Eye Movements and Knowledge Structures

Brian R Gaines
Knowledge Science Institute & Neuro-Motor Laboratory
University of Calgary
Calgary, Alberta, Canada T2N 1N4

Abstract: The availability of eye-movement recording systems allowing the monitoring of fixations by freely moving subjects provides important possibilities for investigating the cognitive processes underlying skilled motor performance, its acquisition and coaching. This paper analyzes the methodological considerations involved in using eye movement data for the derivation and validation of knowledge structures underlying skilled performance in sports and sports coaching. Possible artifacts in the interpretation of eye movement data as indication of mental phenomena are detailed with reference to experimental studies. The encoding of eye movement data relative to a variety of frames of reference is discussed. Methodological issues underlying the processing of experimental psychological data are analyzed. The nature and epistemological status of knowledge structures themselves are discussed.

Introduction

This paper flows from the confluence of four streams of development in the study of cognitive systems:

1) The development of knowledge-based systems in artificial intelligence and cognitive science that may provide operational models of human mental behavior (Sharkey 1986).
2) The application of knowledge structures to the elicitation, representation and application of expert knowledge, particularly their application to perceptual-motor skills and sports coaching (Vickers 1983, 1986, 1987, Vickers & Brecht 1987, Vickers & Kingston 1987).
3) The needs to empirically validate mental models for theoretical purposes and to elicit expert knowledge structures for practical purposes (Vickers 1988, in press a,b, Vickers & Gaines 1988).
4) The availability of eye-movement recording and analysis systems allowing the monitoring of fixations by freely moving subjects under natural conditions, offering the possibility of using eye movement data to investigate cognitive processes (Borah 1987, Vickers & Canic 1987).

What we hope to achieve in the combination of knowledge science and neuro-motor laboratories are theories of human skills which are theoretically grounded, empirically validated, lead to significant practical applications and increase understanding of foundations and methodologies for performance, acquisition and coaching.

The problems of validating mental models, and the hopes that eye movements may play a significant role, have been well-expressed:

> "One of the central problems of contemporary cognitive psychology concerns the question of empirical testability. Although there is a vast abundance of information processing models, the access to any observable counterparts in reality is very limited. This scarcity might be one of the main reasons for the increasing popularity of eye movements in cognitive research as a measure of the selective information pick up in the visual domain." (Groner & Groner 1982)

However, too simplistic a view of the interpretation of eye movement data is clearly dangerous:

> "Eye movements are often taken as indicators of cognitive activity, the assumption being that what the eye is looking at testifies to what the mind is making of what the eye is looking at. To put it in other terms, the implication is that the location of the fixation testifies to the semantic aspects of the processing of the material fixated." (Gonzalez & Kolers 1985)
>
> "The claim that the eye fixation is a perfect index of the mind's comprehension seems to us both unwarranted and implausible." (Gonzalez & Kolers 1985)

The problems of interpretation of eye movement data are major and must not be underestimated. However, the opportunities for empirical investigation of cognitive models offered through eye movement recording under natural conditions are also major and must not be neglected. This paper addresses the fundamental epistemological issues involved in the gathering and interpretation of eye movement data, and its relation to cognitive models. It summarizes the major issues, reviews the related literature, and makes methodological recommendations for cognitive studies based on eye movement data.

Phenomena of the Mind

What is mind that we are mindful of it? The human mind is the most mysterious phenomenon open to study by science. From the perspectives of the humanities and biosciences, the phenomena of mind are at the apex of the unique features of living systems. From anthropological and sociological perspectives, mind is the hidden variable underlying social and cultural phenomena. From the reductionist perspectives of the physical sciences, mind is the most complex manifestation of the emergence of novelty and power through successive layers of organization of matter. From philosophical and system-theoretic perspectives, the self-referential problems of mind reflecting upon the phenomena of mind to model mind strains notions of rational methodologies to their utmost boundaries.

Modern experimental psychology long neglected phenomena of the mind. The behaviorist reaction to the introspective methodologies of Jamesian psychology went so far as to reject the very notion of mind as, at least, misleading, probably without possibility of scientific foundation, and, in any event, unnecessary to a positive, 'scientific' psychology. The development of cognitivism in the 1960s (Baars 1986) and the possibility of operationalizing 'mental models' through computer simulation, has led to a revival of scientific interest in mental phenomena. Those involved often use various forms of circumlocution to avoid the use of the term 'mind', but it is implicit in their discussion, if only in its normal colloquial sense as an abbreviation capturing an assumed basis for mental phenomena.

In the late 1980s we have entered an era where very rapid progress in the empirical foundations for cognitive modeling can reasonably be expected. Advances in computer hardware and software have made feasible computational simulations of large scale mental models that can be developed at reasonable cost, run at reasonable speed, and operate at various levels of reductionism from the emulation of skilled performance to neurological functioning. Advances in the underlying structures of mental models have improved both the internal coherence of the models as logico-mathematical systems and their external correspondence to human behavior. Advances in instrumentation, signal processing technology and data analysis techniques have made feasible the collection of large-scale data-sets with which to investigate the empirical validity of mental models in explaining and predicting human behavior. Successful applications of knowledge structures to the development of learning and coaching procedures for sports skills is raising questions as to the elicitation, validity and measurability of these structures.

There seems to be a reasonable window of opportunity opening up through which we can begin to perceive the operations of the human mind with a depth and clarity not previously available. It is not at all clear that the window is yet adequate to allow the most critical philosophical, psychological and practical questions to be answered. However, there is prima facie evidence that it would be advantageous to investigate in some detail how far we might progress with intensive use of currently available technology, models and empirical methodologies.

Eye Movements as Instrumentation of the Mind

The difficulty with the scientific study of mental phenomena is the lack of instrumentation with which to make objective measurements of mental processes. As noted in the introduction, eye movement data is attractive in cognitive research as a measure of the selective information pick up in the visual domain. Krause has stated common assumptions:

"a) The critical supposition is that the eyes fixate those items which are processed at the same moment.

b) The eye fixation sequence should agree with the sequence of processing.

c) The fixation time of an item is directly proportional to its processing time." (Krause 1982)

As also noted, the naive assumption that eye fixation is a perfect index of the mind's comprehension is a dangerous one. It is important that the experimental evidence related to this assumption is critically examined and used as a foundation for the derivation of cognitive models from eye movement data. The major significant results are:

1) Perception requires attention (Rock, Schauer & Halper 1976)

2) Immediately after a mentally directed saccade attention is directed to the foveal region (Shepherd, Findlay & Hockey 1986)

3) Attention may be directed to visual stimuli not in the foveal region fixated (Posner 1980, 1986)

4) Saccades are driven by both external stimuli and internal mental processes (Lévy-Schoen 1982)

5) Saccades may be triggered by non-visual stimuli, for example, auditory stimuli (Zambarbieri, Schmid & Ventre 1987)

6) Attention may be not directed to visual stimuli (Mayfrank, Kimmig & Fischer 1987)

7) Other visual functions, interacting with saccadic motion, such as the vestibulo-ocular reflex are also driven by both external stimuli and internal mental processes (Jones 1985)

8) Saccades are not completely pre-programmed but may be changed in response to in-saccade stimuli (van Gisbergen, Optstal & Roebroek 1987)

9) Intensive mental processes decrease the accuracy of saccadic movements (Osaka & Koga 1982)

Result 2 coupled with 1 is the basic justification of the use of eye movement data to infer mental events—a voluntary saccade indicates foveal attention and probable perceptual input from the foveal region immediately following that saccade.

Result 3 indicates that as time progresses after the voluntary saccade there is less evidence for the focus of visual attention.

Results 4, 5 and 6 indicate that visual and other stimuli may, or may not, cause involuntary saccades with, or without, shifts in visual attention.

Results 7, 8 and 9 indicate that the form of saccades is part of a complex system of control with interaction from mental processes, voluntary and involuntary head motion and external stimuli.

These results clearly undermine Krause's assumptions a) through c) stated above. They may be seen as indicating possible artifacts in eye movement data treated as instrumentation of the mental processes of attention and perception.

All scientific measurement is subject to artifacts. It is impossible to reduce them to zero, and it is important to know what they are, compensate for them if possible, and take them into account in interpretation. The requirements of an empirical methodology are:

i) The methodology should be as free of artifacts as possible

ii) Artifacts in the empirical methodology should be clearly defined

iii) Artifacts in the empirical methodology should be measurable

iv) Artifacts in the empirical methodology should be uniform

v) Artifacts in the empirical methodology should be consistent

In terms of i) there are few competing methodologies. We can attempt to access attention and perception through introspection and verbalization, or attempt to infer it through overt behavior. Both are valid methodologies, complementary to one another, and to eye movement recording, but both suffer from their own artifacts of comparable magnitude to those of eye movement data.

In terms of ii) through iv), the emphasis is on our experimental and interpretation schema taking into account the known sources of artifacts noted in 3) through 9) above, determining when they are likely to affect the interpretation and designing experiment and interpretation to filter them out as far as possible.

Criteria i) through v) also apply to the basic measuring instrument. The ASL helmet mounted eye tracking system (Borah 1987) has a number of important features which are major advances in satisfying these criteria. The freedom of subjects' motion is an important removal of artifacts in cognition induced by unnatural experimental situations. The ease and stability of calibration, and the insensitivity to helmet rotation relative to the head, reduce basic measurement errors. The naturalistic playback of scene and eye position data from the videotape make it easy for the interpreter to detect many artifacts in the experimental data which would be extremely difficult to detect in raw and computer-processed numerical data.

The ASL system has artifacts of its own, notably the sampling of the eye position at the video frame rate, and the one frame delay between the eye movement position and the scene data in the composite display. However, these are very well-defined and subject to compensation in processing and interpretation.

Frameworks of Encoding for Eye Movement Data

The interpretation of eye movement data is notoriously difficult, both in the labor involved and in form of encoding of the data. The advantages of the ASL system in allowing subjects freedom of movement also creates major problems in data processing.

First, the head and body are free to move and hence the eye movement data must be interpreted with respect to scene data. Currently, the automatic processing of scene data is extremely difficult involving computer image processing at, or beyond, the current state of the art in scene analysis. There are techniques which could reduce the scene analysis problem, such as the use of infra-red beacons to give fiduciary markers for image processing unseen by the subjects, but even these leave major computational problems to be overcome. For the immediate future, we must assume that human encoding must be used to prepare the eye movement data for analysis. This has advantages in bringing to bear human pattern recognition and intelligence on the encoding problem. It brings problems not only of the effort involved but also of the possible artifacts arising from human modeling of the phenomena in the video images. The ASL system lets you see the world through the subjects' eyes and somehow to feel as if you were 'in their heads.' This is a significant source of hypotheses about their cognitive and behavioral processes. However, it can places the encoder in a hermeneutic role of imposing their own interpretation based on their own experience, not that of the subject. It is important that the coding scheme fully compensate for this by being demonstrably objective through its clear definition and inter-encoder replicability.

Second, the multiple frames of reference relevant to the subject's visual perception make the choice

a) The *retinotopic frame* captures the raw image at the retinal level of part of the environment dependent on gaze, lighting, and so on

b) The *stable feature frame* captures the processed image after feature extraction including compensation for eye and body motion

c) The *world knowledge frame* captures the subject's knowledge of worlds in general and the current one in particular in terms of objects, their properties, relations and situations

d) The *environmental frame* captures the world embedding, and including the subject and the subject's activities, as it is cognized to be by the subject

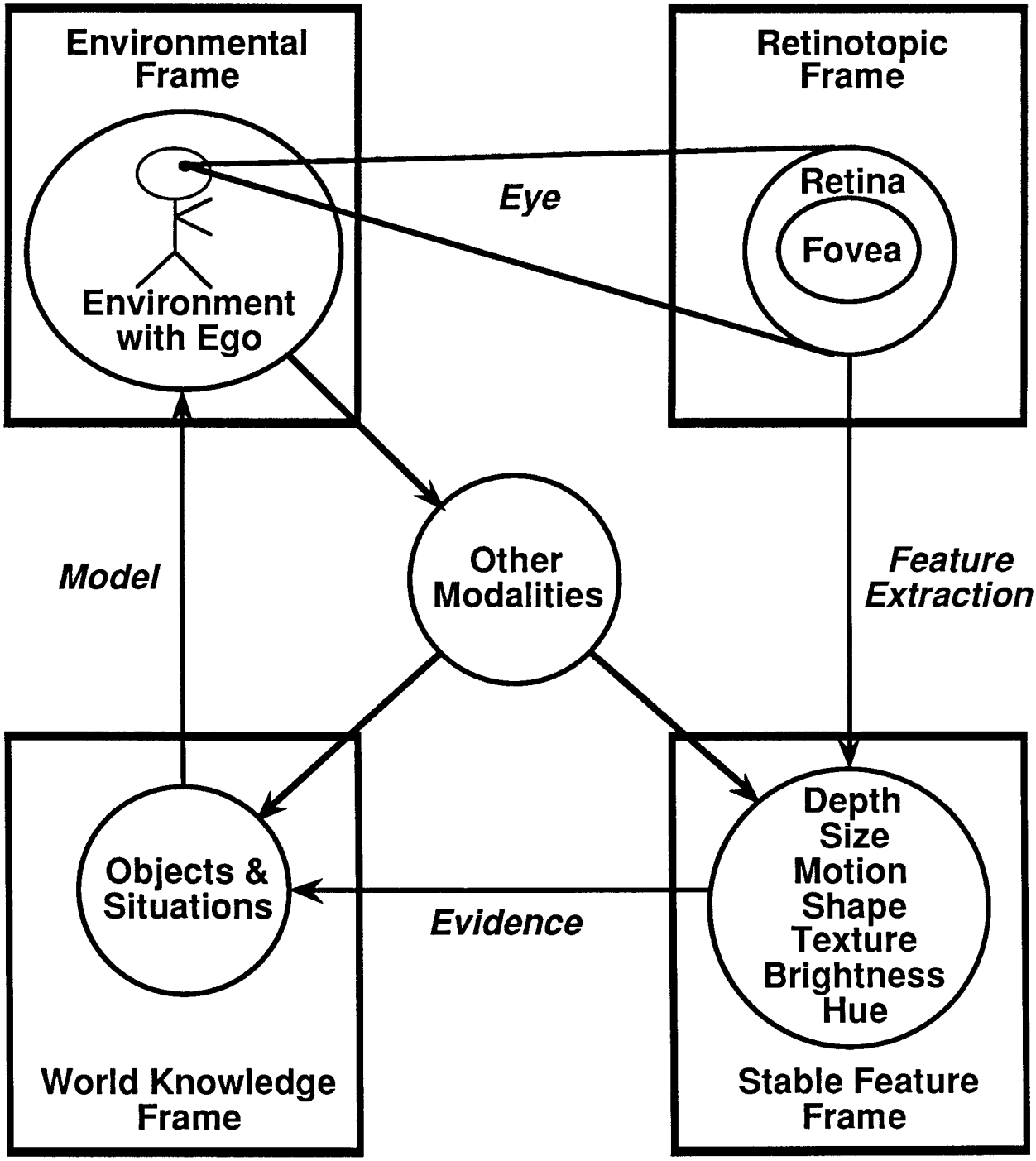

Fig.1 Frames of reference in visual perception and cognition

The difficulties with encoding may now be phrased in terms of this model. What we can infer from the ASL composite display is strictly data in the retinotopic frame. Our own visual processes will parallel those of the subject in converting this into stable features, although we have to be careful that our more leisurely and wide-ranging examination of the scene does not add features not perceived by the subject. Our world knowledge may be used to attempt to parallel that of the subject although even greater care is necessary in interpretation. Our reconstitution of the environmental frame will probably have little resemblance of that of the subjects since we are not in their situations, processing at their speed, with their intentions, and their world knowledge.

A proper encoding scheme should capture information in the retinotopic frame, recording the relation of this frame to the actual environment, and the state of the actual environment. This should be done with encoders in a deliberate phenomenological objective knowledge mode, consciously disregarding all inferences. The encoding scheme should then annotate this information with inferred probable features, inferred possible world knowledge, and inferred possible environmental frame, using encoders with experience similar to that of the subjects, and the subjects themselves if possible, to aid with the annotation. Provided this clear separation of frames is maintained in the encoding, the full richness of the experimental data can be explored without loss of control over the scientific method.

Methodological Foundations of Interpretation of Eye Movement Data

Research on human skills in the past forty years has undergone a number of shifts of perspective. The positivist scientific paradigm dominated early research emphasizing empiricism, behaviorism and neurological reductionism. Later research has questioned the validity of this paradigm in psychology, or, at least, its universality as the only valid methodology for a science of psychology. Most later developments, although they may have been presented confrontationally initially, are best seen as extending, refining and enriching the positivist paradigm. For example, reductionism may be rejected as invalid or impossible, theoretically or practically, but it is most constructively criticized in terms of levels of explanation—even if we had a neurological description of a skill that was causally, functionally, anatomically, chemo-electronically, signal-processing, and so on, correct, could it be used to generate descriptions and explanations of skilled behavior which would be deemed appropriate by all those requiring them. This one step, of introducing the roles of explanations and requirements in science, and science in explanations and requirements, is a major extension of the positivist paradigm, yet it does not conflict with it.

What is required in research on human skills in general, and in the interpretation of eye movement data in particular, are methodological foundations rich enough to encompass all these issues and the relations between them. The foundations should allow for a plurality of methodological positions, and provide the means for the presuppositions underlying these positions to be clearly expressed and inter-translated. The only untenable presupposition is that any methodology can be presupposition-free. The inductive processes underlying our modeling of the world, either informally from our experience, or formally from scientific experiments, are necessarily critically dependent on the presuppositions we make, including our choice of descriptive language and choice of models. In logical terms, induction places far stronger requirements on language and models—systems which are deductively equivalent because they are inter-translatable are not inductively equivalent because they involve different orderings of approximation and complexity (Gaines 1977).

Induction requires presuppositions.

There is no such thing as an empirically substantiated presupposition-free theory. One can use a finite amount of empirical data to discriminate between a finite number of hypotheses. The choice of this set of hypotheses involves presuppositions. These may be explicit or implicit but they exist.

Presuppositions are not unique.

There is no unique set of presuppositions underlying the choice of a given set of hypotheses. Different sets of presuppositions may lead to the same choice of a set of hypotheses.

Explicit presuppositions may not be consistent with the set of hypotheses.

One may believe that certain presuppositions underlie one's choice of hypotheses, yet these may be inconsistent with the choice.

The determination of the implicit presuppositions underlying a set of hypotheses is itself an inductive process.

The experimenters and commentators are intrinsically part of the experiment. This is as true in basic physics as it is in the human sciences.

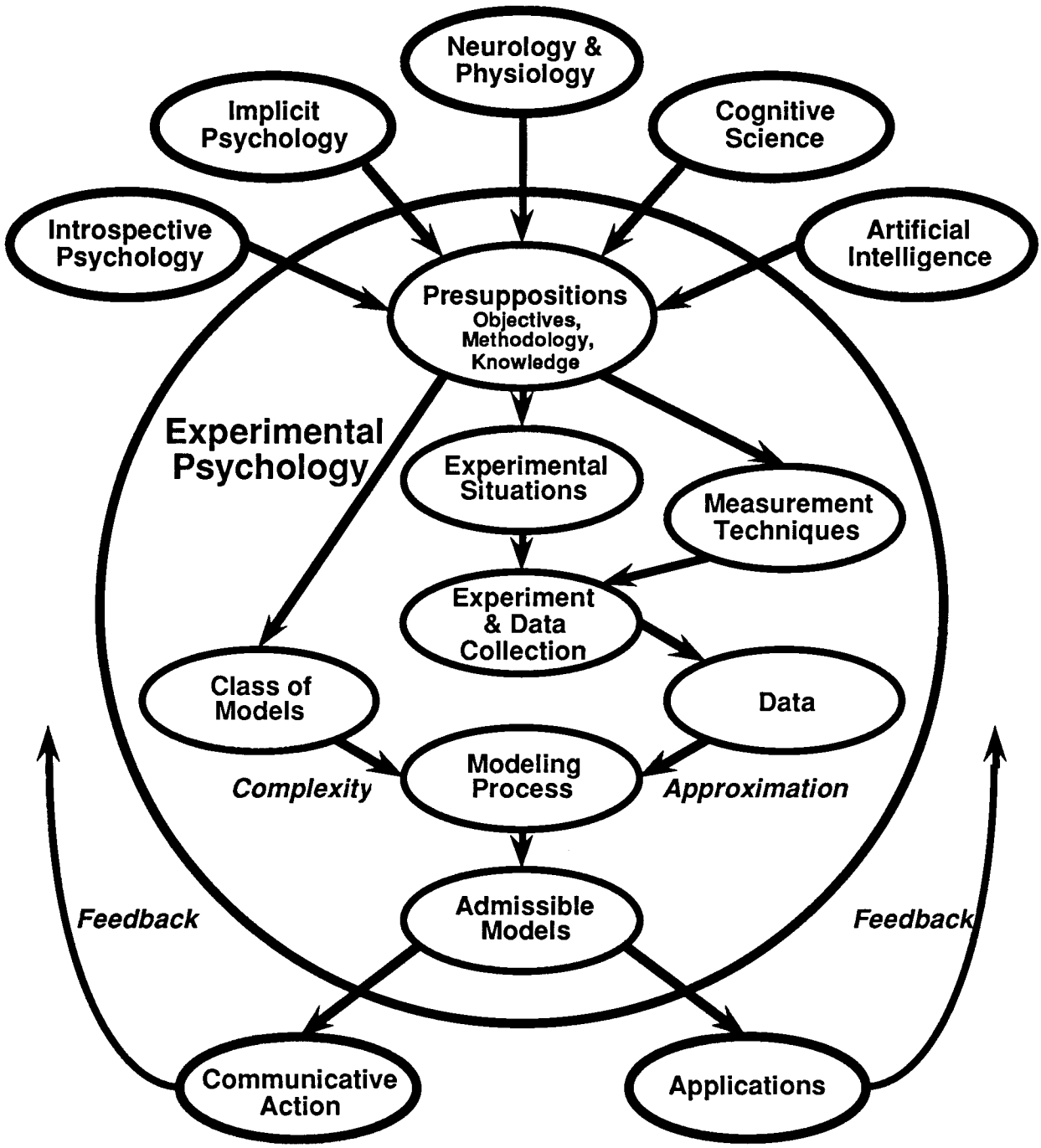

Fig.2 The scientific process in experimental psychology

Figure 2 shows the scientific process in experimental psychology within the central ring together with the sources of presuppositions at the top and the outcomes and feedback from them at the bottom.

Within the central ring the process is one of proceeding from presuppositions defining objectives, methodology, knowledge, and so on, to define: *experimental situations*; a *class of models* that may apply to them, including criteria of model *complexity* and degree of *approximation* to data; and *measurement techniques* that may be used to investigate them.

Playing out a situation and applying the measurement techniques leads through *data collection* to a set of *data* representing the experimental situation.

A mechanical *modeling process* may be applied to test the approximation to the data of models from the class in increasing order of complexity.

This generates a set of *admissible models* which are such that there are none better in being both less complex and a better approximation.

These models may be used outside the string framework of the experimental psychology method for purposes of *communicative action* in Habermas' (1981) terminology, that is to be part of scientific discourse aimed at mutual understanding of the underlying phenomena, and as a basis for *applications*. Both scientific discourse and the results of applications may result in feedback to the presuppositions and an iteration of the process, in whole or in part.

The presuppositions are also subject to the changing influences of material from other sources such as introspection, implicit psychology, neurology, physiology, cognitive science, artificial intelligence and so on. This can also lead to an iteration of the process, in whole or in part.

The importance of presuppositions are that they are a fundamental component of the scientific method. There are many interesting consequences of this for the scientific process. For example, data may be viewed as currency used to "purchase" validation of a model under a set of presuppositions. It is like a currency in that it can be spent on one of two different validations with alternative sets of presuppositions, but can not used to purchase both. It is unlike a currency in that copies of data may be made without expense and used by different individuals, within differing epistemological frameworks, to purchase different validations. This causes no problems until the individuals attempt to communicate about the results of the validations when it will be impossible for them to do so meaningfully unless they first communicate their differing presuppositions.

Various philosophy of science positions may be modeled within Figure 2. The class of models, experimental situations and measurement techniques form Kuhn's (1970) scientific *paradigm* for the domain under investigation. The uncontrolled diversity of sources of presuppositions leads to the *anarchy* that Feyerabend (1975) has noted in scientific practice. The modeling process based on complexity/approximation sifting of models against data is predominantly Carnap's (1971) *confirmation* if the experimental situations are chosen to be representative of the paradigm. However, it is predominantly Popper's (1972) falsification if the experimental situations are chosen to be as non-representative as possible while still marginally acceptable within the stated presuppositions. The complexity/approximation evaluation reflects the process whereby falsifying a particular model very rarely leads to a paradigm shift but rather a model of greater complexity or an acceptance of lesser approximation.

In the preceding sections the collection of eye movement data has been presented as a measuring technique for the study of human cognitive processes involving attention and perception. The discussion has focussed on the presuppositions underlying the encoding and interpretation of such data in the modeling process of Figure 2. The next part of the paper will focus on the role of knowledge structures as a class of models for human cognitive behavior.

What Are Knowledge Structures?

The concept of knowledge structure captures the variety of formal representations of human knowledge that have developed in cognitive science and artificial intelligence:

> "A fundamental supposition throughout our work is that knowledge is *schematized*, that is, organized in chunks or packages so that, given a little bit of appropriate situational context, the individual has available many likely inferences on what might happen next in a given situation." (Abelson & Black 1986)

Such schemas have been widely termed knowledge structures. However, there is no agreement on form or representation of schemas.

There are also two distinct epistemological uses of the term 'knowledge structure' in the literature which are often confounded:

a) The presupposed framework within which an individual intelligent system is operating in order to produce skilled behavior.

b) The communicable structure within which skills may be represented and discussed.

The first definition draws on a number of concepts in cognitive psychology and artificial intelligence. It involves an existence hypothesis analogous to the construction behind Dennett's (1981) definition of intentionality as a conveniently short form of explanation of some aspects of animal behavior. It involves recognition that people do not act as raw computational systems, Turing machines programmed as theorem provers, but rather navigate around the vulcanoes of combinatorial explosions by developing and sharing cognitive maps of short-cuts, and safe routes, which enable them to deal with real-world problems. The second definition draws on a number of concepts in systemic sociology and discourse analysis. It involves a normative hypothesis analogous to that behind Habermas' (1981) definition of communicative action as communication in which both parties strive for mutual understanding. It involves recognition that people do not act as overtly rational computational systems, linguistically-driven logical systems, but that people observe, describe and rationalize their own and others behaviors in order to discuss it and understand it.

It is well-known in psychology that these two definitions need not conform, that our communicable rationalizations of our own and others behaviors may have little relation to the actual basis of those behaviors. There is a recognized danger in developing a science of psychology that usage of type b) may be taken as usage of type a). However, this recognition can be fallaciously transferred to an assumption that usage of type b) is erroneous to the extent that it does not conform to usage of type a). In fact the two forms of usage are independent and neither is intrinsically more valuable than the other. In applied psychology usage of type b) can be more appropriate than that of type a). For example, in training communication between trainer and trainee has to be evaluated in terms of its effects on the acquisition of skill, not in terms of its psychological veracity. An acceptable mutual communicative model that leads to improved performance may be far removed from the actual internal framework within which that performance is produced.

This is not to say that there are no relations between the two forms of usage of the term 'knowledge structure.' It is reasonable to suppose that from usage of type a) it should be possible to derive usage of type b), that is that meaningful communication has an underlying basis in reality. The reverse line of reasoning makes it reasonable to suppose that effective usage of type b) delineates in some way usage of type a), that a theory of reality should be able to account for practical phenomena. However, the rationale for mutual constraints does not legitimate assumptions of one-to-one correspondence, many different foundational theories may lead to the same practice, and successful practice only constrains theory rather than defines it.

Recent advances in the study of natural and artificial neural networks (Rumelhart & McClelland 1987) make it plausible to argue that only usage of type b) is legitimate. It is possible for a highly skilled activity to be induced in a network through a wide variety of highly distributed and intrinsically unstructured local changes resulting in some global pattern of activity. The "knowledge" in the network is in no way schematized until we generate a separate modeling system to describe and predict the skilled behavior, and hence impute schemas to the network. Smolensky has given a very clear methodological analysis of this position noting that:

> "The *competence* of models in this framework can sometimes be neatly expressed by symbolic rules, but their *performance* is never achieved by explicitly storing these rules and passing them through a symbolic interpreter." (Smolensky 1986)

Knowledge Structures in Coaching

The discussion above of the different uses of the term 'knowledge structure' may be made more concrete by considering the coaches' roles in skills acquisition:

i) In training, a coach manages the learning processes of the team and individuals

ii) In a game, a coach manages the performance processes of the team and individuals

Note the use of the word 'manage', meaning 'directed administration', to describe the coaches' roles. The coaches' skills are in the administration of the learning and performance environments to enhance learning and performance. The knowledge structures underlying these skills will reflect this managerial role. They will not coincide with those underlying the athletes' skills, and will not necessarily subsume them. It is possible to have skills in establishing effective learning environments without having detailed knowledge of the skills resulting from learning. The coaches skills and cognitive structure are different in nature from those of the athlete and should not be confused with them. The communication between coach and athlete is distinct from either's performance skills, deriving from and affecting them, but having an identity and characteristics of its own.

Thus, in developing knowledge-based systems for teaching coaching there are at least four distinct knowledge structures involved:

1) The knowledge structures underlying the performance skills of the athletes involved

2) The knowledge structures underlying communication about the performance skills of the athletes involved

3) The knowledge structures underlying the performance skills of the coaches involved

4) The knowledge structures underlying communication about the performance skills of the coaches involved

Knowledge structures of type 4) are the primary ones for the development of coaching systems, and these structures have knowledge structures of type 2) embedded within them. The 'scientific foundations' for coaching systems involve knowledge structures of type 3). The 'scientific foundations' for coaching itself involve knowledge structures of type 1).

These subject-domain-specific knowledge structures are not the only ones involved in the development of coaching systems. There are technology-domain-specific knowledge structures which are also critical to success in system development:

5) Knowledge of the representation and presentation of knowledge-based coaching material in book formats

6) Knowledge of the representation and presentation of knowledge-based coaching material in expert system and videodisc formats

We tend to take the first knowledge structures for granted until we actually attempt to write an instructional book and realize the skills involved in the task. The second knowledge structures are novel and developmental and as much subject to acquisition currently as are those for the subject domains. We are learning to harness new technologies for enhancing skills acquisition at the same time as we are learning about the processes underlying skills acquisition. The two learning processes are symbiotic as we need the challenge of applications to develop the technology and we need the technology to deliver the applications.

Validation of Knowledge Structures

Figure 3 summarizes the various discussions above to give a framework for the validation of knowledge structures. It is based on a condensation of Figure 2 extended to take into account the notion of modeling expertise as a complement to, or an alternative to, modeling actual events.

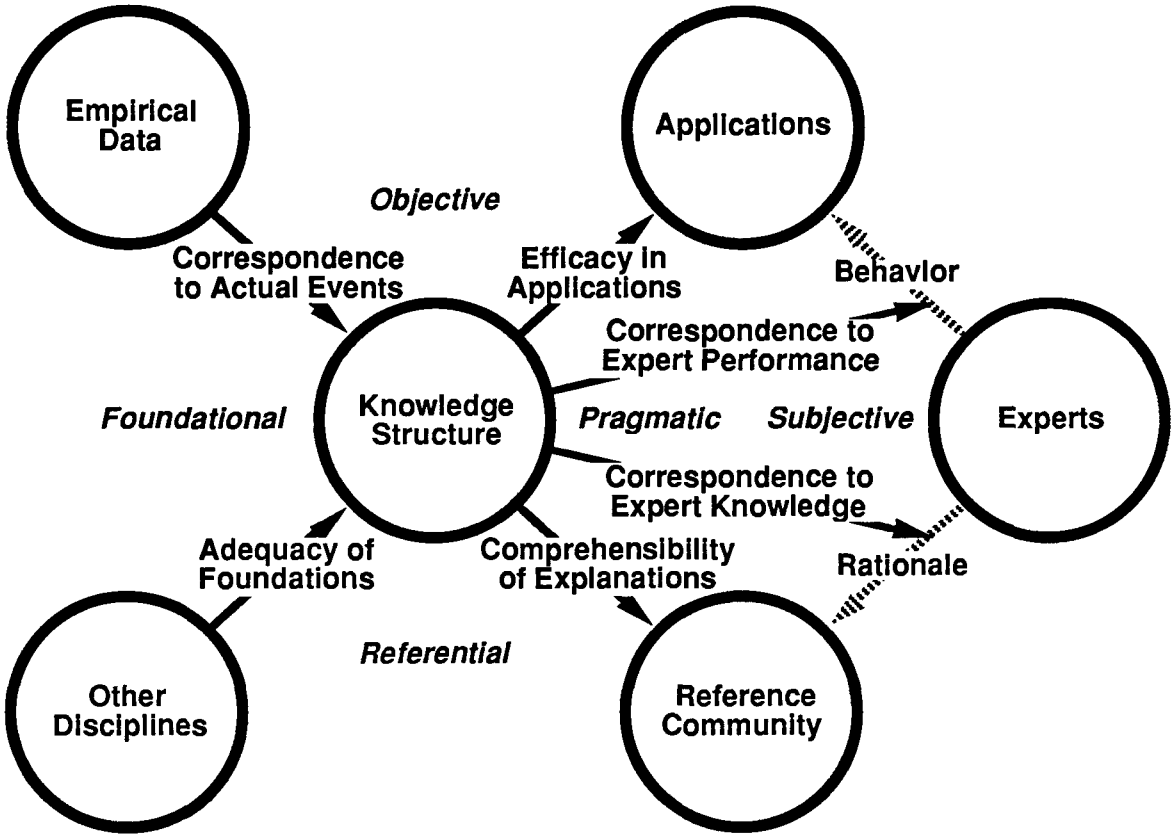

Fig.3 Validation of knowledge structures

The knowledge structure can be validated through four primary pathways:

1) Through its correspondence to actual events checked against empirical data corresponding to the processes in the inner circle of Figure 1
2) Through the adequacy of its foundations checked against other disciplines corresponding to the derivation of presuppositions from other disciplines in Figure 1
3) Through its efficacy in applications checked against actual applications corresponding to the applications outcome in Figure 1
4) Through the comprehensibility of explanations given checked against the relevant reference community corresponding to the communicative action outcome in Figure 1

The expert systems paradigm introduces two additional pathways by taking into account the possibility that there may be "experts" who are competent in applications and explanations:

5) Through its correspondence to expert performance checked against the behavior of experts in applications
6) Through its correspondence to expert knowledge checked against the rationale of experts in communicating with their reference community

This diagram may be iterated a number of times to show the source of the knowledge structures of experts from empirical data and other disciplines, introducing considerations of the validity of experts and reference communities. Similarly, it may be iterated to show the way in which other disciplines in turn are validated against their own empirical data, deeper foundations, applications and reference communities. There is no intrinsic conflict between the additional pathways of validation introduced and the positivist viewpoint of science emphasizing the primacy of empirical data. However, there is a major increase in the realism of this model in modeling the actual processes of scientific advance rather than the normative criteria adopted as ultimate arbitrators.

Conclusions

To live in "exciting times" as the Chinese proverb notes is not always easy. Advances in scientific theory, measurement techniques, expectations and applications generate at least as many problems as they solve. The web of interacting, mutually constraining, relations and processes underlying the scientific endeavor is complex, and major experimental programs need to incorporate the structure of this web in their own overt knowledge structures. This paper has attempted to summarize the major feature of the web relevant to the application of new possibilities for empirical access to mental processes resulting from advances in eye movement recording, and their application to the validation of models of knowledge structures underlying sports coaching.

In terms of Figure 3, eye movement data have application to the two *correspondence* arrows: to actual events and to expert performance, to the behavior of the athletes and to that of the coaches in viewing that behavior. The merits and problems of using eye movement data in this way have been identified, and the basis for encoding schema for data analysis have been derived.

The other four pathways in Figure 3 are also subject to validation activities that interact with those supplied by eye movement studies: the analysis of foundations, for example, in biomechanics; the testing of applications, for example, in expert systems for coaching; the acceptance of explanations through books and papers to the physical education community, and, in particular, to recognized world-classes coaches.

Paradigm shifts are never fully validated. They are accepted by the reference community in the light of a plurality of validation paths, no one of which is complete or paramount. For those involved, this social process of acceptance may be extremely disconcerting in contrast to the stark positivist empirical criteria which form the ultimate value system of science. Those criteria are unrealistic as absolute requirements for verification. However, they normative guidelines that sculpture the essence of scientific knowledge from within the creative anarchy of scientific endeavor. Eye movement data under increasingly naturalistic conditions coupled with improved encoding schema and applicable knowledge structures offer major opportunities for the empirical investigation of that most elusive of all phenomena, the human mind.

Acknowledgements

Financial assistance for this work has been made available by the Natural Sciences and Engineering Research Council of Canada. I am grateful to my colleague Joan Vickers for many stimulating discussions on the issues discussed in this paper.

References

Abelson, R.P. & Black, J.B. (1986) Introduction. Galambos, J.A., Abelson, R.P. & Black, J.B. (Eds) **Knowledge Structures**. pp.1-18. Hillsdale, New Jersey: Lawrence Erlbaum.

Baars, B.J. (1986) **The Cognitive Revolution in Psychology**. New York: Guilford Press.

Borah, J. (1987). Applied Sciences Laboratories' New Helmet Mounted Eye Tracking System. **Proceedings of the First International Conference on Eye Movements in Sport and Physical Activity.** Pre-Conference Symposium of the Canadian Society for Psychomotor Learning and Sports Psychology. University of Calgary (October).

Carnap, R. (1971) A basic system of inductive logic, Part I. Carnap, R. & Jeffrey, R.C. (Eds) **Studies in Inductive Logic and Probability, Volume 1**. pp.33-165. Berkeley: University of California Press.

Dennet, D. (1981) Three kinds of intentional psychology. Healey, R. (Ed) **Reduction, Time and Reality**. Cambridge: Cambridge University Press.

Feldman, J.A. (1987) A functional model of vision and space. Arbib, M.A. & Hanson, A.R. (Eds) **Vision, Brain and Cooperative Computation**. pp.531-562. Cambridge, Massachusetts: MIT Press.

Feyerabend, P. (1975). **Against Method**. London: NLB.

Gaines, B.R. (1977). System identification, approximation and complexity. **International Journal of General Systems, 3**, 145-174.

van Gisbergen, J.A.M., van Opstal, A.J. & Roebroek, J.G.H. (1987) Stimulus-induced midflight modification of saccade trajectories. O'Reagan, J.K. & Lévy-Schoen, A. (Eds) **Eye Movements: From Physiology to Cognition**. pp.27-36. Amsterdam: North-Holland.

Gonzalez, E.G. & Kolers, P.A. (1985) On the interpretation of eye fixations. Groner, R., McKonkie, G.W. & Menz, C. (Eds) **Eye Movements and Human Information Processing**. pp.251-259. Amsterdam: North-Holland.

Groner, R. & Groner, M. (1982) Towards a hypothetico-deductive theory of cognitive activity. Groner, R. & Fraisse, P. (Eds) **Cognition and Eye Movements**. pp.100-121. Amsterdam: North-Holland.

Habermas, J. (1981). **The Theory of Communicative Action: Reason and the Rationalization of Society**. Boston: Beacon Press.

Jones, G.M. (1987) Adaptive modulation of VOR parameters by vision. Berthoz, A. & Melvill Jones, G. (Eds) **Adaptive Mechanisms in Gaze Control**. pp.21-50. Amsterdam: Elsevier.

Krause, W. (1982) Eye fixation and three-term series problems, or: is there evidence for task-independent information units. Groner, R. & Fraisse, P. (Eds) **Cognition and Eye Movements**. pp.122-138. Amsterdam: North-Holland.

Kuhn, T.S. (1970). **The Structure of Scientific Revolutions**. Chicago: University of Chicago Press.

Lévy-Schoen, A. (1982) Perception, exploration and eye displacements. Groner, R. & Fraisse, P. (Eds) **Cognition and Eye Movements**. pp.10-23. Amsterdam: North-Holland.

Mayfrank, L., Kimmig, H. & Fischer, B. (1987). The role of attention in the preparation of visually guided saccadic eye movements in man. O'Reagan, J.K. & Lévy-Schoen, A. (Eds) **Eye Movements: From Physiology to Cognition**. pp.37-45. Amsterdam: North-Holland.

Osaka, R. & Koga, K. (1982) Variations of voluntary fixations during mental tasks. Groner, R. & Fraisse, P. (Eds) **Cognition and Eye Movements**. pp.74-83. Amsterdam: North-Holland.

Popper, K.R. (1972) **Objective Knowledge**. Oxford: Clarendon Press.

Posner, M.I. (1980). Orienting of attention. **Quarterly Journal of Experimental Psychology, 32**(1), 3-25 (February).

Posner, M.I. (1986) **Chronometric Explorations of Mind**. New York: Oxford University Press.

Rock, I., Schauer, R. & Halper, F. (1976). Form perception without attention. **Quarterly Journal of Experimental Psychology, 28**(3), 429-440 (August).

Rumelhart, D.E. & McClelland, J.L. (1987) **Parallel Distributed Processing: Explorations in the Microstructure of Cognition. Volume 1**. Cambridge, Massachusetts: MIT Press.

Sharkey, N.E. (Ed) (1986) **Advances in Cognitive Science 1**. pp.204-235. Chichester, UK: Ellis Horwood.

Shepherd, M., Findlay, J.M. & Hockey, R.J. (1986). The relationship between eye movements and spatial attention. **Quarterly Journal of Experimental Psychology, 38A**(3), 475-491 (August).

Smolensky, P. (1986). Formal modeling of subsymbolic processes: an introduction to harmony theory. Sharkey, N.E. (Ed) **Advances in Cognitive Science 1**. pp.204-235. Chichester, UK: Ellis Horwood.

Vickers, J. N. (1983). The role of expert knowledge structures in an instructional design model for physical education. **Journal of Teaching in Physical Education 2**(3) 17-32.

Vickers, J. N. (1986). The resequencing task: determining expert-novice differences in the organization of a movement sequence. **Research Quarterly for Exercise and Sport 57**(3) 260-264.

Vickers, J.N. (1987). ActionMark: a software package designed to facilitate the acquisition of complex physical skills. Norrie, D., Ed. **Learning in Future Education: Proceedings of International Conference on Computer Assisted Learning in Post-Secondary Education**. pp.235-237. University of Calgary.

Vickers, J. N. (1988). Knowledge structures of expert-novice gymnasts. **Journal of Human Movement Science 7** 47-72.

Vickers, J. N. (in press a). **Instructional Design in Sport and Physical Activity: A Knowledge Structures Approach**. Champaign, Illinois: Human Kinetics.

Vickers, J. N. (in press b). The role of knowledge in teacher preparation programs in physical education. **Quest**.

Vickers, J. N. & Brecht, D. (1987). **Badminton: A Structures of Knowledge Approach**. Calgary: University Printing Services.

Vickers, J. N. & Canic, M. (1987). Eye movements while catching, shooting, hitting/striking: Observations on ASL's new 3100H helmet system. **Proceedings of the First International Conference on Eye Movements in Sport and Physical Activity.** Pre-Conference Symposium of the Canadian Society for Psychomotor Learning and Sports Psychology. University of Calgary (October).

Vickers, J.N. & Gaines, B.R. (1988). A comparison of books and hypermedia for knowledge-based sports coaching. **Microcomputers for Information Management**, 5(1), 29-44 (March).

Vickers, J.N. & Kingston, G.E. (1987). Modelling the master coach: building an expert system for coaching. Norrie, D., Ed. **Learning in Future Education: Proceedings of International Conference on Computer Assisted Learning in Post-Secondary Education**. pp.207-212. University of Calgary.

Zambarbieri, D., Schmid, R. & Ventre, J. (1987) Saccadic eye movements to predictable visual and auditory targets. O'Reagan, J.K. & Lévy-Schoen, A. (Eds) **Eye Movements: From Physiology to Cognition**. pp.3-5. Amsterdam: North-Holland.