Chapter 7

The history of complex problem solving

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Complex problem solving (CPS) is about reaching one's goals taking into account a large number of highly interrelated aspects. CPS has a rich history in experimental and psychometric research. The chapter highlights some of the most important findings of this research and shows its relationship to interactive problem solving. More specifically, it 1) characterises typical human strategies and shortcomings in coping with complex problems; 2) summarises some of the most influential theories on cognitive aspects of CPS; and 3) outlines the history of including CPS skills and competency in assessment contexts. The last section summarises the current state of play and points out some trends for future research.

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Introduction

Research on complex problem solving (CPS) arose in the 1970 (e.g. Dörner, 1975; Dörner, Drewes and Reither, 1975) when real problems like the limits of growth (Meadows, Meadows, Zahn and Milling, 1972) and the oil crisis of 1973 made it increasingly clear that we needed more than traditional reasoning tasks to examine the ways humans solve problems and make decisions in naturalistic complex and dynamic situations (Brehmer, 1992; Klein, Orasanu, Calderwood and Zsambok, 1993; Gonzalez, Vanyukov and Martin, 2005). Recent examples of complex problems are found in decision making about global climate politics (e.g. Amelung and Funke, 2013), in avoiding bankruptcy for mismanaged corporations (e.g. Funke, 2003), or in coping with nuclear disasters like Fukushima and their consequences (e.g. Dörner, 1997).

Formally speaking CPS can be defined "as (a) knowledge acquisition and (b) knowledge application concerning the goal-oriented control of systems that contain many highly interrelated elements (i.e., complex systems)" (Fischer, Greiff and Funke, 2012:19). This definition is very broad and includes "interactive problem solving" as one aspect of controlling complex and dynamic systems. More than 20 years ago, Frensch and Funke defined 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 intransparent. The exact properties of the given state, goal state, and barriers are unknown to the solver at the outset. CPS 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." (1995:18)

Since the early 1980s, the pioneers of CPS research have developed computer simulations of real complex[1] problems in order to examine learning and decision making under realistic circumstances in psychological laboratories (e.g. Berry and Broadbent, 1984; Dörner, Kreuzig, Reither and Stäudel, 1983). Some of the most famous computer simulations of complex problems were developed during this period, involving ruling a city (Lohhausen; Dörner et al., 1983), organising developmental aid (Moroland; Strohschneider and Güß, 1999), managing a tailorshop (Putz-Osterloh, 1981), controlling a sugar factory (Berry and Broadbent, 1987) or finding out about a complex toy (Big Trak; Klahr and Dunbar, 1988). In the years that followed, the simulation of complex problems was increasingly established as new research paradigm and the scientific community documented characteristic human strategies and shortcomings in coping with complex problems (e.g. Dörner, 1982). In the late 1980s, a set of theoretical contributions significantly expanded the information processing theory of human problem solving (Newell and Simon, 1972) by elaborating on aspects such as the role of hypothesis testing (Klahr and Dunbar, 1988) and implicit learning (Berry and Broadbent, 1987) in the process of solving complex problems (see Frensch and Funke, 1995; for a recent overview, see Fischer et al., 2012). Dörner (1986) proposed using CPS simulations for assessments, and initiated a lively debate on the incremental value of those simulations beyond traditional measures of intelligence (Funke, 2003). In the 1990s CPS simulations were increasingly criticised from a psychometric point of view: the different problems seemed to have little in common (Funke, 1992, 2001, 2010) and often conclusions about a person's ability were drawn from interventions in a single problem only (Greiff, 2012; Wittmann and Süß, 1999). The research community increasingly elaborated on how to compare different simulations and the effects of a system's features on a problem's difficulty, which was an important prerequisite for the psychometric approach to CPS (Funke, 2001). In the early 21st century, the psychometric quality of CPS simulations was rehabilitated (Danner et al., 2011a; Wüstenberg, Greiff and Funke, 2012) and CPS skills and performance proved to be an important complement to traditional measures of intelligence in large-scale assessments such as the Programme for International Student Assessment (PISA) 2000, 2003 and 2012 (OECD, 2010; Fischer, 2015).

In the following sections we will outline some of the most important findings in the history of CPS research. This chapter will 1) characterise some typical human strategies and shortcomings in coping with complex problems; 2) summarise some of the most influential theories on important aspects of CPS; and 3) outline the history of CPS in assessment contexts. The final section summarises the current position and points to some trends for future research.

Human failures and strategies

In the early 1980s, the research group around Dörner, Kreuzig, Reither and Stäudel (1983) elaborated on some of the most frequent errors problem solvers make in complex situations, such as ignoring trends, underestimating exponential growth and thinking in causal chains instead of causal networks (Dörner, 1982). By comparing people who do well in CPS situations with those who do not, Dörner (1989, 1996) was able to determine some important aspects of problem-solving competency: On an aggregate level, good problem solvers made more decisions simultaneously than bad ones (and increasingly so in the course of problem solving), that is, they saw more possibilities to influence their situation. They also made more decisions per goal and took different aspects of the system into account. Good problem solvers focused on central causes early on, and did not gradually shift from trivial effects to important issues as bad problem solvers did.

Interestingly, good and bad problem solvers did not differ in the number of hypotheses they generated, but in the number they tested: good problem solvers tested their hypotheses and asked more questions about causal links behind events. Good problem solvers also were less often distracted by urgent but unimportant subproblems (contrast with "ad-hocism"; Dörner, 1996:25) and their decisions were more consistent over time, whereas bad problem solvers tended to change their current subproblem more often and were more easily distracted. Good problem solvers structured, reflected, criticised and modified their own hypotheses and behaviour to a greater degree, whereas bad problem solvers tended to delegate subproblems instead of facing them responsibly. Jansson (1994) reported seven erroneous responses to complex problem situations: 1) acting directly on current feedback; 2) insufficient systematisation; 3) insufficient control of hypotheses and strategies; 4) no self-reflection; 5) selective information gathering; 6) selective decision making; and 7) thematic vagabonding. For a more recent summary of human failures in complex situations, see Schaub (2006).

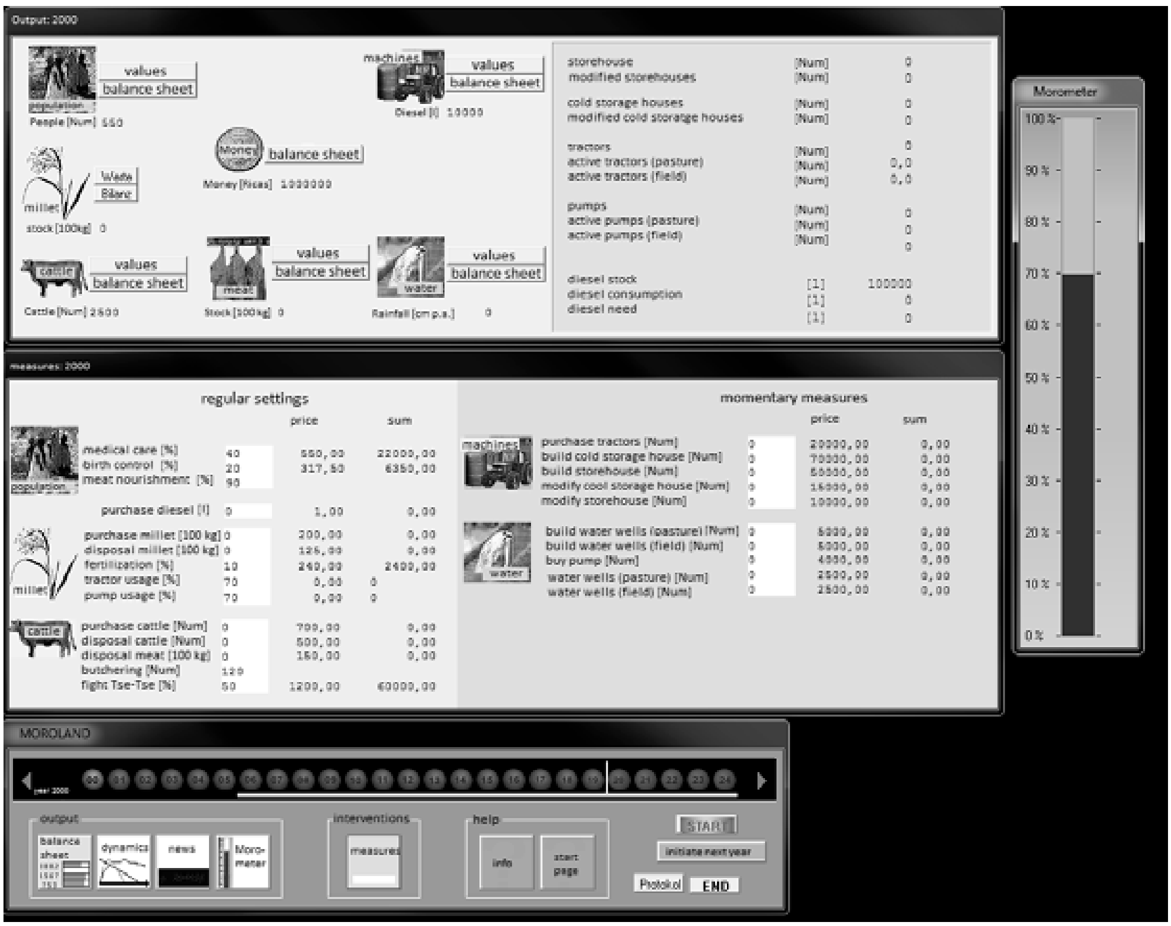
In earlier research, the behaviour of bad problem solvers was often explained by a lack of general intelligence, or insufficient domain-specific prior knowledge of subjects (compare Fischer et al., 2012), but according to Strohschneider and Güß (1999), recent evidence indicates a strong relationship with domain-general strategic knowledge (see below).

Based on the complex Moro problem (see Figure 7.1 for a modern implementation of the simulation), where the problem solver has to manage developmental aid for a small tribe of semi-nomads, Strohschneider and Güß (1999) defined a set of deficient strategic, operational and tactical patterns, which may indicate a lack of strategic knowledge:

- **incomplete exploration of domains**: the problem solver selectively considers certain problem areas and misses other aspects of the complex problem situation
- **feedback strategy**: the problem solver selectively reacts to signals emanating from the system – such as alarm messages or complaints
- **insufficient adaption of interventions**: the problem solver does not adapt his or her decisions – such as the annual sale of millet – to changes in the situation such as insufficient cattle
- **decisions without information**: the problem solver does not gather information relevant to his or her decisions such as the prices of goods

- **lack of effect control**: the problem solver fails to monitor the effects of decisions, for example not viewing population figures, birth rates or death rates after implementing medical services
- **collisions**: the outcomes of the problem solver's decisions cancel each other out.

Figure 7.1 **Screenshot of a simulation of the complex Moro problem**



Source: Lantermann et al. (2000), SYRENE: Umwelt- und Systemlernen mit Multimedia.

Building on these and other strategic shortcomings in coping with complex problems, many promising training approaches have been developed to foster problem-solving performance. For example, Dörner (1996) and Vester (2007) proposed computer simulations to learn CPS (compare with Kretzschmar and Süß, 2015). Hestenes (1992) proposed modelling instructions to teach a systematic way of building viable models of complex situations (continuously adapting them to empirical feedback) and D'Zurilla and Goldfried (1971) developed training for problem solving that proved to be helpful in a variety of contexts (Liebeck, 2008). Kluge (2008) provides a critical review of such training.

Cognitive theories on the process of solving complex problems

This section presents some of the most significant theories about important cognitive aspects[2] of CPS, which began to emerge in the late 1980s: a brief outline the theory of Klahr and Dunbar (1988) on scientific knowledge acquisition as well as an important expansion of Schunn and Klahr (2002) – an expansion that introduces the aspect of information reduction which is of special importance to CPS (Fischer et al., 2012). We will then look at theories of system control and knowledge application, namely Broadbent, Fitzgerald and Broadbent's theory (1986) about the role of explicit and implicit knowledge in CPS, and a recent expansion of Osman (2010) elaborating on the role of monitoring in CPS.

Theories on knowledge acquisition

Based on the ideas of Simon and Lea (1974), Klahr and Dunbar (1988) expanded the theory of human problem solving (Newell and Simon, 1972) – which described problem solving simply as the search for as solution (structured by methods such as means-end analysis, planning, hill-climbing, analogy or domain-specific knowledge) – in order to explain scientific discovery learning in the process of CPS. They described the endeavour of scientific discovery as a dual search. On the one hand, the problem solver has to search for experiments (i.e. empirical data) in order to generate and test hypotheses. On the other hand, the problem solver has to search for hypotheses (i.e. chunks of knowledge) that sufficiently explain the data gathered. With their dual-search theory, Klahr and Dunbar (1988) elaborated on an important aspect of the process of CPS (Funke, 2001). Later on, the theory was expanded by Schunn and Klahr (2002), who identified an additional search space, namely the search for data representations that highlight the elements that are crucial for finding a solution; they realised that in CPS people did not just search for hypotheses and experiments, but also for which set of variables to consider as relevant "data" at all. For example, problem solvers had to find out that the colour, form or size of houses didn't matter when explaining the route of a simulated milk truck. Thereafter, participants increasingly focused their knowledge acquisition on the relevant aspects of the problem and reduced irrelevant information (compare with the information reduction of Gaschler and Frensch, 2007; and the *Schwerpunktbildung* of Dörner et al., 1983). This is an important prerequisite for efficient planning in complex problem solving (Klauer, 1993; Fischer et al., 2012).

Theories on knowledge application

Broadbent, Fitzgerald and Broadbent (1986) researched the impact of explicit and implicit knowledge on performance in dynamic decision making: in their instance-theory of complex system control they pointed out that performance in a problem-solving situation can change without changes in explicit knowledge due to instances of the system (consisting of the current output and a corresponding input) being remembered instantly as a result of implicit learning. The theory poses that problem solvers get better at controlling dynamic systems by storing their reactions to the states perceived as an instance in a kind of "look-up-table" and by applying instances to similar situations (compare with Gonzalez, Lerch and Lebiere, 2003; Dienes and Fahey, 1995). But in addition to knowledge about the states of a system, there also can be knowledge about the system's structure, i.e. about the abstract rules governing the system's behaviour (Berry and Broadbent, 1987; Schoppek, 2002). With this latter kind of knowledge in mind, different heuristics, such as planning (e.g. Klauer, 1993), can be applied in the process of CPS (Fischer et al., 2012). Schoppek (2002) emphasised that in more complex systems the application of explicit structural knowledge may be of crucial importance for system control, because a tremendous amount of instances would be needed to control the system based on instances. The question of when and if a problem solver searches for either rules or instances to apply was elaborated on by the dual-search models of problem solving outlined above. For instance, the search for rule knowledge may increase with factors like the relevance of structure (Dienes and Fahey, 1995) or a lack of goal specificity (Vollmeyer, Burns and Holyoak, 1996).

But even when problem solvers know about both instances and rules, and apply them to the best of their knowledge, the effectiveness of an intervention (derived from explicit and/or implicit knowledge) cannot be taken for granted in a CPS situation. Particularly where prior knowledge is mostly false or incomplete (Dörner, 1997), the effectiveness of interventions has to be monitored. In her monitoring-control framework, Osman specified how individuals intensify monitoring as a result of experiencing uncertainty: "High uncertainty will lead to continuous monitoring of the task and goal directed actions, and low uncertainty will lead to periodic monitoring of the task and goal directed actions" (2010:73). Behaviour intended to control the environment generates feedback on one's hypotheses and plans, while monitoring the consequences of one's actions (self-monitoring) or the problem's dynamics (task-monitoring) allows for adjusting one's plans and hypotheses. Thus, monitoring is both informed by and guides control behaviours.

The process of solving complex problems

Fischer et al. (2012) have proposed an integrative theory on the process of complex problem solving. According to this theory, CPS involves the acquisition of implicit and/or explicit knowledge about relevant aspects of a problem, as well as the application of this knowledge in the search for a solution (compare with Funke, 2001; Fischer, 2015).

1. **Knowledge acquisition**: in order to sufficiently understand the problem, a problem solver has to systematically generate information (search for informative data), to sufficiently integrate this information into a viable mental model of the situation (search for adequate hypotheses), and to selectively focus on most relevant, central and urgent aspects of the problem (search for viable data-representations).

2. **Knowledge application**: based the explicit and implicit knowledge acquired, the problem solver has to make a set of interdependent decisions[3] (dynamic decision making) and to continuously monitor prerequisites and consequences of these decisions (monitoring) in order to systematically solve the problem at hand.

The interplay between knowledge acquisition and knowledge application is in a way similar to the idea of the generation and reduction of information, because an adequate subset has to be considered from all the knowledge available for effective knowledge application (for instance, structural knowledge has to be referred to only in cases when no sufficient instance knowledge is available). The advantage of the new formulation proposed by Fischer et al. (2012) is the broader perspective connected to the term "knowledge" with a lot of differentiation.

Assessment of complex problem solving

Dörner (1986) introduced the concept of operative intelligence as the crystalline ability to co-ordinate one's cognitive operations in a goal-oriented, wise and sustainable way: "Operative intelligence implies declarative and procedural knowledge about when and how to apply certain operation, as well as implicit knowledge about both the utility of applying and the contexts in which to remember operations" (compare with Fischer et al., 2012; Dörner and Schölkopf, 1991). As the various processes involved in CPS are intertwined and can hardly be assessed in isolation, Dörner (1986) proposed using simulations of complex problems to assess operative intelligence. Indicators for this kind of problem-solving competency in computer-based CPS simulations are typically based on states or processes of the system's variables (such as capital, population, or number of alarm messages, compare with Strohschneider and Güß, 1999), on the problem solver's inputs to the system (such as information requests or decisions made, compare with Dörner, 1986) or on separate knowledge tests that are administered afterwards or simultaneously (compare with Greiff, 2012).

During the 1990s the research community increasingly elaborated the prerequisites for a psychometric approach to CPS, that is, which kind of simulations to use and which scores to rely on. Some issues with complex problems had to be solved in order to use CPS simulations as reliable assessment instruments. First, they lacked comparability, as it proved hard to identify common aspects of different complex problems. Complex problems can be highly heterogenous in nature which hindered reliable scoring of specific CPS skills (Fischer, 2015). Funke (1992, 2001) proposed a solution to this problem, introducing formal frameworks to compare different complex problems based on their underlying causal structure. A series of experimental studies identified important structural determinants of a complex problem's difficulty: aspects such as the number of interrelations (Funke, 1985), the amount of dynamic changes (Funke, 1992) or the delay in feedback (Funke, 1985; Heineken, Arnold, Kopp and Soltysiak, 1992) were empirically proved to influence a complex problem's difficulty (for an overview, see Funke, 2003).

This introduction of formal frameworks for describing complex problems in a comparable manner was a first important prerequisite for the psychometric approach to CPS and a fruitful approach within CPS research (Funke, 2001). But even with the lack of comparability solved, in the 1990s many studies on CPS in assessment contexts were criticised for another methodological shortcoming that may have led to mixed results in early CPS research. When performance scores were built based on a scenario's states at multiple points in time (e.g., after every input), each state depended not only on the last input but on every prior input (i.e., measurement errors were not independent from each other).

Figure 7.2 **Screenshot of the Tailorshop problem**

Variable	Value	Planning
Account Balance	165775	
Shirts Sold	407	
Raw Material Cost	3.99	
Shirts in Stock	61	
Workers 50	8	
Workers 100	0	
Wage	1080	
Shirt Price	52	
Retail Stores	1	
Empl. Satisfaction %	57.7	
Loss of Production %	0.0	

Variable	Value	Planning
Company Value	250685	
Customer Interrest	767	
Raw Material in Stock	16	
Machines 50	10	
Machines 100	0	
Maintenance	1200	
Staff Events	50	
Advertising	2800	
Business Location	City	City
Machine Damage %	5.9	

Source: Danner et al. (2011a), "Measuring performance in dynamic decision making: Reliability and validity of the Tailorshop simulation".

Take the Tailorshop problem (see Figure 7.2) for example: when a person is instructed to maximize company value, company value v after each month i could be measured as indicators (v_i) for the person's ability. But as company value changes by an additive amount c each month ($v_i = v_{i-1} + c_i$), the indicators are not experimentally independent and measurement errors would be correlated. In order to resolve the problem of correlated measurement errors, Danner and colleagues (2011a) proposed using the change in capital value after each month (c_i) – or the sign of this change (s_i) – as an adequate indicator of a person's competency. Results indicate that the sum of s_i over all but the first months was a highly reliable and valid estimate[4] of a person's problem-solving competency that was substantially correlated to performance on the Heidelberg finite state automaton (HEIFI; see Figure 7.3) and to Supervisor Ratings, even beyond reasoning (measured through Advanced Progressive Matrices). A tau-equivalent model (with factor loadings of all indicators on a single construct being constant and all measurement errors being constant as well as independent from each other) fitted the data sufficiently well (RMSEA = .07; CFI = .98). According to Danner et al. (2011b) a latent CPS factor (indicated by performance in the Tailorshop and the HEIFI simulation) was related to Supervisor Ratings even after controlling for IQ (measured by the Berlin Intelligence Structure Model test) whereas IQ did not have a unique contribution when compared to CPS.

A different approach to resolve the problem of correlated measurement errors is to apply a set of multiple complex systems (MCS approach; Greiff, Fischer et al., 2013). In contrast to single time-consuming simulations of highly complex problems, the idea is to use a larger number of less complex problems to allow for reliable scoring of specific problem solving skills (Funke, 2010). A typical example of this approach is the MicroDYN[5] test of Greiff, Wüstenberg et al. (2013) which consists of multiple independent simulations. Each simulation is based on a dynamic linear equation model with six variables (three independent variables that can be manipulated by the problem solver and three dependent variables that directly depend on the input variables). The problem solver has to find out about the system structure by interacting with the simulation (knowledge acquisition) and to reach certain goal-values for the dependent variables by a series of decisions concerning the independent variables (knowledge application). The time per simulation is limited to about 5 minutes and after each simulation a score for knowledge acquisition and knowledge application is derived. The simulations applied in the MicroDYN test are far less complex than the Tailorshop,[6] allowing reliable multi-item testing of specific problem-solving skills – the dual search for information and hypotheses, and the subsequent search for a multi-step solution (Greiff, Fischer et al., 2013) – even if it does not represent the full range of CPS requirements (Fischer, 2015). The skills reliably assessed by MicroDYN are important for many kinds of CPS beyond measures of reasoning (e.g. Greiff, Fischer et al., 2013; Wüstenberg, Greiff and Funke, 2012), but of course it takes more than these skills to solve complex problems of various kinds (Fischer, 2015). As Funke put it, "two measurement approaches, Tailorshop and MicroDYN, illustrate two different understandings of CPS. Whereas Tailorshop stands for a broad interpretation of CPS but has some weak points from a psychometric point of view, MicroDYN represents the psychometric sound realization of selected but important CPS aspects" (2010:138).

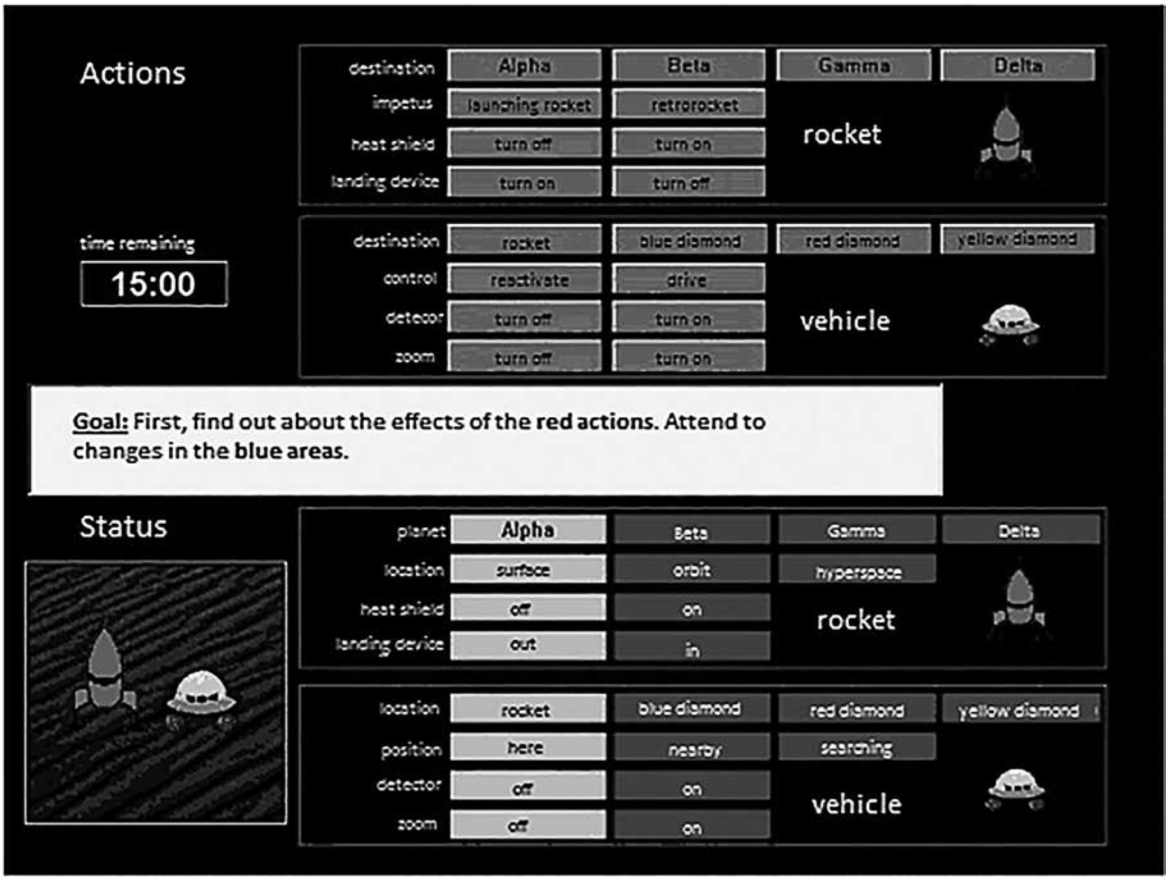
Discussion

Having considered the history of CPS we now review some of the more recent developments and outline possible trends for future research directions. These research directions are strongly aligned with PISA (OECD, 2010). The assessment of CPS in PISA is a showcase for an educationally motivated application of a construct originating from cognitive psychology and how this research can be meaningfully applied in the context of a large-scale assessment.

For the first time in a large-scale context, CPS skills were assessed in a national extension study to PISA 2000 in Germany. The finite state machine Space Shuttle was used to assess the skills related to interactive knowledge acquisition and knowledge application, as described above. Leutner and colleagues (2005) were able to identify a two-dimensional latent factor structure for Space Shuttle with one factor explaining the interactive knowledge acquisition in complex situations and another factor explaining knowledge application. Both aspects of CPS proved to be correlated to but separable from general intelligence[7], analytical problem solving (APS), and domain-specific competencies (Leutner et al., 2005).

These national efforts were followed by an assessment of analytical problem solving (APS) in the PISA 2003 international survey in all participating countries using a paper-and-pencil test. This kind of APS is closely related to the CPS skills measured by MicroDYN even after controlling for reasoning (Fischer et al., 2015).

Figure 7.3 **Screenshot of the finite state machine HEIFI**



Source: Wirth and Funke (2005), "Dynamisches Problemlösen: Entwicklung und Evaluation eines neuen Messverfahrens zum Steuern komplexer Systeme", p. 57.

The most recent PISA cycle in 2012 included MicroDYN and MicroFIN tasks to complement the static APS tasks as indicators of domain-general problem-solving competency. This was a major breakthrough for problem-solving research, because in PISA 2012, all participating countries could opt for computer-based assessment, and thus CPS could finally be included in the main survey. Besides the switch in mode of delivery, there were at least two more reasons why CPS was included in PISA 2012. First, PISA aims to capture skills relevant for real-life success and has made efforts to go beyond the mere assessment of skills in the classical literacy domains. To this end, Autor, Levy and Murnane (2003) remind us that over the last decades non-routine skills such as problem solving have gained in importance as routine skills decrease in our everyday lives. Thus, the OECD (2010) identifies problem solving as one of the key competencies relevant for acquiring domain-specific skills for success in life, rendering CPS a prime candidate for educational assessment and explaining its inclusion in PISA 2012. Second, psychometrically sound assessment is a prerequisite for any educational large-scale assessment and the unresolved assessment issues in CPS discussed above had delayed the inclusion of CPS in PISA at earlier stages. With the psychometric advances of the MicroDYN test, a valid and psychometrically acceptable assessment of important CPS skills became feasible and was, therefore, implemented in PISA 2012 as an innovative and first-time construct going beyond the classical literacy domains usually targeted in surveys such as PISA.

Trends for future research

Based on these considerations, two points can be concluded. First, the psychometric advances in the assessment of CPS as outlined above have equipped researchers with the means they need to better understand the cognitive structures underlying CPS and its relation to other constructs (e.g. Fischer, 2015). Second, assessment of CPS is not only theoretically important, but yields additional information shown by the empirically reported added value of CPS outlined above. To this end, with the results of PISA 2012 reporting how countries differ in their CPS level and how these differences may be related to other variables on different levels of analysis, CPS is highly relevant for educational research and extremely exciting for policy makers and educators around the world.

As we have seen, complex problems are manifold: usually there are many variables, multiple goals and dynamic dependencies. The interdependencies are often nonlinear, not transparent, and time-delayed, and sometimes there are random shocks, oscillations and interactions. It is difficult to combine all of these under the common roof of a standardised assessment instrument. However, each of the psychometric approaches described above manage to capture some of these aspects of complex problems and allows assessing non-routine problem-solving skills in the sense of Autor et al. (2003).

But are the psychometric advances reported so far already the end of the entire CPS story? Probably not. PISA 2015 merges social aspects with complex problem solving into a construct labelled "collaborative problem solving". While in individual CPS, problem solvers have to interact with a dynamically changing system, collaborative problem solving extends this interaction towards exchange with other problem solvers. Obviously, working in teams and efficiently solving problems together constitutes a set of skills increasingly needed in the 21st century. However, an assessment of collaborative problem solving (see Chapter 14) faces many obstacles and has a long way to go. Considering success story told for CPS over recent years, this should encourage researchers to further pursue the path towards a valid and standardised assessment of collaborative problem solving.

Notes

1 All these problems can be considered complex, as multiple highly interrelated aspects have to be considered in order to systematically transform a given situation into a desirable situation (Fischer, Greiff and Funke, 2012; Weaver, 1948). As Rey and Fischer pointed out,"Complexity refers to the number of interacting elements that have to be processed in working memory simultaneously in order to understand them" (2013:409).

2 Please note, that this short review can by no means be complete: there are many other theories on cognitive processes that may also be considered relevant for CPS such as representational change (Ohlsson, 1992), and there are theories on the complex interactions of cognitive processes with motivational and emotional processes, such as Dörner et al. (2002). For a recent overview concerning theories on CPS please refer to Fischer et al. (2012).

3 Either a solution is implemented instantly (triggered by the current goals, the situation perceived, and/or the content of working memory) or as a result of searching processes (such as planning, means-end analysis, hill-climbing, analogy, or domain-specific knowledge). If implementation fails or no solution can be derived at all, the problem solver is assumed to switch back to knowledge acquisition in order to change means or goals (Fischer et al., 2012).

4 Please note, the sum of changes ci was less valid, a result that could partly be explained by outliers.

5 The MicroDYN test is based on multiple simulations based on dynamic linear equations. A similar test of the same skills, MicroFIN, is based on multiple simulations of finite state machines (Greiff, Fischer et al., 2013; Fischer, 2015).

6 In principle the MicroDYN approach would allow the implementation of problems with arbitrary complexity and difficulty. Up to now, research has focused on additive main effects of exogenous and endogenous variables, but the formal framework also allows for powers or interactions of variables to be included in models as additive terms (e.g. b*b or b*c).

7 In general, the relation between general intelligence and problem-solving performance seems to depend on the amount of prior knowledge in an inverted U-shaped way: correlations are low if there is either 1) not enough knowledge to solve the problem; or 2) sufficient knowledge to not have a problem at all (compare the Elshout-Raaheim-Hypothesis, see Leutner, 2002).

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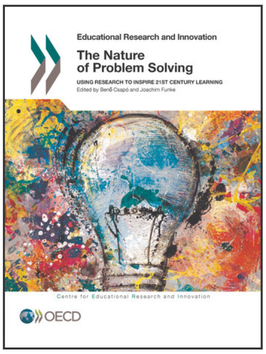

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