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Modelling Action in Complex Environments

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MODELLING HUMAN ACTION IN COMPLEX ENVIRONMENTS

Jens Rasmussen

Abstract: The paper reviews the different levels of cognitive control of human actions in a complex environment in terms of the skill-, rule-, knowledge-based framework. The temporal aspects of the interaction among the levels of control is discussed together with the transfer of control taking place during training. The problem of creating an interface that serves a natural interaction among the three levels of control in artificial environments is discussed with reference to musical performance, process control, and search in databases.

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1. INTRODUCTION

In many large-scale systems like chemical process plants, air traffic control centres, business management systems, etc., which present increasing potential for loss and damage in case of mal-operation, computer based interfaces are now introduced in the interfaces between the systems and their users and operators. This development creates an urgent need for models of human control of actions in complex environment. It is mandatory that such models cover not only human behaviour in routine situations in terms of task and action models, but also include higher level cognitive abilities to solve problems and to cope with new and unforeseen situations. The usual academic approach by which well defined, separate psychological mechanisms are studied in well controlled circumstances will not be adequate. The model required should also include the interaction between the different cognitive mechanisms active in complex work settings and on the change of this interaction as skill evolves through adaptation to the work conditions.

2. INTERACTING COGNITIVE CONTROL MODES

Humans have different modes of control of their goal oriented interaction with the environment. Sensory-motor routines take care of the direct control of integrated patterns of movements during familiar circumstances. Once in a while, direct chaining of motor patterns is not possible, either because two or more familiar patterns apply to the immediate situation, in which case a conscious choice may have to be made from stored decision rules, or because new circumstances for which no course of action is known and resort to problem solving and 'thought experiments' is necessary. In a complex, real-life situation, this leads to a very dynamic interaction between three different levels of cognitive control which elsewhere is described as the skill-, rule-, and knowledge-based control levels. The interaction is illustrated by figure 1.

One important feature of this interaction among levels of control is that the different levels may be applied to different activities and have different time frames. At the skill-based level, control takes care of the co-ordination of movements, at the rule-based level, actions are controlled by proper sequencing of patterns of movements and, finally the knowledge-based level takes care of planning of actions for new situations.

Interaction at the sensory-motor skill level is based on real-time, multi-variable, and synchronous co-ordination of physical movements with a dynamic environment. Quantitative, time-space signals are continuously controlling movements, and patterns are interpreted as signs serving to adjust the world model and maintain synchronism with the environment. The dynamic control of the patterns depends on high capacity signal processing in a feed-forward mode governed by the internal world model. During run-off of such routines, the conscious attention is free to cope with other matters on a time sharing basis.

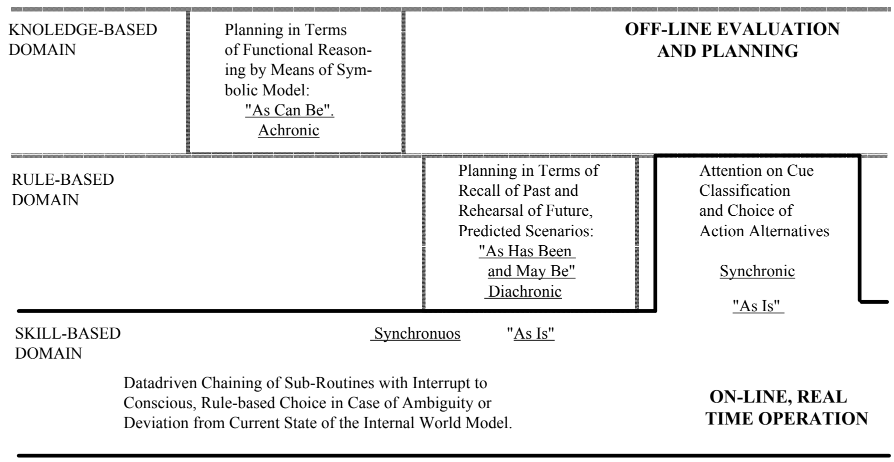

Figure 1. The figure illustrates the complex interaction between the different levels of cognitive control. Tasks are frequently analysed in terms of sequences of seperate acts. Typically, however, several activities are going on at the same time, and at the skilled level, activity is more like a continous, dynamic interaction with the work environment. Attention, on the other hand, is scanning across time and activities for analysis of the past performance, monitoring the current activity, and planning for foreseen future requirements. In this way, the dynamic world model is prepared for uncomming demands, rules are rehearsed and modified to fit predicted demands, and symbolic reasoning is used to understand responses from the environment and to prepare rules for foreseen but unfamiliar situations. Attention may not always be focused on current activities, and different levels of control may be involved in different tasks, related to different time slots, in a time sharing or a parallel mode of processing.

At the rule-based level, the conscious attention may run ahead of the skilled performance, preparing rules for coming requirements. It may be necessary to memorise rules, to rehearse their application, and to update more generic rules with the details of the present environment. Stored rules will frequently be formulated at a general level and, therefore, will need to be re-formulated and supplemented with details from the present physical context. In other cases, rules are not ready in explicit formulation, and previously successful coping with a similar situation will have to be memorised to establish transfer. In general, control at the rule based level require conscious preparation of the sequence ahead of the timing of the skilled run-off, if not, a break in the smooth performance will take place. The conscious mind only very infrequently is operating in synchronism with the interaction with environment. The attention will wander ahead to identify the need for rules, and backwards, to recollect the rules of past encounters. If non is available, switch over to deduction of rules by means of 'a mental model' is required which, in general will require even more foresight if a break in performance is not to occur. In this case, thought experiments and causal reasoning at the knowledge-based level will be necessary. One important feature of this complex interaction is the incessant change of the control and its allocation to the different levels which take place as high skill evolves. Control moves from level to level and the complexity of behavioural patterns, rules and models within levels will grow with training. For a more detailed discussion we will have a look at the different levels.

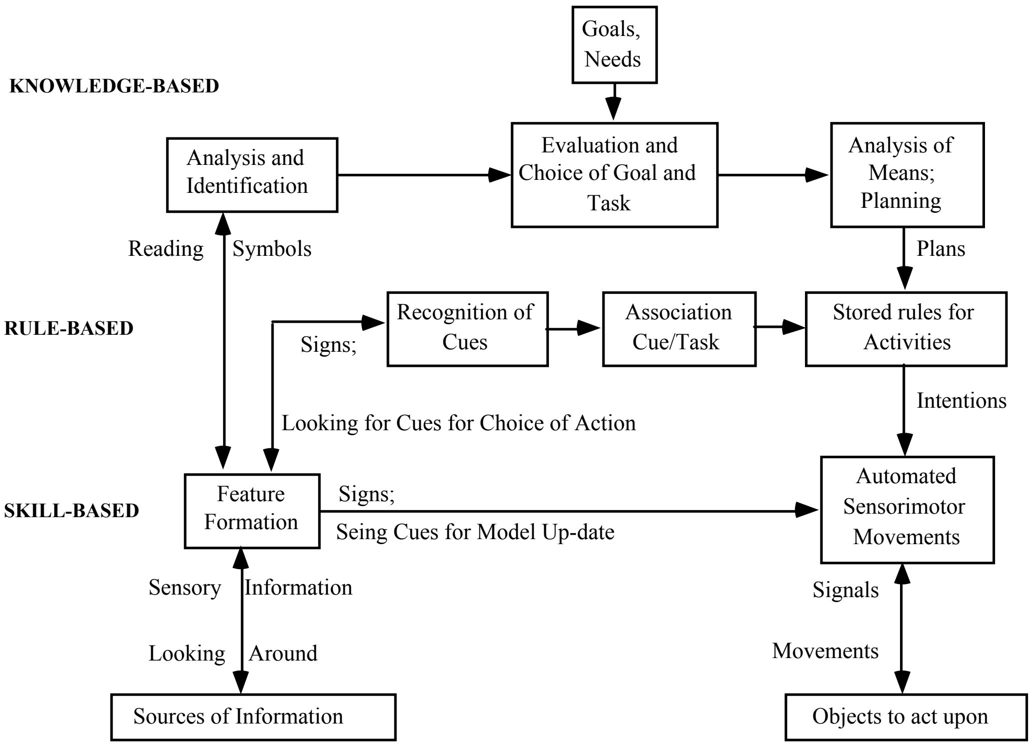

Figure 2. Schematic map illustrating different levels in cognitive control of human behaviour. The basic level represents the highly skilled sensori-motor performance controlled by automated patterns of movements. Sequences of such sub-routines will be controlled by stored rules, activated by signs. Problem solving in unfamiliar tasks will be based on conceptual models at the knowledge based level which serve to generate the necessary rules ad-hoc. The figure illustrates the flow of information, not the control of this flow. The figure is not meant to show humans as passive and subjects to information 'input'. On the contrary, they actively seek information, guided by their dynamic 'world model'. Human actions are explained by reasons as well as by causes. Skilled, integrated patterns of movements, however, are not **caused** by signals, but determnined by signals and the internal world model. Only **changes** in skilled patterns are 'caused'.

Skill-based control is characteristic by the ability to generate to movement patterns required for interaction with a familiar environment. The flexibility of skilled performance is due to the ability to compose from a large repertoire of such movement patterns the sets suited for specific purposes. The individual patterns are activated and chained by perceived patterns that are acting as signs, and the person is not consciously choosing among alternatives. In these cases the higher-level control may take the form of conscious anticipation of upcoming demands in general terms, resulting in an updating of the state of the dynamic world model and thereby in the appropriate 'modulation' of the skilled response. This formulation of skilled performance is in line with Gibson's (1966) attunement of the neural system underlying direct perception of invariants of the environment in terms of 'affordances'.

The performance at this level is typical of the master, or expert, and the smoothness and harmony of an expert craftsman has been fascinating philosophers and artists through ages. Listen, for instance, to Chuang Tsu. In 'The Genius of the Absurd' he describes how the cook of the ruler Wen Hui cuts up an oxen: "Whenever he applied his hand, leaned forward with his shoulder, planted his foot, and employed the pressure of his knee in the audible ripping off of the skin and slicing operation of the knife, the sound were all as in the dance of 'The Mulberry Forest' and the blended notes of 'The Ching Shou'." To the admiring comments of the ruler, the cook answers: "...When I first began to cut up an ox, I saw nothing but the entire carcass. After three years I ceased to see it as a whole. Now I deal with it in a spirit-like manner and do not look at it with my eyes. The use of my senses is discarded and my spirit acts as it wills...". The need to abandon rational control based on conscious observation is a theme frequently discussed in oriental sources. At several occasions, a Japanese master of Raku pottery has been quoted for saying that it took him 20 years to learn the rules of his craft, and another 20 years to forget them again before he felt he approached mastery. Recently, similar experience has been presented by Herrigel (1948), the German philosopher learning archery from a Zen master who desperately try to avoid giving him rules: "Don't ask questions, practice!" Upon his fiasco, the master remarks: "Do not think about what to do, do not speculate about how to do it. -- The shot is only proper if it surprises even the archer himself." Another aspect the lack of explicit consideration of the goal at the skilled level of performance is stressed by the master: "The proper art is without goal, without intention. The more stubbornly you maintain, you want to learn archery in order to be sure to hit the target, the less chance you have of success." The attitude in such Zen sources is strictly against the use of explicit statement of rules during training, but apart from that the descriptions given appear to be very accurate accounts of the nature of an expert's manual skill and of the processes active during later phases of skill optimisation. This discussion demonstrates the qualities of expert abilities as experienced by the performer and raises the question to be discussed in a later section: Which are the requirements to the human-work interface for giving the user opportunity to develop expert skills, and will it be possible in largely automated systems?

The very effective adaptation to the dynamic properties of the environment is a complex learning process which includes two phases. The initial training can take place within the skilled level by imitation and trial-and-error, as for instance, learning to play an instrument by ear or children learning to talk, walk, etc. However, in most cases, control at the rule-based level will be active. The rules involved may be supplied by an instructor or a textbook, as is typically the case when learning to drive a car, to operate tools and technical devices supplied with an instruction manual, or to manage social interactions from 'rules of good manners'.

Once an effective patterns of movements has been formed, an optimisation process will be active for fine-tuning of manual skills by a continuous updating of the underlying sensory-motor schemata to match closer the time-space features of the task environment. Human errors are closely related to this learning process. If the optimisation criteria are speed and smoothness, the limits of acceptable adaptation can only be found by the once-in-a-while experience gained when crossing the precision tolerance limits, i.e. by the experience of errors or near-errors (speed-accuracy trade-off). Some errors, therefore, have a function in maintaining a skill at its proper level. They are not related to particular error mechanisms but intimately connected with the basis for expert skill.

At the next level of rule-based behaviour, the composition of a sequence of subroutines in a familiar work situation is typically consciously controlled by a stored rule or procedure that may have been derived empirically during previous occasions, communicated from other persons' know-how as an instruction or a cookbook recipe. If such support is not present, rules have to be be prepared on occasion by conscious problem solving and planning. his is possible by persons with a basic knowledge of the structure and functioning will be able to generate themselves a set of rules to control activities related to various purposes during early phases of learning. In AI terminology, this involves transformation of declarative knowledge into procedural knowledge, i.e., what Anderson (1983) calls 'compiling declarative knowledge.'

An important point is that control of behaviour at this level is goal-oriented, but structured by 'feed-forward control' through a stored rule, in other words, the person is aware that alternative actions are possible and has to make a choice. The choice is based on 'signs' in the environment which have been found to be correlated to one of the alternative actions. Very often, the goal is not even explicitly formulated, but is found implicitly in the situation releasing the stored rules. The control is teleologic in the sense that the rule or control is selected from previous successful experiences. The control evolves by 'survival of the fittest' rule.

Also at this rule based level, adaptation to the properties and requirements of the environment will lead to an unending change of the cue-rule repertoire. As more integrated patterns of skilled movements evolve at the lower level of control, less detailed rules will be needed for co-ordination. Along with the experience obtained, more convenient cues for action will be found. Humans typically seek the way of least effort. Therefore, it can be expected that no more cues will be used than are necessary for discrimination among the perceived alternatives for action in the particular situation. Along with the evolution of an effective internal, dynamic world model underlying the skilled performance, patterns available for control of movements will be more tightly synchronised with the environment. Less uncertainty will be present for the next actions, and simpler cues will be needed for control in a particular situation at the same time as the repertoire of rules for choice grows. A precondition for this is, however, that the manual skill is related to the actual task content, not only to a separate interface manipulation as it typically is the case, for instance in process control, which separates the manual skill context from the perception of action alternatives at the actual work level.

Development of know-how and rules-of-thumb in this way depend on a basic variability and opportunity for experiments to find shortcuts and to identify convenient and reliable signs making it possible to recognise recurrent conditions without consulting all defining attributes of a situation. In other words, effective, rule-based performance depends on empirical correlation of simple cues to successful acts. This implies that the choice is 'under-specified' (Reason, 1987) outside this situation. When situations change, reliance on the cue sub-set which is no longer valid, and will cause an error due to inappropriate 'expectations'. Again an important conclusion is that error mechanisms cannot be separated from very effective adaptive mechanisms.

The role of cue-pattern/action matching involved in the rule-based performance brings into focus the studies of cue utilisation in the social judgement paradigm (Brehmer, 1987) as well as the judgement biases studied in psychological decision theory discussed by Reason (1987a).

During unfamiliar situations for which no know-how or rules for control are available from previous encounters, the control must move to a higher conceptual level, in which performance is goal-controlled, and knowledge-based (knowledge is here taken in a rather restricted sense as possession of a conceptual, structural model or, in AI terminology, of deep knowledge. The level, therefore, might also be called 'model-based'). In this situation, the goal is explicitly formulated, based on an analysis of the environment and the overall aims of the person. Then a useful plan is developed - by selection. Different plans are considered and their effect tested against the goal, physically by trial and error, or conceptually by means of 'thought experiments'. At this level of functional reasoning, the internal structure of the system is explicitly represented by a 'mental model' that may take several different forms (Rasmussen, 1987). A major task in knowledge-based action planning is to transfer those properties of the environment which are related to the perceived problem to a proper symbolic representation. The information observed in the environment is then perceived as 'symbols' with reference to this mental model.

Also at this level there appears to be a close relationship between adaptation and error. When no established procedure or solution exists, it can be difficult to define acts as error, and this is typically done after the fact when the ultimate effect is realised. Involved in problem solving, test of hypothesis becomes an important need. It is possible and, under risky, irreversible circumstances, often desirable, to test hypotheses conceptually - by thought experiments - before acting physically. It may, however, be tempting to test a hypothesis by physical action or experiment in order to avoid the strain from reasoning in a complex causal net.

Not all cognitive processes at the knowledge-based level are subject to rational, conscious control. As it was the case at the rule-based level, the process will depend on the perception of promising alternatives to consider which, in turn, depend on the subconscious intuition with respect to knowledge, aspects of the available repertoire of mental models, to access in the long term storage (see Reason, 1987, for the discussion of similarity matching and frequency gambling in memory retrieval). In consequence, to enable effective inference at the knowledge-based level, it is important to maintain an integrated relationship between activities at all three cognitive levels, i.e., there should be a consistent common structure behind the configuration of the manipulation surface, the cue-action patterns, and the representation of the relational structure which is effective for knowledge-based inference. This mapping problem will be discussed in a later section.

3. TRANSFER OF CONTROL DURING LEARNING AND ADAPTATION

It is clear from the discussion in the previous section that all the three levels of control are intimately interacting and that the cognitive control of actions will be allocated dynamically to the three levels in a way closely related to the level of training.

Distinctions between different categories of human behaviour similar to the SRK-levels have previously been proposed in relation to learning a skill. Fitts and Posner (1962) distinguish between three phases: the early or cognitive phase, the intermediate or associative phase, and the final or autonomous phase. If we consider that in real life a person will meet situations with a varying degree of training when performing his task depending on variations and disturbances, the correspondence with the three levels in the present context is clear.

During learning and adaptation to a work environment, it is not the behavioural patterns of the higher levels that are becoming automated skills. Automated time-space behavioural patterns are developing while they are controlled and supervised by the higher level activities - which will eventually deteriorate - and their basis as knowledge and rules may deteriorate. In fact, the period when this is happening may lead to errors due to interference between a not fully developed sensory-motor skill and a gradually deteriorated rule system. Anderson (1983) also discusses the interaction between declarative knowledge and procedural knowledge. He describes the development of procedural knowledge during learning as a 'compilation'. Generally, compilation refers to a transformation of knowledge by means of a formal procedure. However, procedural knowledge derived by compilation of declarative mental models is a possible, but not an inevitable, first phase of rule-based behaviour. In later phases procedural knowledge is typically not derived from the basic, 'deep' knowledge, but has an empirical, heuristic basis, and compilation is not a suitable metaphor.

The transfer of control to new mental representations is a very complex process involving change along several different orthogonal dimensions. First, when trained responses evolve, the structure of the underlying representation shifts from a set of separate component models toward a more holistic representation. This is discussed by Bartlett (1943) in relation to pilot fatigue, and Moray (1986) analyses how such model aggregation can lead process operators into trouble during plant disturbances, because the process is irreversible, i.e., the regeneration of a structured model needed for causal reasoning in unfamiliar situations is not possible from the aggregated model. The learning model implied in the SRK-framework indicates that skill acquisition involves not only an aggregation of mental models. Typically, control by a structural, declarative model will also be replaced by an empirical procedural representation concurrent with a shift from a symbolic to a stereotype sign interpretation of observations. This means that training involves at least three concurrent and structurally independent shifts, in terms of aggregation, of declarative-procedural knowledge, and of interpretation of information.

A consequence of this discussion is that basic causal or functional understanding will tend to deteriorate as skill evolves. This is in fact what is the evidence found by Ackermann and Barbichon (1963) from their analysis of the organisation of knowledge and the explanation of phenomena as presented by electrical and chemical technicians in industry. Based on an analysis of interviews, their conclusions were that the professional knowledge of the technicians was fragmented, showed a lack of relationship among phenomena, had barriers between theory, practice, and extra-professional life, and lack of relationship among various representations - mathematical, graphic, concrete, and analogical - of a particular phenomenon. This will be the case when basic symbolic knowledge and representations are used to support stereotyped lines of functional reasoning in various typical situations, and causal reasoning therefore turns into rule- and skill-based manipulations of symbolic representations which will thereby lose their symbolic nature and theoretical relationship. A general trend found is the replacement of functional arguments by reference to human interaction, a tendency that can be explained by the tight relationships between human acts and symbols which are degenerated into mere signs.

The distinction between interpretation of the representation of knowledge in terms of signs and symbols in the sense discussed has been studied from a semiotic point of view by Cuni and Boye (1981). They analysed the role of electrical circuit diagrams in terms of signs controlling activities during design, installation, and repair of electrical power supply systems in private houses, and investigated how different appearance of the same functional diagram was effective for support of the different activities.

This intimate relationship between the three levels of cognitive control during learning and adaptation supports the requirement, discussed in the previous section, that a common structure should be present in the mapping between the actual work content and features effective for control of action at the three levels.

4. IMPLICATIONS FOR CONTROL OF ACTION IN HIGH TECH SYSTEMS

Modern technological systems have several characteristics which influence the natural allocation of control of action to the different cognitive levels. In natural environments, the interaction will typically be controlled at the two lower levels. Work will be related to manipulation of objects in a more or less familiar setting. If exceptional situations occur, the effect of decisions will typically be reversible and interaction can be like an explorative navigation through new territory. Much of the joy of this interaction - compare evolution of high levels of skill in sports - will be related to the experience of success in exploration of the borders of a skill.

The interaction with modern technical systems have features which are very different. Frequently, such as for instance it is the case for process plants, the process to be controlled will be invisible and control will be indirect in the sense that there is no simple mapping between features of the system surface which are the objects of skilled sensory-motor manipulation and the actual control object, the chemical or thermodynamical process. In addition, effects of inappropriate acts may be irreversible and lead to very great losses. Consequently, there is typically not the harmonious relation between manual skill and higher level activities which are found in more traditional work settings, and the need for control of actions from the knowledge or model based level becomes very pronounced in particular for control of the unusual conditions which is typical for automated systems.

Planning of action at the knowledge based level in its pure and systematic form is characteristic of work like research and engineering design. Such activity is based on search and inference in a problem space of conceptual, frequently causal or means-end relations representing the functional properties of the work domain. These activities are typically supported by formal calculation or simulation tools. In modern complex systems, operators have to cope with disturbances and faults by reconfiguration of the components of the system, frequently why it is still operating, in order to protect plant and/or production. If the particular situation has not been foreseen by the designer and the operating staff properly instructed, the task is, in fact, a supplement or continuation of a design task which could not be completed by the designer himself. Consequently, it will require the same kind of knowledge based behaviour as the design itself and unfortunately under much more difficult circumstances.

The basic problem in this situation is that, for modern, reliable systems, situations calling for actual knowledge-based reasoning will be infrequent and, therefore, the knowledge required to cope with them will degenerate during the adaptation to the work requirements, as it was discussed above. Another argument against the requirement that plant operators should be able to reason at abstract functional levels has been that this way of reasoning is unnatural for operators who normally think in terms of physical components and their behaviour. During major disturbances, operators are supposed to take over control. However, the task will not be to take over the usual automatic control. The plant will typically require the operating staff re-designing plant configuration and operating procedures to meet the abnormal condition. For this task they have to understand the basic process. A keeping-the-man-in-the-loop philosophy will not solve the problem of the rare events, since normal operation will not support the required knowledge. For large scale, high risk installations, therefore, other solutions are necessary. It will be required to supply at the surface of the system an adequate representation of the internal process of the system, to arrange an education of operators reflecting the new requirements, and to change the organisation of work in order to give them tasks between disturbances that will maintain their basic knowledge and supply the proper intuition at the conceptual level.

Of particular interest in large-scale systems is the support of performance in order to avoid effects of errors. From this point of view, error mechanisms can be divided into the following categories in consequence of the preceding discussion of control mechanisms: Interference among different control structures; change of control structures because of adaptation and learning; lack of resources such as cognitive capacity, knowledge, and time in response to new situations. The first two categories call for a representation of the process to control at the display surface which serve a close mapping between this process and the cognitive control structure. The third category will need support in terms of a data base with design information and tools for hypothesis generation and testing at the knowledge-based level.

In the following sections the problem of mapping between the internal process parameters, the display surface, and the representations at the various levels of cognitive control will be discussed in some detail by means of examples.

5. EXAMPLES

5.1 Cognitive Control of Musical Skill

It will be useful to analyse the perceptual and motor mapping evolved in activities where high capacity manual skills are involved. Musical performance is such a direct manipulation activity involving very high information processing capacity in a real-time, on-line mode of control. Another particular feature of this performance is that the manipulation surface in the information surface are separate like it is typically the case in human-machine interfaces.

Musical performance is based on a repertoire of highly automated and co-ordinated patterns of movements. The musical notation in a score is perceived in terms of signs referring to such complex patterns. In a text book for playing e.g., a recorder, a table of fingering patterns are given for the individual notes. From such instructions, therefore, playing an instrument can be learned without any knowledge about the symbolic meaning of the notation. When high performance skill evolves with practice, increasingly complex patterns of notes are related to integrated patterns of movements giving very high capacity and speed in performance. This re-coding requires a notation in which chunking is possible of the individual signs in a way which maps directly onto a concurrent chunking of the required movements.

The structure active for the aggregation in the sign domain should map onto the structure useful for 'chunking' patterns of movements. Chunking of movements involves operation in a part-whole relationship and, consequently, this structure should be reflected in the notation. Organisation of movements should be reflected directly in the spatial, graphic organisation of the musical representation. The important feature of the present musical notation system is that the perception of patterns of signs can be changed concurrent with the evolution of higher level motor patterns. The mapping between perceptual and motor patterns is not a simple one-to-one mapping, but can be changed dynamically by higher level signs indicating key-changes, rhythmic instructions, musical style indications, etc. The internal dynamic world model (the attunement of the organism) can be modulated at will by the performer.

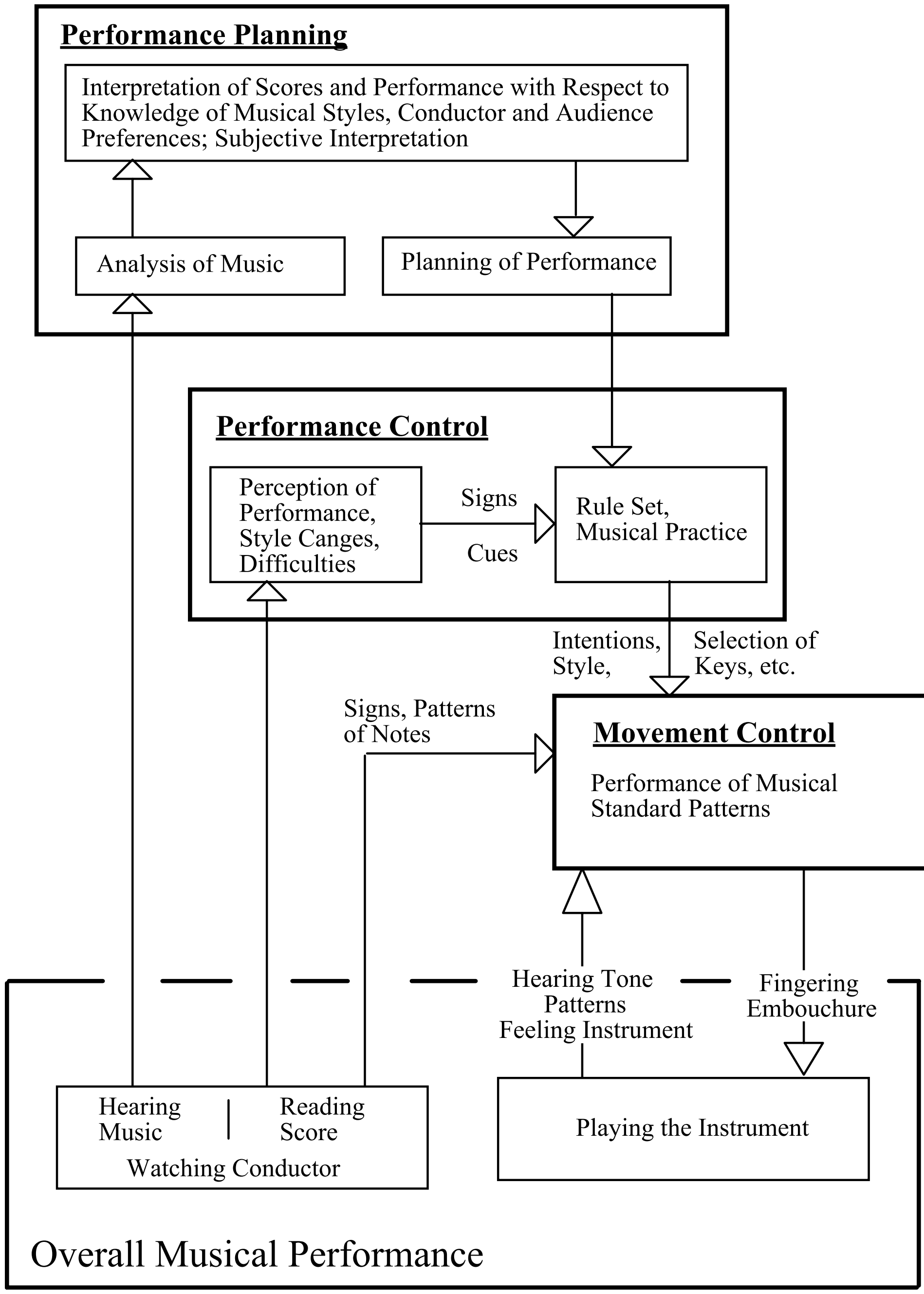

Figure 3. The figure illustrates the interaction between control of movements, control of actions, and planning of actions during musical performance.

The direct analogical mapping from visual patterns to motor patterns serve to that changes in the part-whole dimension in both domains can easily and dynamically be performed according to level of practice, and to higher level performance indicators, e.g., from a conductor.

It is possible to design more informationally 'economic' notations system which is not directly structured in a part-whole hierarchy, but according to a generic tree in combinatorial coding. In that case, the transformation to action patterns would require analytical, rather than perceptual, re-coding which would be more difficult to change according to practice and style. Such a system has, in fact, been proposed by Jean-Jacque Rousseau in a presentation for the Academy of Sciences in Paris August 1742 (Confessions, Vol. 2, Book 7). His system was based on a logical notation in terms of a number code and, typically, he was introduced to the Academy by Reaumur. It was well accepted by the scientists of the Academy, and a committee was founded to review the system for recommendation. The arguments of this committee mostly considered whether the system was new and therefore useful. Apparently, numerical system for musical notation were subject to discussion at that time. However, as soon as Rousseau presented his system to the composer Rameau, he was met with arguments that convinced him: "Your signs are excellent, with respect to representation of tone and interval ---; but they very poor because they require an activity of thought which cannot keep pace with the performance. The location of the signs in our usual notation imprint on the eye without support of this kind. If two notes, one very high and another very low is connected with a sequence intermediate notes, I immediately by first glance perceive the gradual rise from one to another. By your system, however, I necessarily have to spell my way through from number to number, one glance will not do it." Rameau's arguments fit very well the discussion presented above.

A point worth a closer look is the character of 'direct manipulation' in musical performance even when the visual presentation of the score and the manipulation surface are separated. The determining issue probably is related to the fact that the music attended to and the score perceived visually has the same part-whole structure and merge into one perceived pattern - one 'see' the music in the score - which maps directly onto the patterns of movements. This, in fact, implies that the attention and manipulation 'surface' merge at the level -in the domain- of music.

Another example similar to the musical performance is the high performance skill developed by users of the Abacus of China and Japan. It is well known that for the elementary arithmetic operations, the speed and accuracy of skill Abacusians are comparable to that of calculator users. The trick appear to be the same as in musical performance, namely that the numbers to introduce in a calculation is read in terms of actions on the abacus, while the arithmetic operations signs + or - act like the transposition signs in music to select the number-action mapping set needed in the particular operation. It is interesting to see that instruction books (Anonymous) for abacus users stress the need to be consistent in the use of the proposed number-action mapping, even simpler actions are possible in some cases, in order to develop a high capacity sensory-motor skill.

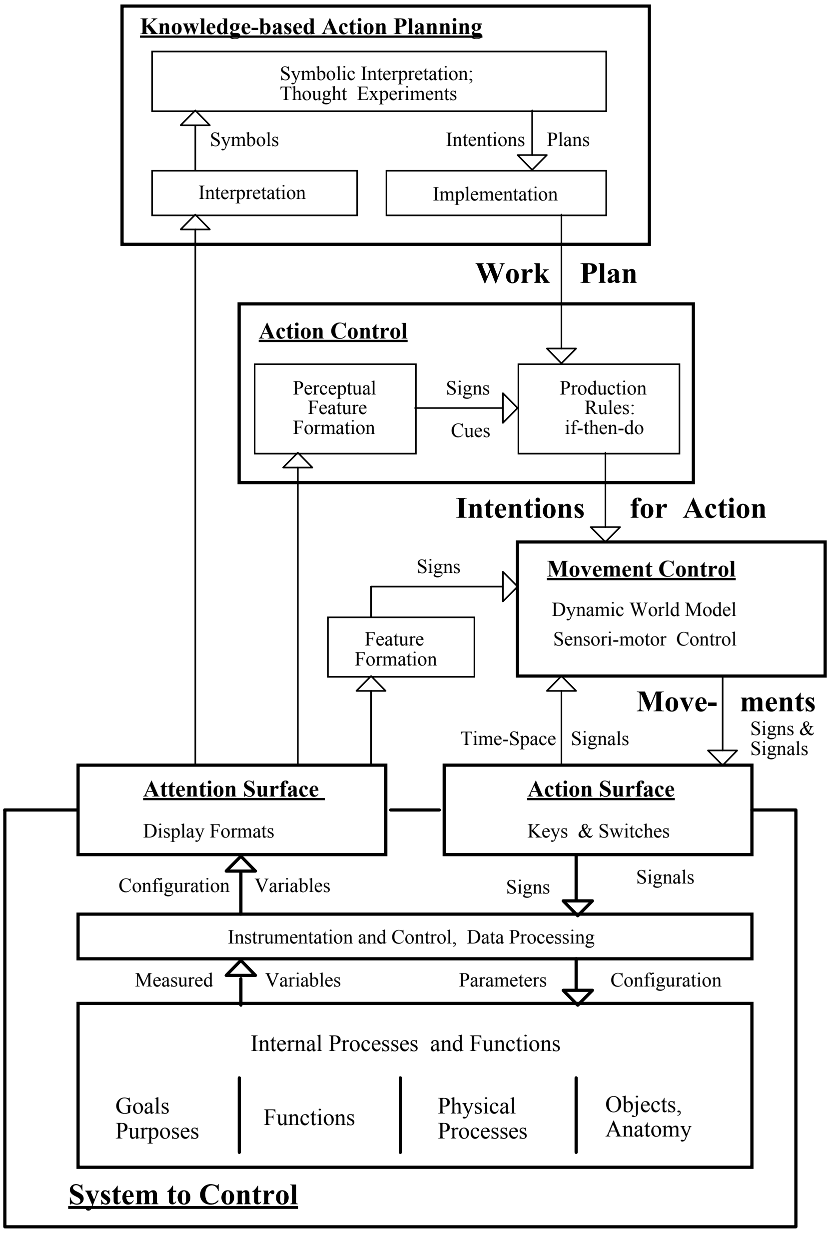

Figure 4. The figure illustrates the interaction between control of movements, control of actions, and planning of actions during supervisory process control.

5.2 Cognitive Control of Actions in Process Control

Industrial process plants have a stable and well defined structure and their response to control actions depend on stable physical laws. They are built from technical components designed to perform specific physical processes. The components are connected into systems in which their physical processes interact to serve higher level functions which can be very specific for the particular type of plant. The functions, in turn, serve as means to meet the ultimate plant purpose within constraints given by economy and regulations. The components are standardised and have properties which are typical for the applied technology. At the functional level properties are typical for the particular industrial branch, whereas at the highest level they are related to the particular installation. In this way, a process plant can be conceptualised at several means-ends levels which form the problem space of the operators.

For the operators, the functions and processes are only indirectly accessible by inference from a number of measurements of basic physical variables such as temperature, pressure, flow, etc., supported by information about the actual physical configuration such as valveing and switching state indications. All variables are measured in the physical components. Depending on the situation and the task of an operator, however, he interprets variables with reference to the physical processes of the components or to the higher level functions. As a result of the operator's decision, control actions ultimately are performed at the level of physical components. In consequence, decisions includes three main phases: 1. data integration for identification of the state of affairs; 2. consequence prediction, goal evaluation, and decision; and 3. decomposition and re-formulation of the control intention into basic acts. In traditional installations of the one-sensor-one-indicator technology, these functions are left operators. In modern installations, the control interface and the operators share these functions in varying degrees.

In order to identify advantages offered by interfaces based on modern information technology, it is useful to have a look at the problems found in systems based on the traditional one-sensor-one-indicator technology. In such systems, sensory-motor skill will be active only for manipulation at the surface of the system because there is no close mapping in time-space terms between the data patterns obtained from the array of instruments and the movement patterns required for actually controlling the internal, physical process. This mapping depends on symbolic, combinatorial coding, not direct analogical mapping as it was the case for musical notation.

In direct, every-day object manipulation, the state of affairs in the environment can be perceived directly in terms of actions to take (cf. Gibson's affordance). The objects of attention for reading off actions and for controlling movements are the same, the manipulation and observation surfaces are merged into one. This is not the case for traditional control rooms. Control of movements is concerned with the location and form of switches and keys. Cues for actions are derived from observation of meters and indicator lights. Direct sensory-motor manipulation, therefore, is unrelated to the actual, deeper control task. Cues for actions have to be formed by sequential observation of indicators. As already mentioned, reading instruments will only include those necessary to discriminate the perceived alternatives for action in the present context. Frequently, the intended action will involve a familiar sequence of acts which will be performed 'open-loop' due to the separate observation and manipulation surfaces.

Advanced interfaces can perform the appropriate information transformations between the state of control object task and the representation displayed to operators and, therefore, can serve an integration of the observation and manipulation surfaces, see figure 3. At the lowest level, cognitive control is concerned with co-ordination of movements. Mapping of control intentions onto a sequence of acts on the components of the system can be performed automatically by the computer or by an operator. A computer is able to accept orders at a higher intentional level. Examples are well known: the automatic sequence controller used to start process plants or, in the musical analogy, the automatic 'beat-master' giving percussion accompaniment when the one-man-band musician selects the beat and style.

On the other hand, an operator will be able to develop skilled patterns of movements for control of the internal plant process, if feedback information about the effect of actions is structured in part-whole patterns mapping the structures of the movement pattern (cf. the music example), and when control of movements and cues for actions can be read from the same surface, as has been suggested in direct manipulation interfaces. In this case, a repertoire of automated sub-routines related to stable configurations of physical components can evolve. An integrated manual skill subject to control by higher level intentions.

This skill, however, will only be related to control of the process, rather than the surface, when a number of requirements are met by the information transformation of the interface. In general, for systems like industrial process plants there will be no one-to-one mapping from movement patterns onto the consequence for higher level functions of the system, and the delay of the higher level effects will be to long to allow sensory-motor patterns to develop. High manual skill can only be developed within a restricted range of time constants (compare the difficulty in navigating slow response super tankers). A solution might be to use 'virtual machine' feedback in terms of sound patterns representing the immediate effect of the control actions upon the physical configuration and state of the individual components. A blacksmith, for instance, use sound patterns for the on-line control his manual skill, not the delayed effect on the finished, forged piece. The development of manual skill and, not the least, the opportunity for performance monitoring and error recovery could possibly be supported effectively by a stereophonic sound pattern representing the operation of the virtual machinery (Note, that the sounds in a blacksmith is not perceived to be noise because it is meaningfully correlated with the activity, the 'music of work').

Merging the observation and manipulation surfaces in purely visual displays implies a spatial-temporal, graphic representation in which spatial features will serve to maintain the time-space signal loop necessary for automated skills while, at the same time, configuration patterns will serve as cues for actions. This is, for instance the case for mouse-and-icon interfaces, which support 'direct interface manipulation'. In order to maintain the spatial-temporal signal transmission, isomorphic mapping from presentation to movements is not required. Computer games demonstrate that complex transformations, such as co-ordinate rotation as well as Cartesian-polar system transformations are readily accommodated by the sensory-motor systems. Study of games can be a useful source of data on the role of different kinds of task-display mapping. In order to apply the high capacity features of manual skill at the task level, the movement pattern and the perceptive patterns available should be related to the same relational level, in order to have relational structures with homomorphic part-whole properties, cf. the musical example.

When time constants in the process systems are too long for direct sensory-motor manipulation at the actual task level, control will be based on the higher level rule-based control. In order to avoid 'under-specified' action from single cues, as discussed above, displays should represent the task content in a way supplying integrated, defining cues, i.e., represent the necessary preconditions for the associated task in a way which prevents the selective attention to a convenient, but not defining cue subset. In consequence, representation should be in terms of an integrated pattern. For simultaneous control of movements, the means for manual acts must be represented in a way that allow direct manipulation, i.e., maintains the time-space signal loop.

The musical example suggested that chunking of control actions on physical components into integrated skilled routines will only be possible if the display configuration and the movement pattern have the same decomposition structure. This, however, requires that the manipulation displays are configured according to the physical configuration of the components which are the objects of control actions. Consequently, if the observation surface for task control is integrated with the observation and control surface for movements, the levels of representation of the cues for control of actions and the spatial pattern for control of movements should be part of an integrated visual pattern. Such a design, considering only the control of actions and the related movements is feasible since the cue pattern is an abstract sign and there will be no conflict when integrated with a representation of the configuration at the level of movements. The fact, that signs in their function as cues for action are merely easily recognised patterns with no 'meaning' gives the freedom to choose the conceptual basis for their form such that other cognitive functions in the particular task are supported also, for instance memory or, as discussed below, functional monitoring by means of a combination of sign function and symbolic reference.

A problem is caused, however, by the delay of the effect of control actions. In order to support error visibility and recovery, monitoring at the knowledge-based level can be necessary. This implies the access to a symbolic representation at the functional level at which control decisions are made, i.e., at one level or more above the movement control level. In this case, it appears to be advantageous to look for a representation of system state which can be perceived symbolically with reference to functionally structured display and, at the same time, can serve perceptually as cues for action (for an example, see the displays based on the Rankine cycle, proposed by Beltracchi, 1987). In this way, cues are less likely to be 'under-specified'. Control of movement, then, will be from a separate display field. This approach may in fact be generally useful. First of all, because the same display format will serve rule- and knowledge-based control. Secondly, because the use of separate displays of means for control of movements make it possible to have standardised displays for movement control for the various component configurations to be used for several task configurations. This feature will support development of manual skills.

An advantage of the display design aiming at simultaneous support of rule- and knowledge-based support is two-fold. First of all, shift between the two levels is made easier (cf. Woods' visual momentum (1984), secondly, the confidence to the display information may be better when a display used in the normal work can also be used under unusual conditions and, therefore, shift to unfamiliar display formats are not required. The resulting display seems to be a kind of two-level display: one level for the choice of target state and another for control of actions and the related movements.

For knowledge-based control of disturbances, the identification of the actual state is an important analytical task depending on a symbolic representation, either for the diagnosis itself or for verification of symptom-based hypothesis. The inherent circular nature of the diagnostic task (the level to chose for diagnosis of the present state depends on the primary goal which in turn depends on the actual state, see Rasmussen and Goodstein, 1987) calls for an iterative consideration of the various levels, a kind of 'browsing' through levels and displays to consider. In a previous section it was mentioned that even knowledge-based reasoning is not an objective, rational process and that the knowledge 'coming to mind' depend on intuitive processes. In that case, effective 'browsing' support in search for useful information will be important. From this point of view, analytical diagnosis requiring integration of primary data will probably not be reliable. In stead, information of the actual state of affairs should be presented for direct visual inspection and identification with reference to normal state of affairs in the particular operating mode and to the limits of acceptable states derived from the basic technical and authority constraints. Identification can then be in terms of deviation from a target state. From this, the 'melody to play' is found and the 'score' to support control of actions related to this target state can then be found at a lower level of alternative means referring to 'success paths'. For each of these, an action/movement control map can be made available.

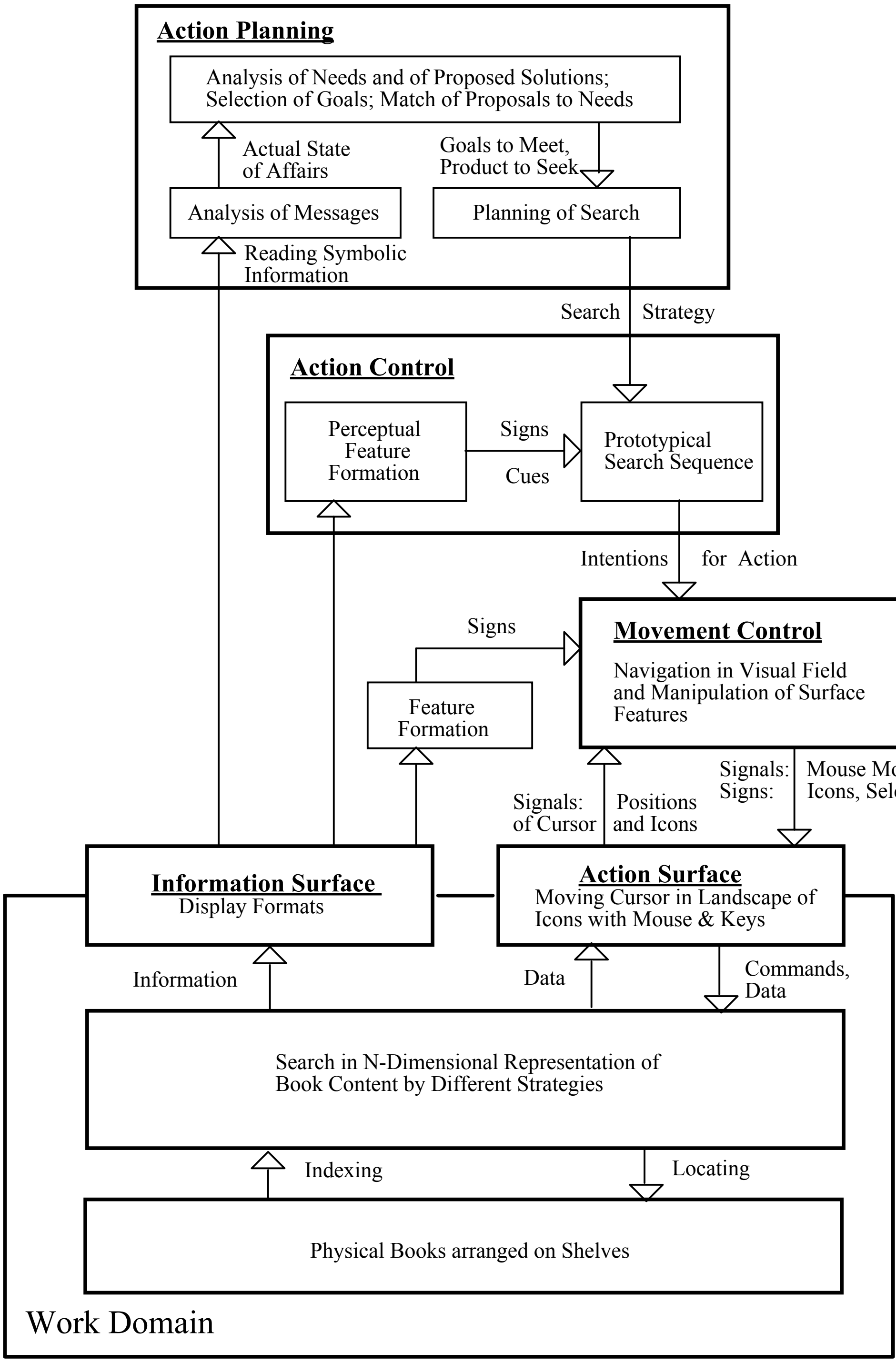

Figure 5. The figure illustrates the interaction between control of movements, control of actions, and planning of actions during search in knowledge bases.

5.3 Cognitive Control of Search in Knowledge Bases

The discussion so far has been focused on the information requirements in control of a physical system, and the features of the mapping between the control surface and the state of the process. The aim has been to counteract interference between control structures and to create a mapping which will support error observability and reversibility and, therefore, give the opportunity for exploration and experimentation which is necessary for learning and adaptation. Another aim of an advanced interface can be to support the operators' resources for knowledge-based reasoning by offering information about basic functional properties of the system and the intentions behind its design. For this support, a knowledge-base is necessary giving declarative information which on occasion can be transformed to the appropriate procedural form.

Search in abstract systems such as knowledge bases is characteristic by a lack of a coherent internal structure similar to that of physical systems. The items of the database are not interrelated by causal laws like the components of a process plant, neither is there the direct mapping between the action patterns required for interaction with the computer and the feedback from the system at the semantic information level, as it was the case in the musical example. In order to obtain such a mapping, special precautions should be taken to create an internal structure in the information base which is homomorphic with the user's problem space, i.e., which will present a space in which the user can navigate easily by means of the search question which comes natural from the current problem, in contrast to navigation guided by knowledge about the computer system. Typically, the internal structure of a data base is chosen to make location and retrieval of information items unambiguous, effective, and fast, i.e., it is based on a formal generic hierarchy (see, for instance, Smith and Smith, 1977). For effective access by a user, however, retrieval should be possible from several different points of view, in a means-end space for instance, items should be accessible by question of 'what' they are, as well as 'why' and 'how' they should be used.

Sensory-motor control of movement patterns is concerned only with manipulation of items on the visible surface of a system. This is the advantage of the mouse interface because the communication of spatial - temporal aspects in the loop perception-action is intact. The commands to send the computer are selected from a repertoire presented on the screen. They are identified by means of their physical position, and pointed at with the mouse before the selection order is transmitted by a 'click' sign. This implies a direct relationship between the movement pattern and the perceptual control, like it was the case in musical performance. Consequently, very efficient navigation in a database would be possible if the abstract attributes of the items of the database could be consistently recoded to positions in a spatial representation and its location identified perceptual while navigation in the space is analogically controlled by patterns of movements. This has been systematically used in spatially structured database on video disks in which the exploration of the database is done in term of 'wandering around' by a joystick.

For support of knowledge-based reasoning, however, it is a problem that the number of abstract dimensions of the necessary search terms is high, as defined by the dimensions of the relational structure of the mental model; that the number of items in the base is large and, in particular, that the attributes for search are not immediately and explicitly known by the users who, therefore, may want to 'browse'. One way to exploit the capabilities of computers for flexible presentation could be to relate the information items to the location in a virtual space, a store house, in which three dimensions of the multidimensional attribute space is represented by the location in a room, while the remaining, relevant dimensions are taken care of by arranging for several rooms and departments in the store. Computers systems have the advantage that the same item can be found in several locations according to different search attributes, and the stock can be browsed according to location when the rooms representing the most relevant dimensions are visited. In this way, it will be possible to transfer the Simonides (500 BC) mnemotechnic trick (to imagine the items to remember to be located along a familiar street or in a familiar room, see e.g., Fuller, 1898) to a multi-dimensional representation or, in other words, to use the idea of George Miller (1968): Information is a question of 'where'. Visual presentation of the space and analogical control of movements (mouse or joystick) will result in skill-based control of the search itself. There is a direct relation between movements and the location in the information space.

The structure of commands and the organisation of presentation, hierarchical or in the form of different projections onto the two-dimensional display surface, could be suggested from analogy to musical performance. A basic hypothesis to suggest, based on the musical analogy, is that novices are focusing on the manipulation surface, the 'tool handle', while skilled performers are focusing on the performance content. To enable easy shift in the degree of 'chunking' action elements and perceptual elements depending on general level of training and on 'difficult passages' appearing, the structure of the perceptive and motor representations should map one-to-one in part-whole relationships. In this way, the search is formulated as an exploration of a multi-dimensional space, the representation of which depend on the strategy selected by the user, i.e., the representation of the problem space depend on the approach of the user (a native of a city on a business tour need a different representation than a tourist looking for exiting items).

An important aspect to consider will be that also for knowledge-based control of search, the approach will be guided by the intuition offered by the user's 'world model'. One may want to consult familiar regions, to browse, or a more rational, analytical approach may be chosen. An analytical approach is a kind of selective 'addressed' search in a domain selected by from a display of a 'work-room' showing the landscape of topical items which can be selected. In the analogy of a city map, you have an indication at least of the street you want to visit together with a helicopter which will bring there directly. Being there, you will look at the houses. In the 'browsing strategy', you don't know the address, but you will recognise what you are looking for, when you see it. This means, you have to pass through the streets of the city until you recognise an item. In a library this implies scanning the physical books on the shelf. In a computerised system, however, you can choose a sub-space of, or a 'channel' through the multi-dimensional space by specifying some aspects of the target which are known (to be what you want or do not want). In this way, the difference between analytical search and browsing in a computerised system is a question of degree, not of categories.

In conclusion, for design of knowledge support systems, it is necessary that the database reflect the user needs in terms of search attributes. If this is not the case, a user will simply not be able to match characteristics of unfamiliar items with his needs. This implies, that it is not only a problem of designing interfaces to databases, the primary information indexing must be based on intimate knowledge of the users' point of view in the actual situation.

In this type of interface, manipulation is not directly connected to the information content, but to general interface manipulation skills in terms of reading signs for selection, giving signs in terms of commands, etc. In any highly familiar environment, actions are activated by cues or signs which are only related to the actions by conventions, not by their symbolic meaning. The choice of interface messages for control of search activities, therefore, is rather free. This freedom can be used in 'iconic' interfaces to guide the user. For this purpose it is important to consider the possibility of using a form of signs which are clearly related to the actions to make or alternatives to choose among but, at the same time, can be interpreted symbolically with reference to the substance matter of the users' domain. In terms of figure 5, this implies that display icons are chosen, which simultaneously present a close mapping onto effective cues at the levels of movement and action control (their sign function) and onto the semantic content of the data base which is relevant to the user's planning level (their symbolic meaning).

REFERENCES

Ackermann, W., and G. Barbichon. (1963). Conduites intellectuelles et activite technique. Bull. CERP 12, (1), 1-16. Anonymous Instruction Manual: The Fundamental Operations in Bead Arithmetic. How to Use the Chinese Abacus. Peking, 1960s.

Anderson, J. R. (1983). The Architechture of Cognition. Cambridge, MA: Harward Univ. Press.

Bartlett, F. C. (1943). Fatigue following highly skilled work. Proc. R. Soc. Lond. 131, 247-257.

Brehmer, B. (1987): Models of Diagnostic Judgements. In: Rasmussen,J., Duncan,K. and Leplat,J. (Eds.): New Technology and Human Error. London: Wiley and Sons.

Brunswick, E. (1957). Scope and aspect of the cognitive problem, in: Contemporary Approaches to Cognition. H.E.Gruber et al. (Eds.). Cambridge: Harvard University Press.

Chuang Tzu (300 b.C): Genius of the Absurd, Book III-2. See Waltham, C. (Ed.), 1971, New York: Ace Books.

Cuny, X., and M. Boye. (1981). Analyse semiologique et apprentissage des outils-signes: L'Apprentissage du schema d'electricite. Communications, 33, 103-140.

Fitts, P. M., and M. I. Posner. (1962). Human Performance. Monterey, CA: Brooks/Cole Publishing Co.

Fuller, H. H. (1898): The Art of Memory. St.Paul, Minnesota: National Publishing Company.

Gibson, J. J. (1966). The Senses Considered as Perceptual Systems. Boston, Ma: Houghton, Mifflin.

Herrigel, E. (1948): Zen in der Kunst der Bogenschiessens. Konstanz: Curt Weller

Miller, G. A. (1968): Psychology and Information. Am. Docum. 19 (1968) 286-289.

Moray, N. (1987): Intelligent Aids, Mental Models, and the Theory of Machine. Private communication. To be published.

Rasmussen, J.: Mental Models and the Control of Actions in Complex Environments. Invited paper, 6th Workshop on Information and Psychology. June 1987. "Mental Models and Human Computer-Interaction" arranged by the Austrian Computer Society. Risc-M-2656

Rasmussen, J. (1986). Information Processing and Human Machine Interaction: An Approach to Cognitive Engineering. New York: North Holland

Rasmussen, J. and Vicente, K. 1987): Cognitive Control of Human Activities and Errors; Implications for Ecological Interface Design. Fourth Conference on Event Perception and Action, Trieste, August 1987. Risc-M-??

Reason, J. (1987): The Cognitive Basis of Predictable Human Error. Proceedings of the Ergonomics Society's Annual Conference, Swansey, UK. April 1987.

Rousseau, J.J. (1742): Confessions.

Simonides, (500 BC): See Fuller (1898).

Smith, J.M. and D.C.P. Smith (1977): Database Abstractions: Aggregation and Generalization. ACM Transactions on Databaseystems, Vol. 2, No. 2, p.105-133.

Woods, D. D. (1984): Visual Momentum: A Concept to Improve the Cognitive Coupling of Person and Computer. International Journal of Man-Mchine Studies, 21, 229-244.

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Abstract (Max. 2000 char.)

The paper reviews the different levels of cognitive control of human actions in a complex environment in terms of the skill-, rule-, knowledge-based framework. The temporal aspects of the interaction among the levels of control is discussed together with the transfer of control taking place during training. The problem of creating an interface that serves a natural interaction among the three levels of control in artificial environments is discussed with reference to musical performance, process control, and search in databases.

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