THINKING AND PROBLEM SOLVING

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Summary

Human thinking, and in particular, the human ability to solve complex, real-life problems contributes more than any other human ability to the development of human culture and the growth and development of human life on earth. However, the human ability to solve complex problems is still not well understood, partly because it has for a long time been largely ignored by traditional problem-solving research in the field of psychology.

In this article, we present a definition of complex problem solving and describe a theoretical framework that accommodates the theoretical and empirical strides that have been made in understanding complex problem solving thus far and may serve as a guide for future research. We discuss the dominant methodological approaches that have been employed to study complex problem solving, and offer our own recommendations on which of the various approaches might be the most promising.

1. Introduction

March 28, 1979, Three Mile Island, Pennsylvania (Associated Press)

> *One of the Three Mile Island reactors was shut down for routine refueling on March 28. The other, Unit 2, was humming along quietly until, at 3:53 a.m., terrible events began with a whoosh. The fail-safe system failed. Three valves on auxiliary pumps that should have been open weren't. And the chain of human error and mechanical breakdown grew, multiplied, and turned a routine glitch into the worst nuclear accident in the 22 years since the U.S. nation began using nuclear power.*

February 9, 2001, Long Beach, California (Associated Press)

Boeing engineers are working on an 800-seat airliner with wings that blend smoothly into the fuselage instead of protruding from its sides. The so-called blended wing-body aircraft will fly at the same speed and altitude as a 416-seat Boeing 747–400, but it will use 25 percent less fuel and generate less noise. The A-380, which will seat about 600, is expected to be in the air by 2006.

The breadth of human thinking is truly striking. As is evident in the examples provided above, human thinking can lead to catastrophic disasters. Yet, on the other hand, human thinking also makes possible the most wondrous achievements. Whatever "thinking" is, and scientists disagree heartily on the proper meaning of the term, there can be little doubt that human thinking determines human culture to an extent that is unrivalled by any other human ability. Of course, culture determines the way we think as well—as many scientists have pointed out in the past.

In this article, we describe some of the main properties of human thinking. To stay with the general theme of this encyclopedia, after providing a definition of thinking and briefly discussing the various categories or types thinking may be divided into, we concentrate on one particular type of human thinking that contributes more than any other to the development of human culture and the growth and development of human life on earth, namely, problem solving. Our discussion will focus on complex, real-life problem solving rather than on solving small and artificial laboratory-type problems, and will concentrate on both empirical research and attempts to explain the phenomenon theoretically.

2. Defining Human Thinking

Many of our daily activities involve thinking of some sort. For example, we decide what to wear in the morning, which route to take to get to our office, which job-related duties to perform in which sequence once we arrive at our office, what to have for lunch, and so on. Of course, not all thinking is alike. There is thinking that involves only a few mental steps, and there is thinking that requires many steps. Some thinking involves situations we have never encountered before, and other thinking involves familiar situations. Sometimes thinking is tied to clear goals, and sometimes it is not. "Thinking," then, can be distinguished on any number of meaningful dimensions, and the mental processes—that is, the steps we engage in when thinking, as well as the mental representations the processes operate on—may differ widely for different types of thinking.

Given the multidimensionality of thinking, it may come as no surprise that different researchers, all claiming to study the phenomenon of thinking, have in the past differed widely in their definitions of the term thinking. On the one hand, thinking has often been defined in terms of its possible functions. For example, Aebli likens thinking to "bringing order into one's doing," and Johnson, Drner, and many others define thinking in terms of problem solving.

On the other hand, some researchers have attempted to define thinking in a manner that is independent of its assumed functions. We will follow the latter approach and for the purpose of this article define thinking as the "cognitive processing of internal memory representations that may occur both consciously and subconsciously and may not always follow the laws of logic."

Given this definition of human thinking, we can distinguish between various subtypes, or categories, of thinking. Figure 1 displays a taxonomy of thinking that has been developed by Johnson-Laird. According to Johnson-Laird, five different types of thinking can be distinguished. For example, thinking that is goal-oriented, does not follow a predetermined sequence of mental steps, and has no precise starting point is usually labeled "creative." Alternatively, thinking that is goal-oriented, does not follow a predetermined sequence of mental steps, has a precise starting point, and leads to an increase in semantic information in the human memory system is called "inductive." Inductive and deductive thinking together constitute the category of problem solving.

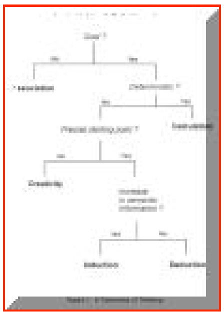

Figure 1. A taxonomy of thinking

Readers should note that the taxonomy has more than just intuitive appeal. The questions used divide the area of thinking into truly distinct subtypes that differ from each other in terms of both the mental processes conducted and the mental representations involved. Thus, "association-based" thinking, for instance, differs from "calculation" both in terms of the underlying processes (i.e. mental steps) as well as in the mental representations that the processes operate on.

In the rest of the article, we focus primarily on one particular type of thinking that is inherent in the taxonomy, namely, problem solving (subsuming both inductive and deductive thinking). We will do so because we are convinced that this type of thinking is the most important in supporting and ensuring lasting local, regional, and global welfare.

In the next section, we summarize the currently dominant empirical approaches to studying problem solving, after first providing a brief historical background within which the development of the dominant approaches can be understood. Notice that we will concentrate almost exclusively on what is called complex problem solving (CPS), that is, problem solving that occurs in the context of real-world problems. We present a definition of CPS, and describe a theoretical framework that accommodates the theoretical and empirical strides that have been made in understanding CPS thus far, and serves as a guide for future research. Last but not least, we discuss the dominant methodological approaches that have been employed to study CPS, and offer our own recommendations on which approach might turn out to be the most promising.

3. Complex Problem Solving: Historical Roots and Current Situation

Beginning with the early experimental work of the Gestaltists in Germany, and continuing through the 1960s and early 1970s, research on problem solving was typically conducted with relatively simple laboratory tasks that were novel to research participants. Simple novel tasks were used for a variety of reasons: they had clearly defined optimal solutions, they were solvable in a relatively short time, research participants' problem-solving steps could be traced, and so on. The underlying assumption was, of course, that simple tasks, such as the Tower of Hanoi, capture the main properties of "real" problems, and that the cognitive processes underlying participants' solution attempts on simple problems were representative of the processes engaged in when solving real problems. Thus, simple problems were used for reasons of convenience, and generalizations to more complex problems were thought possible. Perhaps the best-known and most impressive example of this line of research is the work by Newell and Simon.

However, beginning in the 1970s, researchers became increasingly convinced that empirical findings and theoretical concepts derived from simple laboratory tasks were not generalizable to more complex, real-life problems. Even worse, it appeared that the processes underlying CPS in different domains were different from each other. These realizations have led to rather different responses in North America and Europe.

In North America, initiated by the work of Herbert Simon on learning by doing in semantically rich domains, researchers began to investigate problem solving separately in different natural knowledge domains (e.g. physics, writing, chess playing) thus relinquishing their attempts to extract a global theory of problem solving. Instead, these researchers frequently focused on the development of problem solving within a certain domain, that is, on the development of expertise. Areas that have attracted rather intense attention in North America include such diverse fields as reading, writing, calculation, political decision making, managerial problem solving, lawyers' reasoning, mechanical problem solving, problem solving in electronics, computer skills, game playing, and personal problem solving.

In Europe, two main approaches have surfaced, one initiated by Donald Broadbent in Great Britain and the other by Dietrich Drner in Germany. The two approaches have in common an emphasis on relatively complex, semantically rich, computerized laboratory tasks that are constructed to be similar to real-life problems. The approaches differ somewhat in their theoretical goals and methodology. The tradition initiated by Broadbent emphasizes the distinction between cognitive problem-solving processes that operate under awareness versus outside of awareness, and typically employs mathematically well-defined computerized systems. The tradition initiated by Drner, on the other hand, is interested in the interplay of cognitive, motivational, and social components of problem solving, and utilizes very complex computerized scenarios that contain up to 2000 highly interconnected variables (Lohhausen project).

3.1. Complex Problem Solving: A Definition

With the above considerations in mind, it is not surprising that there exist a wide variety of definitions of CPS that have little in common. Indeed, researchers in the area of problem solving have long been troubled by the absence of agreement on the exact meaning of many of the basic terms in the area. Any general conclusion regarding CPS, however, and any theoretical model of CPS can be meaningful only if all agree on what constitutes a problem and what constitutes CPS. For the rest of this article we define CPS as follows: CPS occurs to overcome barriers between a given state and a desired goal state by means of behavioral and/or cognitive, multi-step activities. The given state, goal state, and barriers between given state and goal state are complex, change dynamically during problem solving, and are non-transparent. The exact properties of the given state, goal state, and barriers are unknown to solvers at the outset. CPS implies the efficient interaction between solvers' and the situational requirements of the task, and involves solvers cognitive, emotional, personal, and social abilities and knowledge.

Readers should notice that this definition differs rather substantially from definitions that feature prominently in the North American tradition. John Anderson, as an example of the North American approach, has defined problem solving as "any goal-directed sequence of cognitive operations" regardless of whether the task is novel or familiar to the solvers, regardless of whether the task is complex, and regardless of whether a single barrier or multiple barriers exist between given state and goal state. Our definition, in contrast, constrains potential problems by requiring that they be (a) novel tasks that problem solvers are unfamiliar with, (b) complex, (c) dynamically changing over time, and (d) non-transparent. In order to solve these problems, solvers have to be able to anticipate what will happen over time, and have to consider side effects of potential actions.

In addition and in contrast to earlier, often implicit, views, CPS is not viewed as deterministic in the sense that any problem-solving activity will always lead to the solution of a problem.

Rather, CPS may lead to an approximate solution that may advance the solvers but may not lead to actually solving the problem. For example, research participants performing the duties of the mayor of a computer-simulated town may, even after some practice, still not be able to generate the best possible solution to a given problem. In fact, many, often computerized, tasks exist for which—due to the complex non-linear relations among the task variables—the optimal solution is unknown. Of course, the absence of an optimal solution, while theoretically reasonable and even desirable, poses a problem to experimenters who want to determine the quality of problem solvers' performances, and to those who use micro worlds for personnel selection purposes.

3.2. A Theoretical Framework for Complex Problem Solving

Adopting any definition has consequences not only for how an area is studied but also for how empirical findings are theoretically interpreted. For example, if problem solving is defined in terms of cognitive rather than neurophysiological, biological, or behavioral processes, then it makes little sense to construct a theory of problem solving at a neurophysiological, biological, or behavioral level. In the following, we present our thoughts on how a general theoretical framework for understanding problem solving that is based on the above definition of CPS might look. The framework is based on the assumptions that (a) the theoretical goal of CPS research is to understand the interplay among cognitive, motivational, personal, and social factors when complex, novel, dynamic, non-transparent tasks are solved, and (b) the interplay among the various components can best be understood within an information-processing model. The framework is constrained, of course, by what is known already about CPS. We therefore first present a brief, nonexhaustive list of the main empirical phenomena that have been demonstrated for the area of CPS in recent years.

3.3. Studies on Person Factors

Studies exploring the effect of person factors on CPS tend to focus on test intelligence as one dominant and important person variable. In addition, comparisons between experts and novices and analyses of clinical groups and of strategic preferences belong in this category. Other person variables that have been explored theoretically as well as experimentally but are not discussed here because of space limitations include self-reflection, emotions, and language.

3.3.1. Test Intelligence

Strohschneider has compared the predictive value of test intelligence for CPS performance under two different experimental conditions. All research participants operated an abstract system called VEKTOR first, and were then confronted with a semantically rich Peace Corps worker simulation system, MORO. The Berlin Intelligence Structure test (BIS) was used to assess participants' intelligence. The BIS differentiates between two factors: a content-oriented component representing knowledge in three different modalities, and a process-oriented component representing four operative abilities. For the MORO system, all of the seven subtest scales correlated significantly with a general measure of control performance; the same was found for the VEKTOR system with respect to six out of the seven subscales. Strohschneider thus concluded that test intelligence was indeed a significant predictor of CPS performance. Comparing the two systems, Strohschneider found that performance on the two systems was not correlated significantly. This indicates that a single CPS trait may not be responsible for performance under all conditions.

S, Oberauer, and Kersting also assessed the value of test intelligence for predicting CPS performance measures. In their study, the authors used the well-known system TAILORSHOP under non-transparency conditions. All research participants were also asked to complete the BIS intelligence test. Using traditional measures of performance for the TAILORSHOP (total assets at the end of simulation and the number of simulated months with a revenue), the authors found no significant correlations with any of the BIS scales. Based on the assumption that the (unknown and therefore perhaps low) reliability of the CPS measures could have caused this null-effect, the authors tried other ways of operationalizing the TAILORSHOP performance. In a task analysis, they discovered that two subgoals were utilized by smart problem solvers that unfortunately conflicted with each other: shirt sales and profit margin. Due to system-inherent characteristics, all research participants had a negative profit margin; lucky problem solvers, however, decreased this negative value and at the same time increased shirt sales. Because revenues are the product of sales and profit margin per shirt, good problem solvers increased their losses despite the fact that they were using efficient strategies. When S, Oberauer, and Kersting constructed a new dependent measure—the sum of the increases in shirt sales and in profit margin—then the new measure of CPS quality correlated significantly with the BIS scale "capacity of information processing."

Taken together, the studies demonstrate that intellectual abilities have predictive value for CPS results when certain conditions are met: (1) instead of using a global I.Q. measure, one needs to separate different components of intelligence of which the capacity of information processing appears to be the most promising predictor; and, (2) CPS quality has to be measured reliably—a condition that is rarely met.

3.3.2. Expert–Novice Comparisons

Reither was the first to validate the developing-world scenario DAGU by comparing the control performances of experienced technical advisers who had about 10 years practice in developing countries (i.e. experts), and of postgraduate students who had just begun their first mission as development aid volunteers (i.e. novices). Both experts and novices worked on the DAGU system in groups of three. The main result of Reither's study was that experts showed a broader range of actions and a greater willingness to make decisions from the start, but also that experts used only standard strategies and were not able to adapt to changing task conditions. Reither calls this behavior the "blindness of the specialists." Despite these strategic differences between novices and experts, both groups performed terribly on the system, however. In both groups, the number of inhabitants of the simulated country had decreased dramatically after 20 simulated years, due to starvation. This finding leads to the (as yet unanswered) question whether either the experts did not acquire any usable knowledge during their 10 years of practice, or the simulated system does not capture reality in a valid manner.

Schaub and Strohschneider examined whether managers and students act differently when dealing with the MORO scenario. In MORO, research participants have to take on the role of a Peace Corps worker in Africa. The authors reported that the managers' problem-solving behavior was characterized by a more intense exploration of the scenario and by a more cautious and adaptive way of adjusting to the demands of the task. On average, the managers achieved better results than the students. One potentially confounding factor in this comparative study was the age of the research participants, however. The managers were 25 years older than the students, on average, and thus had more life experience. Similar studies comparing students of economy with professors of that discipline on their performances on the TAILORSHOP scenario have been conducted by Putz-Osterloh.

Repeated exposure to a problem, of course, also produces a certain degree of expertise and should therefore lead to better problem performance and representation. This could indeed be demonstrated in a number of studies where research participants had to work on the same scenario for more than one simulation period. In general, it seems fair to argue that knowledge is an important predictor of control performance, although dissociations between the two variables in CPS situations have also been reported.

3.3.3. Clinical Groups

In a prospective longitudinal study, Fritz and Funke compared the quality of CPS in pupils who had minimal cerebral dysfunctions (MCD) and in matched controls (CON). Working with the dynamic system OEKOSYSTEM, all participants were asked first to explore and then to control the system. In terms of the quality of participants' knowledge acquisition (as revealed by causal diagrams of the assumed structural relations), the authors found that the MCD group did not acquire significantly less knowledge than did the CON group. However, the strategies used differed markedly for the two groups. Participants in the CON group used single variation interventions that tend to reveal the causal relations among variables three times more often than did subjects in the MCD group. With respect to the quality of system control, there was no significant group difference, although 20% of the subjects in the CON group reached the required goal state at least once, whereas almost none of the MCD participants did.

3.3.4. Strategies

Schmuck used a self-constructed instrument to assess the degree to which problem solvers spontaneously exert executive control and compared solvers with high and low efficiency of executive control on their performances in the FIRE scenario. Solvers classified as highly efficient showed better performance from the start but also needed more time and made more interventions. These solvers also showed a greater variability in behavior than did participants classified as low in efficiency. Schmuck argued that these strategic differences explain the low stability scores found in many CPS studies. The explanation relies strongly on the assumption, however, that Schmuck's instrument allows a reliable differentiation between people who differ in efficiency, a fact that has yet to be demonstrated.

Vollmeyer, Burns, and Holyoak have analyzed the strategies problem solvers use when exploring, controlling, and predicting an unknown complex dynamic system called BIOLOGY LAB. Participants were categorized according to their exploration behavior as using (1) a scientific strategy, (2) systematic variations of a strategy, or (3) unsystematic variations of a strategy. As expected, strategies (1) and (2) led to a better representation of the system and to a better prediction of system states than did strategy (3). Surprisingly however, no group differences were found for participants' control performance. The authors interpret their result as indicating that different types of knowledge are necessary for the three different tasks.

Putz-Osterloh also strongly recommends strategy analyses for the explanation of individual differences. Using the DYNAMIS micro world, she found significant improvements in structural system knowledge for participants using efficient strategies for intervention. Results from Schoppek demonstrate the differential influence of two kinds of knowledge (specific rules, general operations) on strategies and the necessity to consider processes of intention regulation in the control of dynamic systems. This influential role of knowledge could also be demonstrated in experiments from Preuler.

Strategic differences may show up also in cross-cultural studies. Strohschneider and Gss could demonstrate, for example, differences between Brazilian and German students in planning and problem solving. The participants completed two instruments, a planning inventory that consisted of everyday problem scenarios, and the cold-storage problem, a computer-simulated dynamic problem. Results demonstrated that in the planning inventory, Brazilian participants accepted the given descriptions and were more optimistic about the results of their efforts. German participants tended to inquire more about the background of the problems and took a more active approach but were less optimistic. In the cold-storage simulation, the Brazilian participants had more difficulties controlling the system. This was attributed to their orientation toward the present time, making it difficult to detect developmental patterns.

Strategic differences were also found when comparing Indian and German samples working on the MORO scenario. Results show that German students dealt with the computer-simulated problem more actively, whereas Indian participants committed more strategic and tactical errors; experimental variation had minimal effect on participants' behavior. It was concluded that

German students used more control-oriented strategies than the Indian students and were more competent in solving the problem.

Even within one country, marked differences may exist, as was found by Strohschneider who compared East and West Germans after unification with respect to their problem-solving strategies and abilities. Whereas East Germans analyzed problems very carefully and made clear plans, the West Germans tried to work as quickly as possible and did not develop extensive plans.

3.4. Studies on Situation Factors

In studies exploring the role of situation factors on CPS, several variables have been experimentally manipulated, including the type of task, the effects of noise-induced stress, individual versus group problem solving, the transparency of system variables, and the type of the system presentation.

3.4.1. Type of Task

Funke and Mller conducted an experiment with the SINUS system in which the problem solvers' task was first to explore an unknown dynamic system for a given number of trials through either passive observation of another person interacting with the system or active intervention. Later, all participants were asked to control the system such that given goal states were reached. The dependent variables in this study were the quality of knowledge acquisition and the quality of control performance. Results showed that active intervention led to better control performance but reduced the amount of verbalizable knowledge. Surprisingly, the observers, who were poor in control performance, constructed better causal diagrams showing the system variables; thus, they appeared to have acquired knowledge about the variables and their interrelations but not about how to control the system.

Berry performed a similar study using the SUGAR PRODUCTION and the PERSONAL INTERACTION tasks. In her Experiment 1, participants first had to watch an experimenter interacting with the system and then to control the system by themselves. It seemed as if participants did not learn anything through pure observation, neither on the control scores nor on the post-task questionnaires. In a second experiment, Berry found that learning by observation was possible when the task was changed from a task with non-salient relations to a task with salient relations among the system variables. The effect of this modification was apparent on both diagnostic measures, on the quality of control performance as well as on the system knowledge as measured by a questionnaire.

3.4.2. Stress

Drner and Pfeifer tested the effects of noise-induced stress on CPS. Although stress can be considered a person variable, this study is subsumed under situation factors because the experimental conditions manipulated situational aspects. The authors used a version of the FIRE scenario developed by Brehmer and his associates. The participants' task was to manage five different fires either under conditions of a stressful white noise or under quiet conditions. Time pressure was present in both conditions. At a global level, there was no difference between the two conditions with respect to their success and failure rates. A more fine-grained analysis—looking at participants' tactical decisions—revealed, however, that although stress did not affect the number of errors made, it did affect the types of errors made. For example, an incorrect dosage of fire fighting interventions and a more reactive type of behavior was characteristic of the stressed participants.

3.4.3. Individual versus Group Complex Problem Solving

Kller, Dauenheimer, and Strau compared group CPS to individual CPS. In a first session, all participants worked individually on the scenario FUEL OIL DISTRIBUTION. Performance on the system was then used to classify participants as either good or poor problem solvers. Then, in a second session, participants worked on a very similar scenario called TEXTILESHOP, either individually or in a dyad consisting of either two poor or two good problem solvers. It turned out that the individual problem solvers' performances were worse than the performances achieved by the dyads. For the latter, it did not seem to matter whether they were composed of good or poor problem solvers.

Leutner worked with pupils who had to deal with a derivative of TAILORSHOP either as individuals or in groups of three. In contrast to the previously reported work it turned out here that knowledge acquisition was significantly higher for individuals than for groups but with respect to control performance there was no difference.

Badke-Schaub analyzed problem-solving strategies of individuals and groups dealing with a model for the epidemic of AIDS. Participants had to propose interventions to prevent the spread of the disease. Badke-Schaub found that groups have problems defining a common goal but have advantages in finding problem-relevant information. Groups also produced more proposals for solutions but found it difficult to select one or more of these proposals.

3.4.4. Transparency

Putz-Osterloh and Ler investigated the effect of transparency on problem-solving quality in the scenario TAILORSHOP. One group received the system under conditions of non-transparency; here, participants were told only which interventions were possible but did not receive further information. The second group received a graphical representation of the relations among (almost all of) the system variables. After 15 simulated time cycles (i.e. months), participants in the transparency condition had achieved better scores on the performance measure. In addition, the correlation between system performance and test intelligence was also moderated by transparency. Only under transparent conditions was a small but significant rank correlation between the two variables observed; under non-transparency conditions, the correlation was zero. Putz-Osterloh and Ler argued that the equivalence of the two tasks—the intelligence test and the CPS task—might have been much higher under transparency than under non-transparency conditions. In the former case, both tasks shared the attribute that information was given to participants who had to analyze it. In the latter case, CPS required additional information search procedures that were not necessary to complete the intelligence test. Although it may have been true for the Putz-Osterloh and Ler study, Funke has shown empirically that this assumption does not generally hold: the moderating effect of transparency on the I.Q.-CPS relationship is lost in favor of a main effect of test intelligence if one selects a larger range of I.Q. values than those shown normally by student participants.

In a recent study, Putz-Osterloh again manipulated the transparency of a system by presenting, or not presenting, a structural diagram of the DYNAMIS system. In this study, the experimental group that received the diagram was not superior to a control group without a diagram on measures of task performance and strategy selection. But on a follow-up transfer task with a modified system, the experimental group outperformed the control group on both types of indicators. Putz-Osterloh concluded from these results that knowledge acquisition is not necessarily a prerequisite for good control. The strategies that are applied may be more important for predicting the quality of performance.

3.4.5. Information Presentation

Hbner performed an experiment in which 20 participants had to control a simulated GAS ABSORBER. The system state was displayed either in an analog or a numerical format. With respect to the dependent variable quality of control, it turned out that the analog group was significantly better and also needed less time than the group with numeric presentation.

3.5. Studies on System Factors

Experimental research manipulating system attributes has concentrated on the effects of the variables *Eigendynamik*, feedback delay, and semantic embedding.

3.5.1. *Eigendynamik*

In a series of experiments, Funke systematically varied several system factors, one of which was the *Eigendynamik* of the system. *Eigendynamik* occurs when a system changes its state without intervention from outside, due to its inherent dynamics. In more technical terms, *Eigendynamik* is present when a system changes its state at time t due to the values of some variables at time $t-1$ but does so independently of any input by the operator. In the extreme case, *Eigendynamik* means that a system changes over time despite the fact that no active intervention has occurred. Many natural systems show this property requiring an operator to anticipate the system's inherent changes due to the *Eigendynamik*. Funke has used the SINUS system, an artificial system simulating the growth of living creatures from a distant planet with three exogenous and three endogenous variables, to study the effect of *Eigendynamik*. There were three different conditions, a control condition with no *Eigendynamik*, and two conditions with different degrees of *Eigendynamik*. The results demonstrated that increased *Eigendynamik* yielded a decrease in the quality of system control although the quality of system identification remained unaffected by the manipulation. This pattern of findings suggests that the two dependent variables may tap different processes that are differentially affected by *Eigendynamik*.

3.5.2. Feedback Delays

Heineken et al. tested the effects of feedback delay on CPS by using a simple system called TEMPERATURE in which participants had to control the temperature of an artificial system for 1200 simulation cycles. Feedback concerning the quality of the intervention was either immediate or after little or much delay. In addition, half of the participants were informed in advance which delay condition would be realized. Heineken et al. reported that (a) the quality of system control decreased with increasing delay and (b) *a priori* information about the delay was not effective. Interestingly enough, even in the much-delay condition, participants were—after a long period of time—able to control the system. This indicates that although feedback delay may influence the rate of learning, it does not appear to block completely the ability to master a time-delayed system.

3.5.3. Semantic Embeddedness

Hesse has compared two different semantic embeddings for the same underlying system. EPIDEMIC simulates the spread of a disease in a small community. In one condition, participants, as the managers of a local health service, were asked to care for people who had influenza. In the second condition, the disease was changed to a life-threatening smallpox epidemic. The change in semantics changed participants' behavior drastically; in the more "dangerous" situation, participants tended to be, among other things, much more involved and to take more time making decisions.

Another interesting study on the effects of semantic embedding has been reported by Beckmann. The author compared two semantic embeddings (CHERRY TREE vs. MACHINE) of the same system structure with respect to participants' knowledge acquisition and control performances. In this experiment, the semantically rich embedding seemed to prevent problem solvers using efficient analytic knowledge acquisition strategies.

3.6. Studies on Interaction Effects

The interactions between person, situation, and system factors have been researched less frequently than have the individual factors. One selected area concerns the interaction between person and situation variables.

3.6.1. Person and Situation

Rost and Strau analyzed the interaction between type of information presentation (numerically vs. graphically) and type of induced mental model (propositional vs. analog) using a simple simulation system called SHOP. Their study demonstrates the usefulness of interaction analysis in CPS research. The authors started with the assumption that the advantages of a certain presentation format (presentation of system information in numeric or in graphic form) would affect performance only if it corresponded to the format in which knowledge about the system was internally represented. The internal representation format was induced in this study in a short training session that either stimulated thinking about the system in terms of propositions (if-then statements) or in terms of a graphical network in which the nodes represented the variables connected by causal links, and the diameter of the nodes indicated the quantitative state of the variables. Rost and Strau assumed that a propositional representation of system knowledge would best fit a numerical presentation and that the analog representation would best fit the graphic presentation. The central system variable in their scenario was money. For each of the 25 simulation cycles, the dependent variable problem-solving quality was set to +1 if an increase in money had occurred, –1 in case of a decrease, and 0 in case of no change. The results of this rather interesting experiment are summarized in Figure 2.

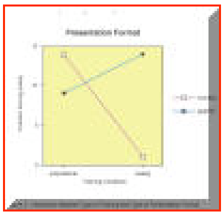

Figure 2. Interaction between type of training and type of presentation format

This figure illustrates a significant interaction between type of presentation and type of training. The analog training condition showed large differences between the two presentation formats whereas the propositional training differences were much smaller for the two presentation formats. The interaction between person (i.e. representation format) and situation (i.e. presentation format) variables clearly indicates a necessity to go beyond main effects in the experimental analysis of CPS. Other work on interaction research has been done by Leutner in his studies on aptitude treatment interaction between pupils' ability and type of learning during CPS.

3.7. The Components of a Theory of Complex Problem Solving

The empirical findings summarized above lead to a simple theoretical framework for understanding CPS that is depicted in Figure 3. The figure summarizes the basic components of the framework and the interrelations among the components. As can be seen, the framework contains three separate components: problem solver, task, and environment.

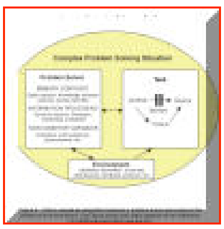

Figure 3. CPS is viewed as interaction between a problem solver and a task in the context of an environment. The figure shows only static aspects of the interaction.

In the problem solver, static memory content and dynamic information processing are distinguished. Memory is divided further into domain-general and domain-specific knowledge both of which affect CPS performance. Information processing includes the task strategies that are selected and the processes of task monitoring and progress evaluation. In addition, non-cognitive problem-solver variables such as motivation and personality also factor into CPS performance.

The task itself is depicted in terms of the barriers that exist between a given state and a goal state. As noted above, the barriers are assumed to be complex, dynamically changing, and non-transparent; the transition from given to goal state is constrained by the problem solvers' memory content and information processing, and by the tools that are available to solvers.

The environment includes the resources available for problem solving, as well as feedback, expectations, cooperation, peer pressure, disturbances, etc. The environment affects both problem solvers and the task. It affects problem solvers by constraining the information processes that can be used and by influencing which knowledge is accessible. The environment affects the task by offering additional information, constraining which tools may be used, and so on. In addition, the environment can be changed actively by the problem solvers but not by the task.

From this relatively simple view of CPS, it should become clear that two of the main questions that will need to be addressed by future research are (a) which components within the problem solver, task, and environment affect CPS in which way and (b) how do the various components (person, task, and environment) interact in affecting CPS performance? Clearly, much more research will need to be conducted before one can attempt to answer these questions.

4. Methodological Approaches to Studying Complex Problem Solving

Of the many different methods that could be used to study CPS, two approaches have become favorites in recent years: the experimental method and single case studies. Although some researchers have argued that CPS cannot be fruitfully approached with classical experimental techniques, others have demonstrated rather convincingly that experimental techniques can be used to further our understanding of CPS. It now appears that the controversy between proponents and opponents of the use of experimental methodology may, at least in part, be based on a false conception of what experimental methods really are. The experimental method is a set of techniques that, at least in our view, can be employed not only to test a set of static assumptions, but also to test dynamic process models. Proponents of the experimentally oriented research strategy argue that false theoretical models can be identified only with the experimental method; that is, only experiments allow one to make ultimate decisions about scientific hypotheses. Thus, the experimental method may be most fruitfully employed for the purpose of theory testing.

The phenomenologically oriented research strategy, on the other hand, relies strongly on the precise reconstruction of single cases of CPS. Cognitive modeling is then used to reconstruct certain aspects of individual behavior. In general, it appears to be rather difficult with this approach to identify false theoretical assumptions. Proponents of the single-case methodology therefore frequently argue that single cases are useful primarily for explorative purposes (i.e. for the development of scientific hypotheses).

We consider the two approaches, the experimental method and single case studies, to be complementary. Single case studies may be employed most fruitfully during theory development; the strength of the experimental method, in contrast, is that it provides a strong test of proposed assumptions. While both of these approaches are helpful and both have the potential to advance our understanding of CPS, the effectiveness of the two approaches is critically affected by some *general* problems of the research domain. Addressing these problems is of critical importance before both the experimental method and the single case studies can be employed. We list four of these general problems below:

1. The first general problem concerns the *measurement of CPS knowledge and performance*. The adequate measurement of the problem solvers' knowledge and performance in CPS situations represents a major hurdle that needs to be addressed and resolved before we can make any real progress toward understanding CPS. To this end, Hbner, for instance, has proposed mathematical procedures for the operationalization of certain aspects of task performance. Kolb, Petzing, and Stumpf propose the use of operations research methods for the same purpose. We believe that real progress will not come from these propositions but will come only from theoretical advances. Any good theory of CPS must prescribe the dependent variables and must outline how these variables can be measured. Additionally, a theory of the formal system itself may help to select important and reliable indicators of system performance.

2. The second general problem concerns *generalizability and external validity*. Although the artificial systems currently used in our labs are much more complex than they were in the early 1980s, we cannot necessarily assume that increased complexity has also led to improved generalizability. Dorner's attempt to bring complexity into the labs of the scholars of thinking and problem solving was successful—but has the situation really changed with respect to our understanding of real-world phenomena? We agree with Hunt, who argues "Geneticists have a theory that explains how one generalizes from inheritance in the fruit fly to inheritance in human beings. Cognitive psychology does not have a theory to explain how we move from game behaviors to behaviors in other situations."

3. The third general problem concerns the *analysis of problem solving processes*. It is critical that we try to understand the process of CPS, rather than the product. The experimental method has not been specifically designed for process analyses, although experimental treatments can help in testing assumptions about parameters and their assumed dependence on external factors. Thus, process models and experiments are not contradictory; they are complementary tools that help us understand CPS. For this reason, modeling approaches of problem-solving processes may offer interesting insights but need to be enriched by empirical data.

4. And finally, the *development of problem-solving theories* is in a rather desolate condition. Developing a theory, or multiple theories, is the most difficult job—and yet at the same time it is the prerequisite for additional experimental research. A good theory prescribes and determines experimental research. Theoretical assumptions can be derived from everyday experiences, from cognitive modeling, or from single case or field studies. Most, if not all, of the assumptions can be tested experimentally—but neither the experimental method nor the single case approach prescribes the development of theories.

It is our view that the experimental method will remain one central method of choice for studying human CPS simply because no other method is as capable of providing decisive answers to clearly formulated questions. At the same time, however, it remains clear that progress in this difficult research area can be achieved only if different approaches work together to achieve insights into how people deal with complex problems.

5. Final Comments

The breadth of human thinking is truly striking—as is the breadth of empirical research and the variety of theoretical explanations on the topic. In this article, we have described some of the main properties of human thinking. In particular, we have concentrated on the human ability to solve complex, real-world problems, an ability that we believe determines human culture to an extent that is unrivalled by any other human ability. We first provided a definition of thinking and briefly discussed the various categories or types thinking may be divided into. Next, we summarized much of the relevant empirical research on the topic and described a theoretical framework for understanding the concept. Last, not least, we discussed the dominant methodological approaches that have been employed to study CPS, and offered our own recommendations on which approach might turn out to be the most promising.

In conclusion, we believe that research on CPS, despite its many shortcomings and despite the diverse approaches taken by North American and European researchers, holds the promise of a more realistic, real-life approach to the psychology of action control in complex environments than has been offered in the past. This is both an important and an exciting area of research and, as the saying goes, "Nothing is as promising as a beginning."

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Glossary

Complex problem solving :Complex problem solving occurs to overcome barriers between a given state and a desired goal state by means of behavioral and/or cognitive, multi-step activities. The given state, goal state, and barriers between given state and goal state are complex, change dynamically during problem solving, and are not transparent. The exact properties of the given state, goal state, and barriers are unknown to solvers at the outset. Complex problem solving implies the efficient interaction between a solver and the situational requirements of the task, and involves a solver''s cognitive, emotional, personal, and social abilities and knowledge.

CPS :Complex problem solving.

Eigendynamik :*Eigendynamik* occurs when a system changes its state without intervention from outside, due to its inherent dynamics. This happens very often in natural systems. Technical systems normally wait for interventions from human operators.

Human thinking :The cognitive processing of internal memory representations that may occur both consciously and subconsciously and may not always follow the laws of logic.

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