
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-098-3
£ 14.95 UK/\$ 19.95 US
\$ 29.95 CDN/€ 18.90

Volume 4

226 pages
47 figures, 22 tables
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-099-1
£ 14.95 UK/\$ 19.95 US
\$ 29.95 CDN/€ 18.90

Volume 5

About 144 pages
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-147-5
£ 14.95 UK/\$ 19.95 US
\$ 29.95 CDN/€ 18.90

NEW

Volume 6

About 200 pages
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-148-3
£ 14.95 UK/\$ 19.95 US
\$ 29.95 CDN/€ 18.90

NEW

Volume 7

112 pages
Paperback, 5³/₄" x 8¹/₄"
ISBN 1-84126-160-2
£ 12.95 UK/\$ 17.95 US
\$ 25.95 CDN/€ 18.95

**MEYER
& MEYER
SPORT**

MEYER & MEYER Sport | sales@m-m-sports.com | www.m-m-sports.com