

# **Modeling Processes of Volitional Action Control in Multiple-task Performance: How to Explain Effects of Goal Competition and Task Difficulty on Processing Strategies and Performance within ACT-R<sup>1</sup>**

**Peter Gerjets**

*Knowledge Media Research Center, Tuebingen, Germany<sup>2</sup>*

**Katharina Scheiter**

*University of Tuebingen, Germany*

**Tina Schorr**

*University of Tuebingen, Germany*

In this paper, we present a cognitive-modeling analysis of processes of volitional action control in multiple-task performance. A central topic of volitional action control is the issue of adaptive goal maintenance and goal switching in multiple-task performance. We analyzed this issue within two rather different theoretical contexts, namely, within the context of elementary executive control processes in the domain of simple choice reaction time tasks, and within the context of the volitional framework PART (Pivotal Assumptions of the Rubicon Theory) that analyzes control demands of everyday actions on an abstract functional level. We explored two approaches to link the volitional

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<sup>2</sup> Address for correspondence: Peter Gerjets, Knowledge Media Research Center, Konrad-Adenauer-Strasse 40, 72072 Tuebingen, Germany. Email: p.gerjets@iwm-kmrc.de.

framework of PART to cognitive concepts, both of which were useful to guide our cognitive modeling efforts; first, reinterpreting volitional aspects of goal competition within the Cognitive Load Theory and, second, constructing intertheoretical links between PART and the cognitive architecture ACT-R. We used the ACT-R architecture to simulate a couple of experimentally obtained effects of goal competition and task difficulty on processing strategies and performance in a high-level learning and problem-solving task. Beyond the model's capacity for explaining the empirical pattern of results, the fundamental processing mechanisms used for modeling – namely, activation mechanisms and executive control productions – are very much in line with current experimental and computational explanations of elementary executive control processes. Thus, we consider our modeling approach to be a fruitful bridging of the conceptual and explanatory gap that exists between volitional control demands in real-world multiple-task performance on the one hand, and experimental findings on elementary executive functions that are obtained in the microscopic world of simple choice reaction time tasks on the other.

**Keywords:** Volitional action control, goal competition, goal switching, executive control processes, distraction, ACT-R, cognitive modeling, multiple-task performance

## 1. Overview

In this paper, we present a cognitive-modelling analysis of control processes in multiple-task performance that focuses predominantly on processes related to volitional action control. We use the term “volitional action control” to refer to abilities that are traditionally ascribed to a hypothetical “will power” (James, 1890). For instance, will power comes into play when we need to maintain goals or intentions over time and in the face of difficulties or competing goals. Goal maintenance requires resisting emotional temptations or alternative motivational tendencies, suppressing strong habits, or tolerating aversive experiences (cf. Goschke, 2002).

A review of recent analyses of multiple-task performance in experimental cognitive psychology and computational cognitive modeling reveals, however, that currently dominant experimental and computational approaches are strongly biased towards studying purely cognitive – and rather elementary – aspects of action control (cf. Monsell & Driver, 2000). These approaches refer to multiple-task performance in the domain of simple choice reaction time tasks that usually can be completed within one second or less. The associated computational models developed to simulate the interplay between multiple tasks at this fine-grained level of description are mainly based on *activation mechanisms* and *executive production rules*. However, it can

be argued that many issues of volitional action control will not show up at this temporal level of analysis and when using this type of experimental task. Accordingly, it is not clear whether theoretical constructs that are used to explain elementary processes of executive control and that are implemented in different cognitive models will scale up to explain processes of action control at higher temporal levels of analysis.

In order to counteract the rather limited perspective of many current approaches to executive functions, we contrast this perspective with a broader framework from the field of volitional action control that encompasses cognitive, as well as motivational and volitional control processes (Gollwitzer, 1990; Heckhausen, 1991; Heise, Gerjets & Westermann, 1994a). We use this framework to analyze processes of volitional action control at a rather abstract functional level and to derive some hypotheses related to issues of goal competition and task difficulty.

In the next step, we outline an experimental paradigm that was explicitly developed to test these hypotheses (Heise, Gerjets & Westermann, 1994b, 1997) and that can be applied to low-level, as well as high-level tasks. Findings obtained within this paradigm (Gerjets, Scheiter & Heise, 2002; Scheiter, Gerjets & Heise, 2000) were used to guide the development of a computational model of volitional action control within the cognitive architecture ACT-R (Anderson & Lebiere, 1998). This model is based on *activation mechanisms* and *executive production rules* that are very similar to those used to explain elementary aspects of action control. Thus, this model provides evidence that activation mechanisms and executive production rules are not only useful to analyze elementary control processes, but also more complex processes of volitional action control in multiple-task performance.

## **2. Multiple-task performance and executive control in experimental cognitive psychology and computational cognitive modeling**

### **Single-task performance and cognitive architectures**

Traditionally, most research efforts in the fields of experimental cognitive psychology and computational cognitive modeling have been devoted to the analysis of *single-task performance* and its cognitive foundations. Usually, an explanation of how a particular cognitive task is carried out by the human information-processing system consists of specifying some cognitive mechanisms and knowledge structures (in a more or less formal way) that may be responsible for the subjects' performance during that task. This approach has been applied in order to analyze a great variety of cognitive tasks that range from low-level cognition (e.g., perception, attention, memory) to high-level cognition (e.g., problem solving, reasoning, decision making).

A particularly promising way of analyzing single-task performance during different tasks is to use *cognitive architectures* as theoretical frameworks (cf. Gray, Young & Kirschenbaum, 1997; Pirolli, 1999; Sweller, van Merriënboer & Paas, 1998; Wallach & Plach, 1999). We use the term “cognitive architecture” to refer to comprehensive theories of human cognitive abilities with broad domains of application (Pylyshyn, 1991). Cognitive architectures “allow us to span parts of cognition that have traditionally been treated as separate in cognitive psychology” (Anderson, 2002, p. 87). According to Newell (1990), cognitive architectures can be considered *unified theories of cognition*. These theories introduce a limited set of theoretical constructs that specify basic cognitive structures and processes and enable the explanation of research findings in diverse domains. An important aspect with regard to the current article is that cognitive architectures provide *cognitive control structures*, e.g., architectural features for resolving conflicts between competing action alternatives. These control features guide the selection, initiation, execution, and termination of individual processes involved in accomplishing a task and thereby enable the cognitive system to engage in organized and goal-directed behavior.

In recent years, a number of cognitive architectures based on production systems have been developed in cognitive science, including ACT\* (Anderson, 1983), ACT-R (Anderson, 1993; Anderson & Lebiere, 1998), SOAR (Newell, 1990), and EPIC (Meyer & Kieras, 1997a, b, 1998). One common element of these architectures is the assumption that procedural knowledge can be represented by production rules that are matched against a set of declarative memory elements. The execution of a production rule represents a discrete step in cognitive processing. Another common element is that information processing is analyzed as goal-directed activity reflecting the lesson learned that “to properly model human cognition, it is necessary to represent its current purpose and organize behavior in response to that purpose. Efforts have failed to achieve organized cognition without the architectural primitive of a goal structure” (Anderson & Lebiere, 1998, p. 39). In recent years, it has become increasingly clear that even very elementary and stimulus-driven cognitive processes depend very much on goal-driven top-down processes (cf. Pashler, Johnston & Ruthruff, 2001).

### **Recent approaches to multiple-task performance**

Beyond the study of single-task performance, issues of multiple-task performance have recently attracted considerable attention in experimental psychology, as well as in cognitive modeling (see Monsell & Driver, 2000, for an overview). Daily life outside laboratory settings often requires performing multiple tasks either *successively* (e.g., interrupting a text-editing task to answer an urgent e-mail request) or *simultaneously* (e.g., using a mobile telephone while driving a car). In order to analyze multiple-task performance, it is not only necessary to analyze the single tasks involved, but

also their interrelations in terms of *coordination*, as well as *potential interference*. With regard to the latter, additional processes may be postulated that go beyond the cognitive mechanisms and knowledge structures necessary to accomplish the individual component tasks involved in multiple-task performance. These coordinating processes are usually referred to as *executive control processes* (e.g., Rubinstein, Meyer & Evans, 2001). Throughout the last two decades, a very popular idea about the implementation of executive control processes has been to postulate some central executive, supervisory, or volitional system that controls the subordinate modules of the cognitive architecture (e.g., Baddeley, 1986; Johnson-Laird, 1988; Norman & Shallice, 1986; Reason, 1984). However, in recent years, it has become increasingly clear that executive functions are probably not accomplished by a unitary control system, but that they are instead implemented by distributed control structures. Thus, the concept of a central executive may not be a satisfactory explanation of executive processes, but merely a label for something that has yet to be explained. According to this view, a deeper understanding of voluntary control requires a functional decomposition of executive functions and a specification of how different executive processes are implemented within the cognitive architecture (cf. Allport, 1993; Goschke, 2002; Monsell, 1996; Pashler, 2000).

In the field of cognitive modeling, the simulation of cognitive control is one of the oldest research topics (e.g., Miller, Galanter & Pribram, 1960; Newell, Shaw & Simon, 1958). In recent years, the cognitive architectures EPIC (Meyer & Kieras, 1997a, b, 1998) and ACT-R (Anderson & Lebiere, 1998) have been widely used to simulate executive control processes by conceptualizing executive functions as fractionated processes. In these simulations, specific *executive production rules* are postulated for scheduling subordinate production rules that do the basic computations involved in performing a task (Meyer & Kieras, 1997a, b). Additionally, *activation mechanisms* are introduced for coordinating the execution of multiple tasks (Altmann & Gray, 2000; Altmann & Trafton, 2002; Norman & Shallice, 1986).

These modeling approaches allow for the simulation of elementary processes of action control that have been studied intensively in recent years in experimental cognitive psychology. The relevant experimental studies on multiple-task performance that are addressed in these simulations implement either a *successive task procedure* (e.g., the task-switching procedure) or a *simultaneous task procedure* (e.g., the psychological refractory period procedure). Much of the empirical evidence has been obtained within a research tradition labeled "attention and performance" that has "sought to illuminate basic questions about the architecture of the human mind by examining the human performance in relatively simple tasks" (Pashler et al., 2001, p. 630). Usually these tasks are choice reaction time tasks in which subjects have to choose the appropriate reaction from a predefined set of responses according to the kind of stimulus presented. These tasks can be completed within

one second or less. The question of whether findings obtained with these microscopic single-step tasks will scale up to explain issues of action control at higher-level time scales – like the 10 second band or the 1 minute band in Newell's (1990) terms – will be discussed after an introduction to recent advances of research on cognitive control.

### *Successive task procedures*

Successive task procedures are used to study people's ability to alternate between different tasks. The most widely used successive task procedure has been the *task-switching paradigm* (Allport, Styles & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). The main idea is to compare an experimental condition in which subjects repeatedly perform the same task to a condition in which subjects have to alternate between different tasks of equal priority. The procedure is strictly successive, i.e., the stimulus for the next task is never presented until after a response to the current task has been given.

The tasks used for experimentation are typically *choice reaction time tasks* (e.g., classifying digits as odd or even) or simple *arithmetic tasks*. Performance is usually assumed to rely on a *task set* that is made up of knowledge of some simple facts (e.g., the fact that 6 is an even number), of a limited set of rules (e.g., mapping rules that specify the appropriate response for a particular stimulus), and of a representation of the task's goal (e.g., the goal of adding two digits). It is assumed that working on repeated tasks involves the same task set for each task, whereas working on alternating tasks involves reconfiguring the task set for each task.

Empirically, alternating between different tasks typically results in temporal switch costs in terms of a prolonged response time compared to task repetition. It could be shown that the total switch costs are made up of different components that have been explained by proposing *activation mechanisms*, as well as *preparatory executive control processes*.

**Activation mechanisms.** Allport et al. (1994) suggested that switch costs go back to persisting activation from a previous task. The residual activation of a previously executed task set – called *task-set inertia* – is assumed to cause a proactive interference that results in time costs for alternating task sequences compared to repeated tasks. While persisting activation from a previous task can be described as an interfering factor when performing alternating task sequences, it can also be seen as a facilitating factor when performing repeated tasks (Sohn & Anderson, 2001): When the same task is performed repeatedly, *priming effects* will facilitate the retrieval of task-relevant information (e.g., knowledge of facts and rules) and thus result in a *repetition gain*. Both concepts, i.e., task-set inertia and priming rely on automatic mechanisms of cognitive control that are based on the degree of activation of cognitive units, on the associative structure of memory, as well as on the temporal decay of activation.

**Preparatory executive control processes.** According to Rogers and Monsell (1995), activation-based accounts are not sufficient to explain the comprehensive pattern of findings on switch costs. They argue that switch costs do not go back to effects of proactive interference from a recently used task set (or to priming effects for repeated tasks), but that they rather reflect the time devoted to engaging in executive control processes necessary for the preparation of an upcoming task. *Task preparation* pertains to processes that reconfigure the cognitive system so that it is compatible with the demands of an upcoming task. This may comprise retrieving the representation of the upcoming task's goal (cf. Goschke, 2000), as well as activating rules and facts required for task accomplishment. Additionally, task-set reconfiguration may include the inhibition of cognitive structures that were used to perform the previous task (cf. Mayr & Keele, 2000).

Cognitive models of the task-switching procedure implement both explanatory approaches discussed so far, but differ in whether they focus on the role of activation (cf. Altmann & Gray, 2000), on the role of executive control (Rubinstein et al., 2001), or on a complementary role of both (Sohn & Anderson, 2001).

**The cognitive model of Altmann and Gray (2000).** In accordance with the concept of task-set inertia (Allport et al., 1994), Altmann and Gray (2000) consider task switching mainly as a memory problem where proactive interference from previous tasks may impede performance on a current task. A combination of two activation mechanisms is proposed that may counteract proactive interference and that is implemented within the cognitive architecture ACT-R. First, *active inhibition* is seen as a resource-bound process that takes a certain amount of time. Inhibition is conceived to be functionally equivalent to relative activation, i.e., it is postulated that a particular item can be inhibited by increasing the activation of a competing item. Actively increasing the degree of activation of a memory item can be achieved by an encoding process that may have to be repeated for several processing cycles in order to reach an appropriate level of activation. Since alternating between tasks involves inhibiting a previously used task representation, the proposed process of inhibition by activation is considered to be the locus of temporal switch costs in the model. Second, *automatic decay* is postulated to avoid an infinite regression, in which every new task has to be made more active than its predecessor. Altmann and Gray (2000) state that their ACT-R model of active inhibition and automatic decay is able to explain a number of task-switching phenomena observed in a serial attention task that they used for experimentation.

**The cognitive model of Rubinstein, Meyer, and Evans (2001).** A rather different approach to the simulation of switch-cost phenomena is taken in the cognitive model of Rubinstein et al. (2001). These authors present a stage model of executive control for task switching that is embedded within the cognitive architecture EPIC (Meyer & Kieras, 1997a, b, 1998) and that distin-

guishes two complementary sets of processes, which are both implemented by production rules. First, *task processes* are used for performing the component tasks involved in multiple-task performance. Second, *executive control processes* guide the implementation of various task and subtask procedures by adding and deleting working-memory items.

In order to simulate task switching, the model's executive control processes are subdivided into two distinct stages, *goal shifting* and *rule activation*. Together, these two processes ensure that the cognitive system is appropriately reconfigured when accomplishing the next task to be performed. The goal-shifting stage monitors current and future tasks and inserts or deletes their goal representations in working memory. This ensures that the system always "knows" what the current task is. The subsequent executive stage of rule activation serves two functions: first, it enables the rules for response selection that are required by the upcoming task and, second, it disables the rules for response selection that have been used for performing the previous task.

The stage model of Rubinstein et al. (2001) explains a number of findings related to task cueing, task complexity, or response-stimulus interval length that have been obtained within a standard task-switching paradigm. Furthermore, the experiments of Rubinstein et al. (2001) yielded evidence that activation-based mechanisms of proactive interference and priming need to be supplemented by executive control processes like the ones simulated in their model.

**The cognitive model of Sohn and Anderson (2001).** In order to account for the fact that both mechanisms – automatic activation or inhibition of task sets, as well as executive control processes – have been shown to influence task switching, Sohn and Anderson (2001) developed an ACT-R model that combines both types of mechanisms. *Task preparation* is described as an executive control process that can be used to reconfigure the cognitive system in accordance with an upcoming task. In contrast, *task repetition* is described as an activation-based mechanism, where the degree of activation of a task representation is increased by performing this task repeatedly. In the cognitive model, the two components of task switching are mapped onto the procedural and the declarative memory system in the ACT-R architecture.

The procedural memory holds preparatory production rules that are responsible for setting or manipulating declarative goal representations, which specify the tasks to be performed. The declarative memory is assumed to hold information required to perform a task (i.e., its task set). Performing the same type of task in succession results in a repetitive use of these declarative components and thereby yields a repetition priming effect. This effect is modeled by relying on activation mechanisms inherent to the ACT-R cognitive architecture. According to these mechanisms, the degree of activation of declarative units will increase each time these units are retrieved. Additionally, an automatic process of decay is postulated that decreases the degree of

activation when declarative units are not retrieved. First, these assumptions explain the emergence of switch costs by postulating priming as a facilitating factor when performing tasks repeatedly. Second, activation decay may also explain why switch costs are reduced substantially when the response-stimulus interval is increased.

The experiments conducted by Sohn and Anderson (2001) yielded a rich pattern of data that suggest "that executive control (e.g., task preparation) and automatic control (e.g., task repetition) are both crucially and yet independently involved in task performance" (Sohn & Anderson, 2001, p. 776).

### *Simultaneous task procedures*

Multiple-task performance, especially in many real-world situations, does not only involve performing multiple tasks successively, but it may also require coordinating several tasks that are executed simultaneously. Cognitive processes that are important for concurrent multiple-task performance have been studied experimentally by using a dual-task paradigm. More recently, data from dual-task experiments have been used to develop cognitive models of executive control processes within the EPIC architecture (Meyer & Kieras, 1997a, b, 1998).

In a dual-task experiment, subjects are required to perform two different tasks in parallel. This procedure may induce problems in allocating cognitive resources to the tasks involved, as well as problems related to competition between different response alternatives or action tendencies. A typical result of dual-task experiments is the deterioration of the performance of one or both activities in comparison to the single-task performance levels. Several theoretical explanations have been offered to account for these observed performance decrements (cf. Donk and Sanders, 1989; Heuer & Wing, 1984; Howe & Rabinowitz, 1989; Kahneman, 1973; Navon, 1985; Navon & Gopher, 1979; Navon & Miller, 1987).

**The psychological refractory period.** To analyze the role of executive control processes in dual-task performance in greater detail, the psychological refractory period (PRP) procedure is usually deployed (Telford, 1931). The PRP procedure is a traditional dual-task paradigm that allows for microscopic temporal analyses of task coordination. It is based on choice reaction time tasks that are very similar to those used in the task-switching paradigm; however, in the PRP procedure, subjects are required to perform two choice reaction time tasks (Task 1 and Task 2) with a substantial temporal overlap. Subjects are usually instructed to make speeded responses with a higher priority given to Task 1. Thus, both tasks have to be performed more or less concurrently with the so-called *stimulus onset asynchrony* (SOA) as the crucial time interval between the presentation of Task 1 and Task 2. The main *PRP effect* obtained in this experimental paradigm is that a short SOA compared to a longer SOA impairs performance on Task 2, but not on Task 1 (for a review, see Pashler, 1994). However, the total time required to

complete both tasks is often less than the sum of times for performing both tasks separately, which provides evidence for a substantial processing overlap. The PRP effect is traditionally explained by assuming specific processing bottlenecks that prevent the cognitive system from performing two tasks completely in parallel.

**The cognitive model of Meyer and Kieras (1997a).** Contrary to this traditional explanation, the EPIC model of PRP effects proposed by Meyer and Kieras (1997a, b) is based on the assumption that PRP effects can be interpreted as a result of *strategic adaptations to current task demands*. This strategic response-deferment (SRD) approach replaces assumptions on structural processing limitations with assumptions on task strategies and executive control processes, by which people adapt to satisfy particular instructions about task priorities. Similar to the task-switching model by Rubinstein et al. (2001), this model distinguishes between two independent sets of cognitive processes that are simulated by production rules: task processes and executive control processes. *Task-specific production rules* are responsible for the accomplishment of the choice reaction time tasks that have to be performed. In order to model how two choice reaction time tasks may be interleaved in the PRP procedure, a distinct set of *executive production rules* is introduced, which schedules and controls the operation of the task-specific rules by monitoring task progress and inserting and deleting task goals and task-strategy notes in working memory. With regard to task-strategy notes, the model distinguishes between two transmission modes: immediate and deferred. When a task is enabled in an *immediate transmission mode*, task-specific rules can be applied directly in order to accomplish the task, whereas in a *deferred transmission mode*, selected actions will be put in working memory in order to avoid conflicts in movement generation. The SRD model can account for numerous phenomena that have been discovered by means of the PRP procedure and that are hard to explain with an immutable central processing bottleneck.

### **Beyond the control of choice reaction time tasks: The issue of scaling up**

On the one hand, the microscopic world of simple choice reaction time tasks has obviously been very useful to explore elementary processes of action control experimentally and to develop cognitive modeling approaches to executive functions, as the preceding review clearly indicates. For instance, the concept of executive production rules postulated by Meyer and Kieras has proven useful for formalizing and implementing executive processes as distributed control structures. Accordingly, this approach may be suitable to replace the traditional idea of attributing executive control to some central supervisory or volitional system that controls subordinate modules of the cognitive architecture (e.g., Baddeley, 1986; Johnson-Laird, 1988; Norman & Shallice, 1986). On the other hand, it is also obvious that multiple-task performance in daily life mostly involves tasks that have a much coarser tempo-

ral grain size than laboratory tasks with their experimental effects on the millisecond time scale. Additionally, the control of everyday multiple-task performance will surely involve many other aspects of action control, for example, aspects related to high-level planning and scheduling or to motivation and emotion.

However, the relevance of experimental paradigms that are mainly confined to choice reaction time tasks is clearly derived from their potential to shed light on "more complex everyday dual-task behavior .... Because such complex tasks are difficult to analyze in the laboratory, the essence of dual-task behavior was boiled down to the simplest dual-task situation, represented by PRP experiments" (Anderson & Lebiere, 1998, p. 177). If one considers that even in standardized experimental situations, very small differences in instructions or materials may lead to very divergent experimental patterns of results, having concerns about how we can be sure that experimental findings on task switching or PRP – and their associated cognitive models – will really be applicable to interesting real-world situations (cf. Pashler, 2000) is certainly justified. Burgess (2000) describes some essential characteristics of situations commonly faced in everyday life that should be tackled by theoretical approaches to multiple-task performance:

1. *Numerous tasks*: A number of discrete and different tasks have to be completed.
2. *One task at a time*: Due to physical or cognitive constraints, it is not possible to perform more than one task at a time.
3. *Interleaving required*: Performance on these tasks must be dovetailed; the most time-effective course of action is not to completely finish one task before moving to another, but to switch between them as appropriate.
4. *Delayed intentions*: The time for a switch or return to a task is not signaled directly by the situation....
5. *Interruptions*: Occasionally, interruptions and unforeseen circumstances will occur.
6. *Differing task characteristics*: Tasks usually differ in terms of priority, difficulty, and the length of time they will take.
7. *No feedback*: People decide for themselves what constitutes adequate performance, and there is no minute-by-minute performance feedback of the sort that participants receive in, for instance, a typical "psychological refractory period" (PRP) dual-task experiment, where errors are apparent.

Although not every multitasking situation will have all these characteristics, it is arguably easier to think of generic everyday activities lasting several minutes or more (e.g., cooking, shopping) that have these characteristics, than it is to think of ones that do not.

(Burgess, 2000, p. 466)

Thus, there may be interesting aspects of action control that will be more salient on higher-level time scales than that of simple choice reaction time tasks, e.g., on the 10 second band or the 1 minute band in Newell's (1990) terms. A central research question with regard to higher-level effects will be whether the same approaches that have been used to analyze elementary processes of action control are suitable to explain these more complex control processes. In discussing the issue of whether experimental findings on executive functions will scale up to realistic multiple-task situations, we will mainly focus on three differences between low-level experimental tasks and realistic multitasking situations that seem to be relevant from the abovementioned quotes: temporal grain size, integration of multiple executive functions, and energetic aspects of action control.

**Temporal grain size.** Real-world tasks may be better analyzed at a coarser grain size than on the millisecond scale used to describe experimental tasks. Whereas experimental tasks in the field of executive processes are usually *single-step tasks*, where input is mapped to output in a single processing cycle, many real-world tasks are *multi-step tasks* that consist of a sequence of processing steps (cf. Carlson & Sohn, 2000; Monsell, 1996). As a consequence, many control issues arise that will not be manifest at lower levels of analysis. For example, most multiple-step tasks offer many options as to how steps may be assembled to solve the task (i.e., different strategies to perform the task). However, there are also other issues of control in multiple-step tasks like suspending tasks, resuming tasks, monitoring, troubleshooting, termination assessment, and resource allocation. It is rather unclear, however, whether activation mechanisms and executive control productions that have been successfully used to explain and model the coordination of multiple choice reaction time tasks, as well as their pattern of interference, can be used to explain these higher-level issues of executive control.

**Integration of multiple executive functions.** A topic that directly results from the idea that additional higher-level processes of executive control may arise at a coarser temporal grain size is the question of how multiple executive functions may be integrated to result in overall adaptive action. Goschke (2000, 2002) describes this interplay between executive functions in terms of control dilemmas that result from the requirement that adaptive action needs to satisfy partially incompatible constraints. Examples of these control dilemmas are the selection-orientation dilemma and the maintenance-switching dilemma (Goschke, 2000, p. 350ff.; Goschke, 2002, p. 29f.).

The *selection-orientation dilemma* expresses the fact that two antagonistic types of control processes are required: On the one hand, processes that allow for the *inhibition of task-irrelevant information* are necessary to avoid cross talk and interference between tasks. On the other hand, *monitoring of the environment* is essential to detect potentially significant information that may be relevant for tasks other than the one currently being performed.

The *maintenance-switching dilemma* describes one of the central problems of volitional action control: On the one hand, *intentions must be shielded against competing goals* in order to enable stability and persistence in the pursuit of long-term goals. On the other hand, it is necessary to be able to *interrupt a current action* at any time and to *switch to a different action* if it is necessary or advantageous.

**Energetic aspects of action control.** A final difference between analyzing low-level experimental tasks and realistic multitasking situations seems to be that energetic, dynamic, or motivational aspects of action control (e.g., effort investment, need deprivation motivation, stress, or emotional arousal) may be much more relevant for high-level tasks than for low-level tasks (although they may also have some relevance for low-level tasks, cf. Meyer & Kieras, 1998, p. 72). Thus, an integration of motivational and cognitive aspects may be useful for a more comprehensive description of action control in everyday multiple-task behavior. The need to combine energetic aspects and aspects of information processing within an integrated framework for the analysis of action control has been advocated by cognitive psychologists (e.g., Meyer & Kieras, 1998) as well as by motivational psychologists (e.g., Kuhl, 1984; Eccles & Wigfield, 2002).

### Summary and implications for further research

Research on action control in multiple-task situations in the fields of experimental cognitive psychology and computational cognitive modeling has yielded promising results in recent years. Numerous theoretical constructs and computational approaches have been explored that may contribute to the explanation of executive functions involved in multiple-task performance. Attempts to model empirical findings obtained from multiple-task experiments within production-rule architectures mainly proposed two approaches to analyze the interrelations of component tasks in multiple-task performance. First, *activation mechanisms* have been useful to represent some aspects of task coordination and task interference in multiple-task performance. Second, *executive control productions* have been successfully introduced to model processes that are not actually involved in the basic computations necessary to perform a task, but that act on these processes by enabling, preventing, and directing them.

However, most research on multiple-task performance has been related to the microscopic world of simple choice reaction time tasks with its very low temporal demands. Therefore, it remains unclear whether the theoretical constructs and computational mechanisms that have been useful in thinking about task-switching effects or the psychological refractory period might be applicable in order to describe and explain everyday multiple-task behavior. First, real-world tasks may be better analyzed at a coarser temporal grain size. Second, there may be many other executive functions beyond switching between two simple tasks that become relevant for everyday

tasks. Thus, the analysis of control processes in real-world, multiple-task performance may require integrating diverse – and maybe even partially antagonistic – executive functions in a coherent conceptual framework. Third, with regard to the control of high-level tasks, energetic, dynamic, or motivational aspects of action control may be much more relevant than with regard to simple experimental tasks.

In order to tackle the scaling-up issue, we propose a *top-down research strategy* comprised of four steps that will be illustrated in the remainder of this paper.

First, this strategy commences with a comprehensive framework of volitional action control – integrating *cognitive and motivational issues* – that is based on an *abstract functional analysis of control demands* at the level of everyday actions. The role of this framework is to identify and classify issues of action control from a unified perspective and to specify basic concepts and principles for the analysis of actions. We use this framework to derive empirical hypotheses with regard to the effects of goal competition and task difficulty in multiple-task situations.

Second, we outline how the volitional framework can be specified by linking it to cognitive concepts and computational mechanisms proposed for the analysis of elementary executive functions. These specifications can explain how different control demands are met by the cognitive systems and how different control processes interact with one another in order to produce overall adaptive action. Filling in the cognitive details of different control processes also allows us to refine our empirical hypotheses. Third, we outline some experimental studies that were conducted to test the proposed hypotheses and their cognitive explanations (Gerjets et al., 2002; Heise et al., 1994b, 1997; Scheiter et al., 2000).

Fourth, we use the postulated computational mechanisms to model our findings within the cognitive ACT-R architecture. We interpret our model as a demonstration that the computational approaches that have been proposed for the analysis of elementary processes of action control can be applied in order to explain more complex volitional control processes.

### **3. Volitional action control in multiple-task performance: A theoretical framework, cognitive foundations, empirical findings, and a computational model**

Modern theories of volitional action control have developed out of expectancy-value theories of motivation (e.g., Atkinson, 1964). Expectancy-value theories – like motivation theories in general – attempt to explain three aspects of human behavior, namely choice, persistence, and effort. That is, it is assumed, that “motivation is responsible *why* people decide to do something, *how long* they are willing to sustain the activity, and *how hard* they are going to pursue it” (Dörnyei, 2000, p. 519f.). However, volitional theorists

have criticized the assumption that motivation can explain all of these phenomena (e.g., Corno, 1993; Gollwitzer, 1990; Heckhausen, 1991; Kuhl, 1984, 1992). They argue that most theories of human motivation have predominantly been concerned with the choice of action goals rather than with the volitional or executive processes that are necessary on the way from goal setting to goal achievement. Additionally, they assume that the energetic processes that guide the implementation and control of goal-directed action – and thus determine outcome measures like effort, persistence, and performance – are rather different from expectancy-value calculations that guide the choice of a particular action goal. Volitional processes of goal implementation will have to take into account the motivational aspects of goals, as well as different cognitive and situational parameters – like difficulties, urgencies, or opportunities related to the current, as well as pending goals – in order to energize and direct behavior in an overall adaptive way. Thus, motivation in terms of the expected value of goal accomplishment will only be a small facet of the energetic factors that come into play during goal accomplishment.

As a comprehensive framework for the analysis of volitional action control, we refer to the *Theory of Action Phases* (also called Rubicon Theory; Gollwitzer, 1990; Heckhausen, 1991). A formal reconstruction of the theory using the set-theoretic language of the structuralist view of theories (Balzer, Moulines & Sneed, 1987) has led to considerable conceptual clarifications, to a detailed comparison between different theory versions, and to the condensed and precise theory version PART (Pivotal Assumptions of the Rubicon Theory; Gerjets, 1995; Heise et al., 1994a) that is used as our starting point for the cognitive modeling of volitional action control in multiple-task performance.

### **PART: A framework for the analysis of volitional action control**

PART is a broad framework that attempts to formulate general cognitive, motivational, and volitional principles of goal-directed action. This framework is guided by an analysis of different control demands at the level of everyday actions and deals with issues of goal setting and goal implementation on a rather abstract functional level. The Theory of Action Phases describes actions from a time-sequential perspective as an idealized sequence of four phases. It deals with the entire course of an action, from deliberating the possible action goals at the beginning, to the planning and execution of goal-related activities, and finally to evaluating the attained outcome (see Figure 1). These processes of action control, as well as the temporal duration of the action phases and the access to executive resources, are determined by several energetic control variables that depend on cognitive and motivational factors. Some of these variables will be explained later on in this paper.

Deliberation (predecisional)	Planning (preexecutive )	Implementation (executive)	Evaluation (postexecutive)
Goal setting ("Rubicon")	Initiation of activities	Termination of activities	

Figure 1. Action phases in PART

In the *predecisional phase*, one out of several possible goal alternatives is chosen as the current goal or intention to pursue. This decision is based on deliberating the expectancies and values associated with each of the possible goal alternatives. Expectancies and values are integrated into a variable called motivational strength. It is assumed that the goal alternative with the highest motivational strength will be chosen as the current goal intention to pursue (i.e., goal setting). In the subsequent *preexecutive phase*, goal-related activities have to be planned and the goal intention has to be maintained until a suitable opportunity for the execution of goal-related activities arises. It has to be decided which of the not yet accomplished intentions should be implemented next. The initiation of intention-related activities marks the transition to the executive phase. In the *executive phase*, the main focus of action control processes is on regulating effort investment and persistence in goal accomplishment, both of which determine performance. The executive phase either ends with goal accomplishment or disengagement in the case of failure. It is followed by the *postexecutive phase*, in which an evaluation and attribution of the attained outcome takes place.

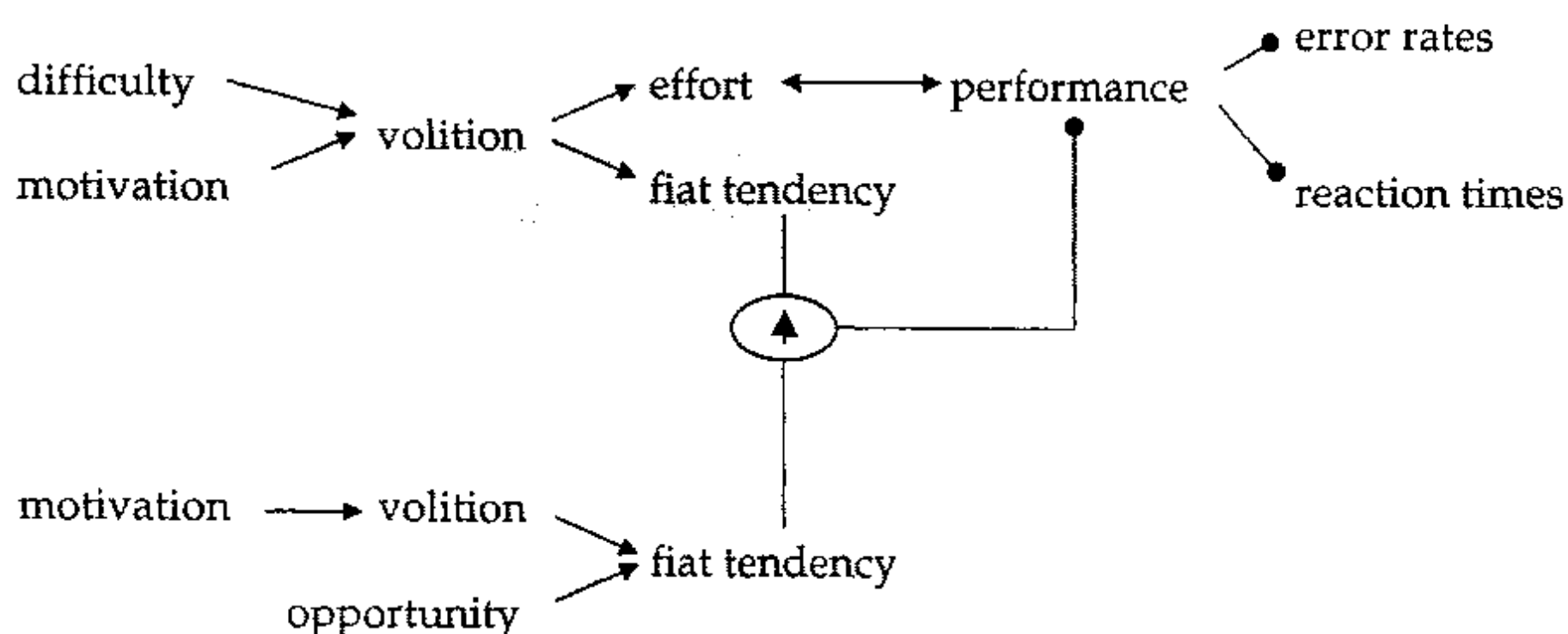
The Theory of Action Phases can not only be used to describe the course of individual real-world actions at a rather abstract functional level, but it is also suitable for the analysis of conflicts that may occur between different actions in multiple-task situations. In our work, we focus on conflicts between a current and a pending goal intention. In PART, this situation is analyzed as a conflict between an executive and a preexecutive goal intention.

Goal competition between a current and a pending goal intention occurs when subjects are instructed to keep working on a Task 1 for a longer period of time, while a pending Task 2 is waiting to be executed subsequently. In this case, one goal intention is supposed to remain in the executive phase, while the other is to remain in the preexecutive phase. However, when situational opportunities in favor of Task 2 arise, a manifest goal competition may occur, making it difficult to comply with the instruction of completing Task 1 before engaging in Task 2. PART allows for a theoretical analysis of this type of goal competition and for the derivation of several hypotheses that can be tested empirically. This analysis is based on the interaction of several energetic control variables as illustrated in Figure 2.

**Current Task 1 (upper part of Figure 2):** The current goal intention is assigned a specific degree of *motivational strength* that results from expectancy-

value calculations during the goal-setting phase. Together with the current level of *task difficulty*, this motivational strength determines the so-called *volitional strength* of the current goal intention. An increase in task difficulty results in an increased volitional strength of the current goal intention. Two functions of the volitional strength are important during the execution of intention-related activities. First, the volitional strength determines how much *effort* will be exerted for the implementation of this goal intention. Second, the volitional strength of the current intention determines the so-called *fiat tendency* of the current Task 1 that expresses this task's push for implementation and is responsible for the persistence in goal accomplishment. The theory assumes that the implementation of the current goal will be continued until the goal is achieved or until a competing goal with a higher fiat tendency occurs. It is important to note that PART implies a dynamic (and supposedly automatic) regulation of volition, effort, and fiat tendency in the face of increasing task difficulty. This is one of the main volitional mechanisms of the Theory of Action Phases and corresponds to the so-called *law of difficulty* (cf. Heckhausen, 1991).

#### Current Task 1 (Goal Intention in Executive Phase)



#### Pending Task 2 (Goal Intention in Preexecutive Phase)

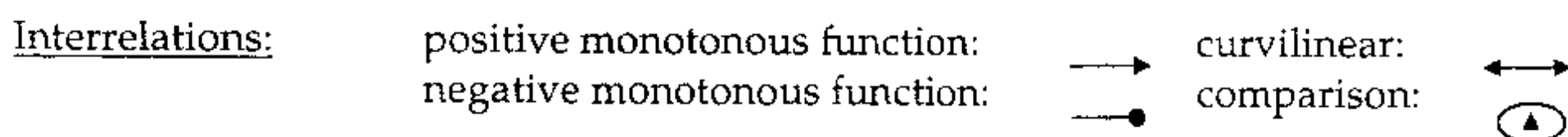


Figure 2. Interrelations between PART variables involved in conflicts between a current and a pending goal intention

**Pending Task 2 (lower part of Figure 2):** The fiat tendency of the pending Task 2 not only depends on its volitional strength (influenced by its motivational strength), but also on the perceived suitability of opportunities to initiate corresponding activities. If the fiat tendency of the pending task's intention becomes sufficiently large (compared to the fiat tendency of the current

Task 1), then the performance with regard to the current task can be impaired (as will be reflected in error rates or reaction times). Furthermore, in a conflict between a current and a pending goal intention, the fiat tendencies of the competing goal intentions determine which of the two intentions becomes dominant, i.e., which of the two intentions is further pursued. Performance impairments for the current task are expected in the event that the current task is maintained, as well as in the event that the current task is suspended in favor of the pending task, i.e., in the case of goal switching. According to the analysis of Goschke (2000, 2002), volitional action control will be most adaptive when it results in a balance between shielding a current intention against competing intentions ("maintenance") and flexibly responding to situational changes ("switching").

The theoretical analysis within the PART framework allows for the derivation of several empirically testable hypotheses, from which we selected two for experimental investigation:

**Hypothesis 1: Distraction due to competing goal intentions.** The performance of a currently executed Task 1 will be impaired if a suitable opportunity for the implementation of a competing intention related to a pending Task 2 occurs. This prediction results from the assumption that an opportunity to implement Task 2 leads to an increase in its fiat tendency. If this fiat tendency is sufficiently strong, then the performance for Task 1 may be impaired, because of activities related to Task 2 or because of processes of decision making that determine which intention should be pursued further. The stronger the fiat tendency of pending Task 2 as compared to the current Task 1, the greater its distracting effect

**Hypothesis 2: Difficulty-related volitional protection.** Performance impairments due to goal competition should be less severe for a high level than for a low level of task difficulty of the currently performed Task 1. This prediction results from the assumption that an increasing level of task difficulty for Task 1 results in an increased volitional strength and thereby in an increased fiat tendency of Task 1. This influences the relation between the fiat tendencies of Task 1 and Task 2 in favor of Task 1 and, therefore, decreases the distracting effect of the pending Task 2.

PART does not only allow for the analysis of goal competition between a current and a pending goal intention, but also enables the classification of other types of conflicts that may occur between different actions in multiple-task situations. Conflicts between potential goal alternatives are the focus of interest in *theories of motivation*, e.g., expectancy-value theories. Some findings on conflicts between potential and chosen goal alternatives have been obtained through the *theory of cognitive dissonance*. Conflicts between two preexecutive goal intentions or between a currently performed goal intention and a pending goal intention are of primary interest for *volitional theories of action control*. Conflicts between two executive intentions are described in *dual-task research*, where subjects have to concurrently pursue two tasks (e.g.,

the *psychological refractory period paradigm*). Conflicts between preexecutive (or executive) and postexecutive intentions can be related to the *task-switching paradigm*, where a task that has just been completed interferes with the preparation or execution of a subsequent task.

Thus, PART seems suitable as a comprehensive framework for the description of control demands in multiple-task performance. However, PART analyzes control demands of everyday actions on an abstract functional level and it is not clear how these control demands may be met by cognitive mechanisms of information processing that eventually have to implement the proposed processes of action control. Therefore, it is necessary to fill in more detailed cognitive and computational assumptions in order to increase the explanatory power of the framework to allow for precise empirical predictions.

### Cognitive foundations of volitional action control

We explore two approaches to connect the volitional framework of PART with cognitive concepts, which are both useful to inform the cognitive modeling of processes of volitional action control within ACT-R. The first approach is to use concepts from *Cognitive Load Theory* (Sweller et al., 1998) to reinterpret the competition between current and pending goals in more cognitive terms. The other approach is to construct *intertheoretical links between PART and the ACT architecture* within the structuralist view of theories.

**Cognitive Load Theory (CLT).** According to Cognitive Load Theory (Sweller et al., 1998), a distinction is made between the load that is imposed on the cognitive system (i.e., *cognitive load*) by task demands and the amount of cognitive capacity that is allocated to accommodate these task demands (i.e., *mental effort*). It is assumed that learners try to allocate as much mental effort to a task as needed to pursue it successfully. There are, however, no detailed assumptions in CLT on factors that may influence effort allocation (cf. Gerjets & Scheiter, 2003). According to the theory, cognitive load caused by processing task-related information (*intrinsic* and *germane workload*) can be distinguished from cognitive load that results from processing task-unrelated information (*extraneous workload*). The theory assumes that only extraneous workload is responsible for performance impairments, because it reduces working memory capacity available for performing a current task. Based on Cognitive Load Theory, it can be hypothesized that the presence of a competing goal with a corresponding opportunity for its implementation increases extraneous workload by activating information in memory that is related to the competing goal. This increased extraneous workload may absorb cognitive resources that are, therefore, no longer available for the execution of the current task. As a consequence, it is likely that simpler processing strategies might be selected to accomplish the current task, as these strategies are less resource demanding, but at the same time less effective (cf. Guttentag, 1995; Logan, 1985; Schunn & Reder, 2001).

This line of reasoning is in accordance with recent research on prospective memory, demonstrating that pending goals reside in memory with a heightened state of activation (Goschke & Kuhl, 1993; Marsh, Hicks & Bryan, 1999). As a consequence of their specific status in memory, representations of prospective tasks will be very easily activated by related external cues (cf. Altmann & Trafton, 2002). On the one hand, it can be interpreted as adaptive if uncompleted tasks come to mind more readily than tasks already completed. On the other hand, the easy access to memories for pending goals can lead to interference, distraction, intrusion errors, and resource costs (cf. Li, Lindenberger, R  nger & Frensch, 2000).

Thus, from a CLT perspective, the PART assumption that a pending goal with a sufficiently large fiat tendency (relative to the fiat tendency of the current task) may lead to performance impairments with regard to the current task can be reinterpreted in terms of cognitive load and strategy selection: A competing goal intention that is activated by situational opportunities may result in a high level of extraneous cognitive load which may in turn lead to the selection of simpler strategies for goal accomplishment. Effects of goal competition on error rates and reaction times may be interpreted as consequences of this resource-adaptive strategy selection. According to these considerations, the *hypothesis of distraction due to competing goal intentions* may be refined by predicting that distraction effects due to goal competition may not only include performance impairments, but also strategy shifts due to extraneous cognitive load.

The cognitive load perspective also allows for refining the *hypothesis of difficulty-related volitional protection* that predicts that detrimental effects of goal competition mainly occur in the case of low task difficulty. This refinement can be based on an augmentation of Cognitive Load Theory by a *first-come-first-served principle of working memory allocation*:

Working on a current task with a *low level of difficulty* may be accompanied by low levels of intrinsic and germane cognitive load and thus leave remaining working memory resources free for disposal. These spare resources can be claimed by either extraneous or germane cognitive load during the course of task accomplishment. Without goal competition, these resources may be used to implement rather sophisticated processing strategies to accomplish the current task. Conversely, goal competition in multiple-task situations may impose extraneous cognitive load that prevents the utilization of sophisticated processing strategies. However, working on a current task with a *high level of difficulty* may be characterized by high levels of intrinsic and germane cognitive load (cf. Daily, Lovett & Reder, 2001) and thus may not leave enough working memory resources available for either implementing sophisticated processing strategies or for being distracted. Thus, distraction effects should only show up at low levels, but not at sufficiently high levels of task difficulty, as predicted by PART.

It is, however, important to note that the described first-come-first-served principle of working-memory allocation is not part of CLT, which contains no assumptions with regard to issues of control of working-memory contents and of effort regulation (cf. Gerjets & Scheiter, 2003). To bridge this explanatory gap, we borrowed the principle of difficulty-related effort investment from PART and other volitional theories that contain similar principles.

**Intertheoretical links between PART and ACT.** Although Cognitive Load Theory proves to be very useful for shedding light on possible cognitive foundations of volitional processes, this cognitive reinterpretation is based on the connection between isolated cognitive and volitional concepts (e.g., fiat tendency and activation of memory contents). To go beyond this rather limited approach of interpreting selected volitional mechanisms in terms of plausible cognitive concepts, it would be necessary to systematically connect a whole volitional framework with a comprehensive system of cognitive structures and processes, i.e., with a cognitive architecture. We took this step by connecting PART with Anderson's (1983, 1993) cognitive ACT architecture in a formalized way.

We used the concept of intertheoretical links provided by the structuralist view of theories (Balzer et al., 1987; Westermann, 1987) for defining precisely formalized conceptual links between PART and ACT. In order to construct a comprehensive set of intertheoretical connections (Gerjets, 1995, 1997; Gerjets, Heise & Westermann, 1996a), we used the model-theoretic reconstruction of the ACT\* version of the ACT architecture (Heise, 1991, 1992) and the formalized version PART of the Theory of Action Phases (Gerjets, 1995; Heise et al., 1994a).

The basic rationale for constructing intertheoretical links between PART and ACT is the assumption that cognitive systems may be analyzed at different *levels of abstraction* (Anderson, 1990; Dennett, 1987; Newell, 1990; Pylyshyn, 1984). Additionally, a kind of *implementation relation* may be assumed between structures and processes that are described at a rather abstract functional level (as in PART) and at a much more detailed level of analysis (as within the ACT architecture). Intertheoretical links express hypotheses about the details of this implementation relation. When constructing intertheoretical links, the main issue is to identify theoretical entities within the two theories that have *identical or overlapping functional roles* in terms of the causal network they are imbedded in. Beyond precisely formulating conceptual mappings between different theoretical frameworks, intertheoretical links may also result in empirically testable intertheoretical hypotheses (Gerjets, Heise & Westermann, 1996b). In our opinion, both high-level and low-level theories will profit from such systematic links.

We elaborated on cognitive counterparts for all terms involved in the PART analysis of goal competition between current and pending goals by mapping the proposed control variables (e.g., task difficulty, fiat tendency)

onto cognitive structures defined in terms of the ACT architecture (cf. Gerjets, 1995; Gerjets et al., 1996a). These mappings mainly refer to different types of declarative goal representations, to associative connections in declarative memory, to mechanisms describing the cognitive strength and activation of declarative representations, to executive control production rules and to pattern matching relations between declarative units currently active in working memory and executive productions. In order to ultimately test whether the proposed mappings are sufficient to explain the cognitive foundations of volitional action control, we developed runnable cognitive simulations of volitional processes based on these intertheoretical connections. The resulting cognitive mechanisms that may underlie processes of volitional action control are in accordance with approaches for the cognitive modeling of executive control processes that were discussed in the first part of this paper (i.e., activation mechanisms and executive production rules). Before we describe our cognitive model in detail, we will outline an exemplary experimental study on goal competition and difficulty-related volitional protection that we used for developing a concrete model that can be compared to empirical data.

### **Empirical findings on distraction due to competing goal intentions**

We conducted several experiments to test the hypothesis of distraction due to competing goal intentions and the hypothesis of difficulty-related volitional protection that were derived from PART. Both hypotheses could be confirmed in experiments with simple word classification tasks (Heise et al., 1994b, 1997), as well as in experiments with complex hypertext-based learning and problem-solving tasks (Gerjets et al., 2002; Scheiter et al., 2000). The results of these experiments yielded evidence for the proposed volitional analysis, as well as for the cognitive refinements based on Cognitive Load Theory and the ACT architecture.

As the focus of this paper lies on high-level processes, we will concentrate on one experiment from the domain of hypertext-based learning and problem solving that is described in detail in Gerjets et al. (2002). A main feature of hypertext is that the user is not reacting to static texts, but rather is choosing according to the current intention when and in which order the information is to be presented (Barab, Bowdish, Young & Owen, 1996). Thus, hypertext users may be especially susceptible to being distracted by conflicting goal intentions that may be activated by situational cues in the hypertext environment and then compete with the current goal intention for execution (Hirashima, Hachiya, Kashiara & Toyoda, 1997).

### *Materials and procedure*

In order to create a complex learning and problem-solving situation that is suitable to study difficulty-related processes of distraction due to goal competition, we developed a hypertext environment that conveys information

on six problem categories from combinatorics (permutations, variations, and combinations, each with and without replacement / repetition). Each problem category can be represented by a formula and is defined by three structural features. Within the hypertext environment, the subjects' main task (i.e., their current goal intention) was to accomplish a learning and problem-solving task, namely to solve three word problems like the following one:

*Knight problem:* 10 knights participate in the 9<sup>th</sup> king's tournament. The king provides the tournament with 12 horses. The knights have to pick their horses blindfolded. The heaviest knight gets to pick first, then the second heaviest and so on. How do you calculate the probability  $P$  of the heaviest knight getting the biggest horse, the second heaviest knight getting the second biggest horse, and the third heaviest knight getting the third biggest horse?

For each test problem, the correct problem category and appropriate values for two relevant variables in the formula had to be marked on a multiple-choice form. In the hypertext environment, all three test problems were presented at the beginning of the experiment. Subjects were instructed to solve the problems as fast and as correctly as possible using information provided in the hypertext environment, which they could browse freely. Each problem category was explained using one worked example; all examples were embedded in interesting cover stories about attractiveness and mate choice.

Each of the six worked examples that could be retrieved in the hypertext-environment was presented on two pages, one containing the *example problem* and one containing the *example solution*. The example-problem page contained the name of a problem category and a word problem belonging to this category. The example-solution page provided a step-by-step solution to the example problem and explicitly mentioned the structural features defining the example's problem category.

### *Design and dependent measures*

As independent variables, two different levels of difficulty were introduced for the word problems to be solved (*easy versus difficult problems*), as were two levels of goal competition during learning and problem solving (*with versus without goal competition*). Both variables of the resulting 2x2-design were varied between subjects.

In accordance with preliminary studies, we manipulated the level of task difficulty by using larger numbers in the difficult test problems and by stating them in a less familiar way than the easy problems. We assume that this manipulation of task difficulty will affect the level of intrinsic cognitive load necessary for the initial representation of a test problem. This is because the problem situation of difficult test problems is harder to understand and thus harder to represent in a condensed way (i.e., in terms of its structural features) than the problem situation of easy test problems. Thus, for difficult

test problems, it may be necessary to additionally represent individual propositions contained in the problem description.

In the *condition with goal competition*, we introduced a competing goal intention and a suitable opportunity for its implementation. Subjects in this condition were informed at the beginning of the experiment that they would have to work on a second task within the same hypertext environment after having finished the problem-solving task. The second task was to answer three questions about attractiveness and mate choice that were presented briefly before subjects started working on the problem-solving task. They were assured they would have enough time afterwards to browse the hypertext environment for information relevant to the second task. As suitable opportunities to execute activities related to the pending intention, we included information about attractiveness and mate choice in the hypertext environment. This information was not helpful for solving the probability word problems, but it was related to the topic of the second task. To make this information available during the first task, the examples used to explain the solution principles contained hyperlinks to access this information.

In the *condition without goal competition*, no competing goal intention was introduced; subjects were only required to solve the three word problems. In order to keep the number of hyperlinks in the learning environment constant, the same amount of irrelevant information was linked to the worked examples as in the condition with distraction. In order to prevent subjects from forming an intrinsically motivated goal intention to browse the irrelevant information, we replaced the interesting additional information about attractiveness and mate choice with rather uninteresting information concerning irrelevant terms in the cover story.

### *Dependent variables*

To test our hypotheses with regard to difficulty-related performance impairments due to goal competition, we obtained two different kinds of dependent variables. As an outcome measure, the percentage of errors for the three word problems was registered. As process measures, several time and frequency parameters were calculated from the log file data recorded during the subjects' interaction with the hypertext environment. In particular, the total amount of time spent on relevant information, as well as time spent on irrelevant information, was calculated. The latter measure was obtained to test whether efficiency impairments can be traced back to cognitive activities related to the competing goal intention.

### *Results and discussion*

In accordance with our hypothesis of distraction, subjects with a competing goal intention and suitable opportunity to initiate corresponding activities showed worse performance in the problem-solving task than subjects without a competing goal intention (Figure 3).

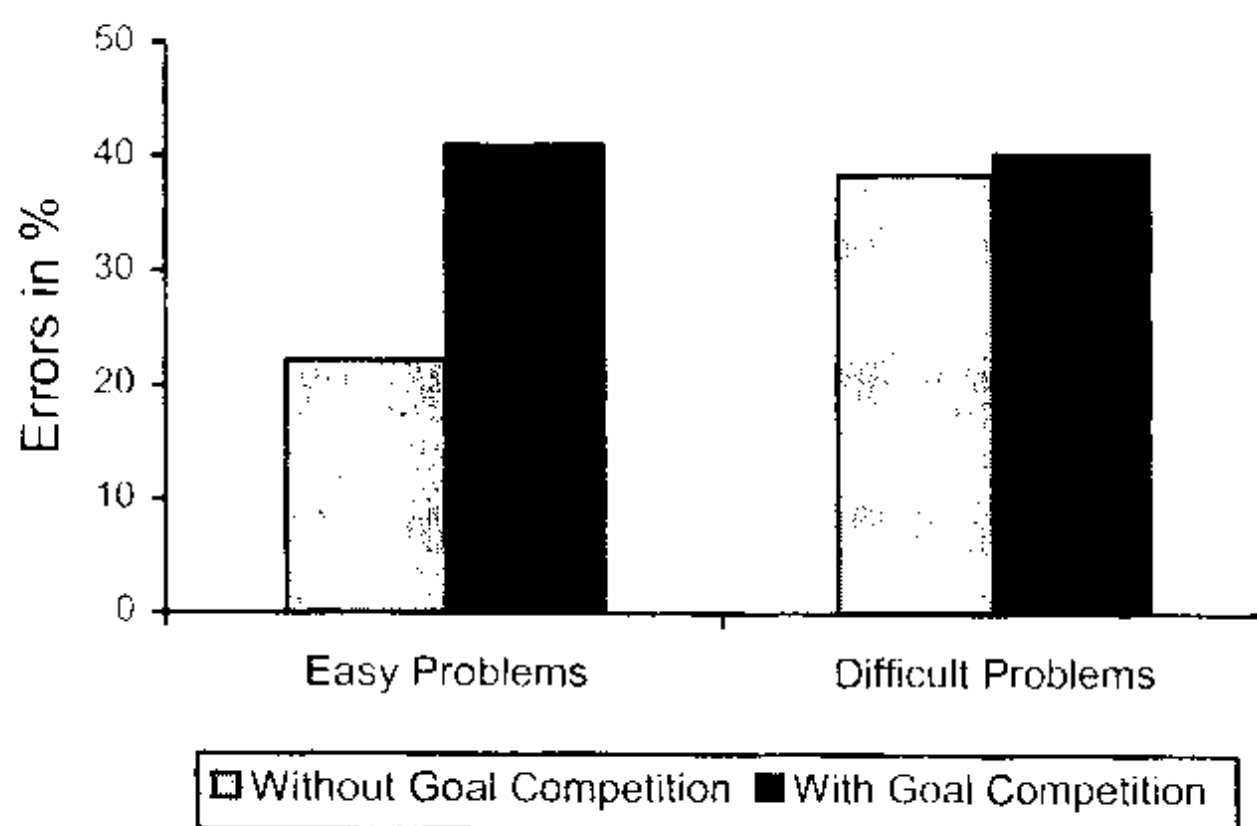


Figure 3. Error rates as a function of task difficulty and goal competition

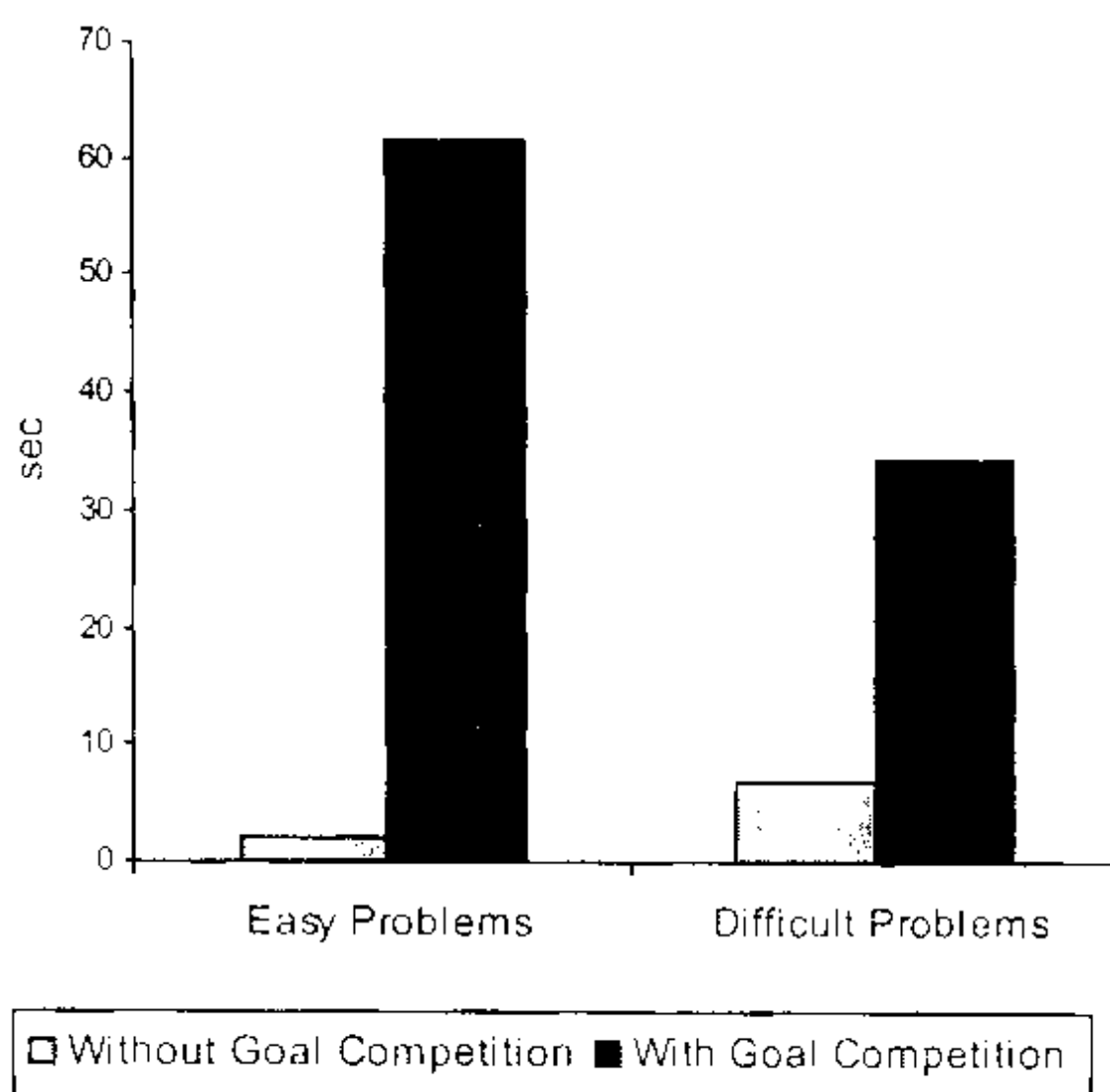


Figure 4. Time spent on irrelevant information as a function of task difficulty and goal competition

Moreover, the influence of the competing goal intention on performance depended on the difficulty of the problem-solving task: distraction effects could be traced back completely to differences in the conditions with easy test problems, whereas there were no performance impairments due to a goal competition in the conditions with difficult test problems. This pattern

of results supports the hypothesis of difficulty-related distraction effects by demonstrating stronger performance impairments due to goal competition for easy test problems than for difficult test problems.

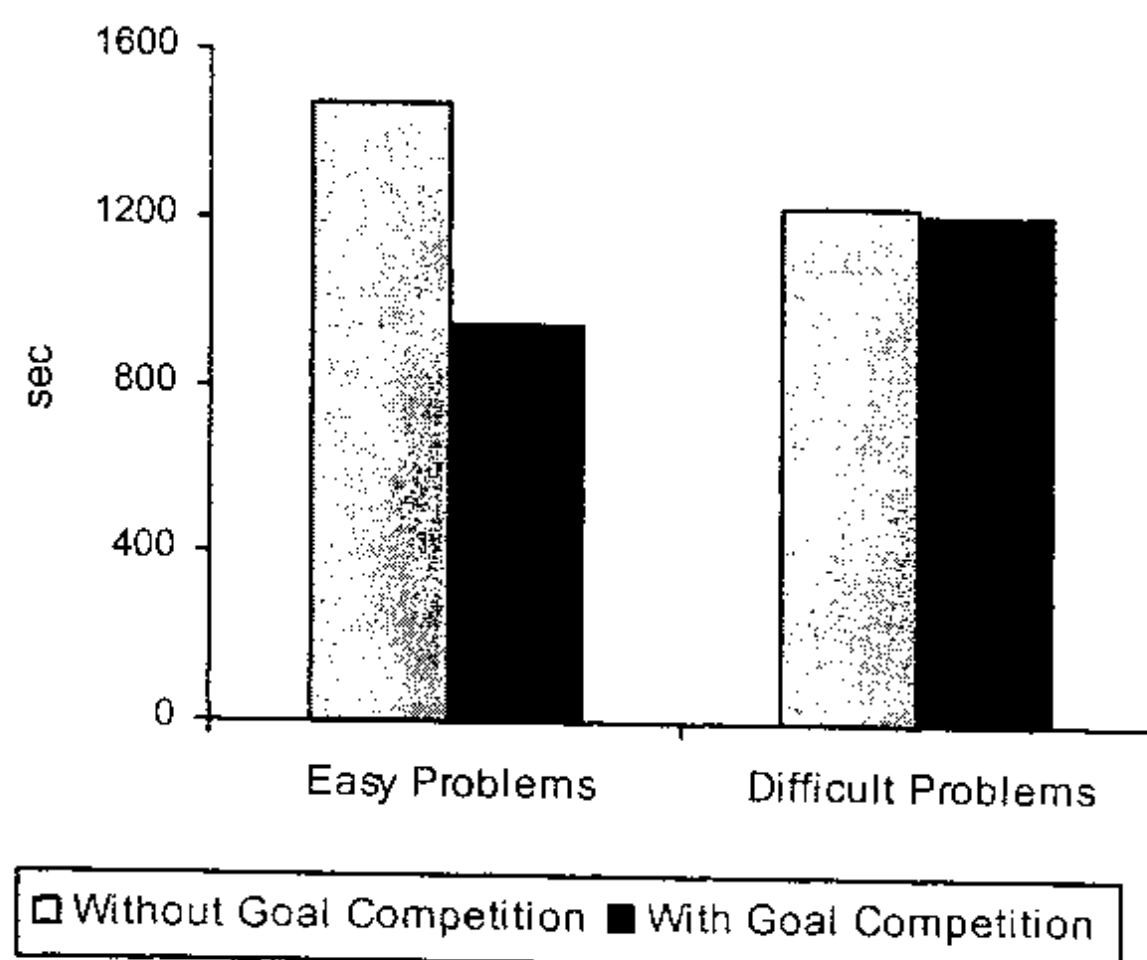


Figure 5. Time spent on relevant information as a function of task difficulty and goal competition

To test the obvious idea that these efficiency impairments may be traced back to overt activities related to the competing time spent on actively retrieving irrelevant information (Figure 4). In the groups with goal competition, the time spent on irrelevant information was significantly longer than in the groups without a competing intention. Although this was more pronounced for conditions with easy word problems than for conditions with difficult test problems, the respective interaction was not significant. Thus, task difficulty did not moderate effects of goal competition on active distraction behavior. This pattern of results raised some doubts concerning the assumption that observable distraction behavior may be responsible for performance impairments. To address this issue in more detail, we distinguished two types of participants in the condition with competing goal and easy test problems, namely participants who showed active distraction behavior and participants who never actively retrieved irrelevant information. It could be shown that even subjects who never goal intention, we compared the four experimental conditions with regard to the actively retrieved task-irrelevant information showed the same performance impairments as subjects who engaged in active distraction behavior.

In a subsequent step, we analyzed the time subjects spent on relevant information (Figure 5). There was no main effect for task difficulty, but a main

effect for goal competition, as well as an interaction. Participants who worked on easy problems under goal competition spent *less* time on relevant information pages than participants in the respective condition without goal competition. There was no comparable speed-up due to goal competition for participants working on difficult test problems.

Taken together, our data support the following conclusions: although goal competition increased the time spent on irrelevant information, this did not lead to distraction effects in terms of performance impairments or rushed learning and problem solving under high levels of task difficulty. However, for low levels of task difficulty, goal competition led to an increase in error rates, as well as to a decrease in the time spent on relevant information.

This pattern of results fits nicely into the analysis of difficulty-related distraction effects that was given from a cognitive load perspective: Especially a situation with goal competition and low task difficulty may lead to an increase of extraneous cognitive load that results from processing task-unrelated information. Extraneous load reduces working memory capacity available for performing the current task so that simpler processing strategies might be selected for task accomplishment. This *resource-adaptive strategy shift* can simultaneously explain the performance impairments and the speed-up in the condition with goal competition and low task difficulty. More detailed analyses of the log file data yielded further evidence to support this idea. For example, subjects working on easy test problems under goal competition are characterized by a cursory processing of example-solution pages. Studying these pages intensively, however, was demonstrated to be a resource-demanding strategy suited to improve performance.

This analysis also explains why we could not obtain a strong relation between performance impairments (and speed-up) and active distraction behavior. From a CLT perspective, in order to suffer from performance impairments due to goal competition, it is sufficient that task-irrelevant information becomes activated in memory and claims available working-memory resources.

Based on this empirical pattern of results, we developed a cognitive model of volitional action control that uses activation mechanisms and executive production rules to simulate effects of goal competition and task-difficulty within the ACT-R architecture.

### **Modeling volitional action control in ACT-R: Activation mechanisms and executive production rules**

In order to describe our approach of modeling volitional action control within ACT-R, we first give a short introduction to the ACT-R architecture and then we present a description of the proposed model. This comprises an overview of the model and three sections that each present information on one component of the model. Subsequently, the model will be evaluated by comparing its performance to the aforementioned pattern of empirical data.

Finally, the general suitability of using ACT-R to model volitional action control will be discussed.

*Pivotal assumptions of the ACT-R architecture (Anderson & Lebiere, 1998)*

The ACT-R architecture combines an activation-based propositional network making up the declarative long-term memory with a procedural long-term memory. Both memory systems can be described at a discrete and symbolic, as well as at a continuous and subsymbolic level.

The *declarative memory* contains knowledge about facts represented by means of atomic knowledge units (chunks). Chunks are schematic structures – consisting of slots (representing attributes) and fillers (representing values of attributes) – with each chunk belonging to a particular category of chunks (chunk-type). Chunk-types differ with regard to their slots used for the representation of attributes. There are two different kinds of relations between chunks. First, a symbolic slot-filler relation exists if one chunk (the filler-chunk) represents a value in a slot of another chunk. Second, subsymbolic associations between chunks reflect how often two chunks have been used together in the same cognitive processing step in the past.

At the subsymbolic level, an activation value is assigned to every chunk. At any point in time, all chunks with an activation value above a specified threshold constitute the contents of working memory that are available for current processing. The activation of a chunk is the sum of its base-level activation and its context activation. The base-level activation of a chunk reflects its general usefulness in the past, which decays over time (i.e., the recency and frequency of chunk utilization). The context activation results from spreading activation and indicates the specific usefulness of a chunk in the context of a current goal of information processing. Processing goals are represented by specific goal-chunks, which are organized by means of a last-in-first-out goal stack. Only the filler-chunks of the current processing goal (that is on top of the goal stack) act as activation sources in declarative memory and thus spread activation to chunks that are associated with them at the subsymbolic level (resulting in context activation). As each goal-chunk possesses the same fixed amount of source activation that is equally divided among its filler-chunks, the number of filler-chunks of a goal influences how much activation each filler-chunk spreads to associated chunks, thereby determining the availability of information units for processing. Thus, the more filler-chunks are used in order to represent a goal, the less source activation is available for each filler-chunk to be spread to associated chunks. Furthermore, the current goal constrains which production rules are eligible for execution. For these reasons, goal structures are of primary importance for the control of cognition in ACT-R.

The *procedural memory* of the ACT-R architecture contains symbolic production rules, which represent discrete steps of cognitive processing. Each production rule consists of a condition-part and an action-part. The condi-

tion-part is matched against the current goal of processing and against sufficiently activated contents of declarative memory (chunk retrieval). If there are several declarative chunks that satisfy one of the specifications in the condition-part of a production rule, the production will be instantiated with the most activated one. Consequences of applying a production rule are described in the action-part and may consist of manipulations of the goal stack, modifications of existing chunks, or generations of new chunks in declarative memory. In the event that multiple production rules are compatible with the current goal of processing, a subsymbolic process of conflict resolution takes place that is based on a cost-benefit analysis. Within this process, the production rule for which the benefit maximally exceeds the costs will be selected for execution. That is, of all conflicting productions, the one with the highest expected gain  $E$  will be executed. The expected gain  $E$  of a production rule is calculated by the formula  $E = PG - C$  with  $P$  representing the probability of goal accomplishment when applying the production rule,  $G$  representing the value of the current goal, and  $C$  representing the costs for the application of the production rule.

A specific ACT-R model for the accomplishment of a particular task can be developed by specifying declarative and procedural memory contents at the symbolic and subsymbolic level. A run of such a model is not deterministic, because several "noise" parameters allow for the simulation of a probabilistic element in behavior. A run consists of a sequence of cycles, each comprising the subprocesses matching, conflict resolution, and execution, i.e., each cycle covers the complete process from selecting a production rule to its application. In the process of matching, the goal specification in the condition-part of a production is matched against the current goal. In the process of conflict resolution, the goal-matching production rule with the highest expected gain  $E$  will be selected. Finally, this production rule will be executed after being instantiated with the most activated chunks retrieved from declarative memory that satisfy the specifications in the condition-part. Time demands for this memory retrieval depend on the number and activation of the chunks used to instantiate the production rule, as well as on the production's strength, which is determined by its frequency of application in the past. After executing a production rule, the next cycle can be initiated.

### *Overview of the model*

The overall structure of our ACT-R model is made up of three components, i.e., a component simulating the mathematical problem-solving task, a component modeling the question-answering task, and finally a component simulating volitional action control itself. As the focus of the model lies on control processes and not on task processes, a rather superficial level of modeling is used in order to simulate the problem-solving task and the question-answering task. Figure 6 provides an overview of the overall symbolic structure of the model, i.e., its processing goals (represented by

squares) and production rules (represented by italic text in brackets). The arrows represent the execution of the production rules. The top goal of the model is to participate in a hypertext-based experiment that consists of performing the mathematical problem-solving task and the question-answering task. An executive control production named "interrupt" is introduced to simulate the interaction between the two types of tasks.

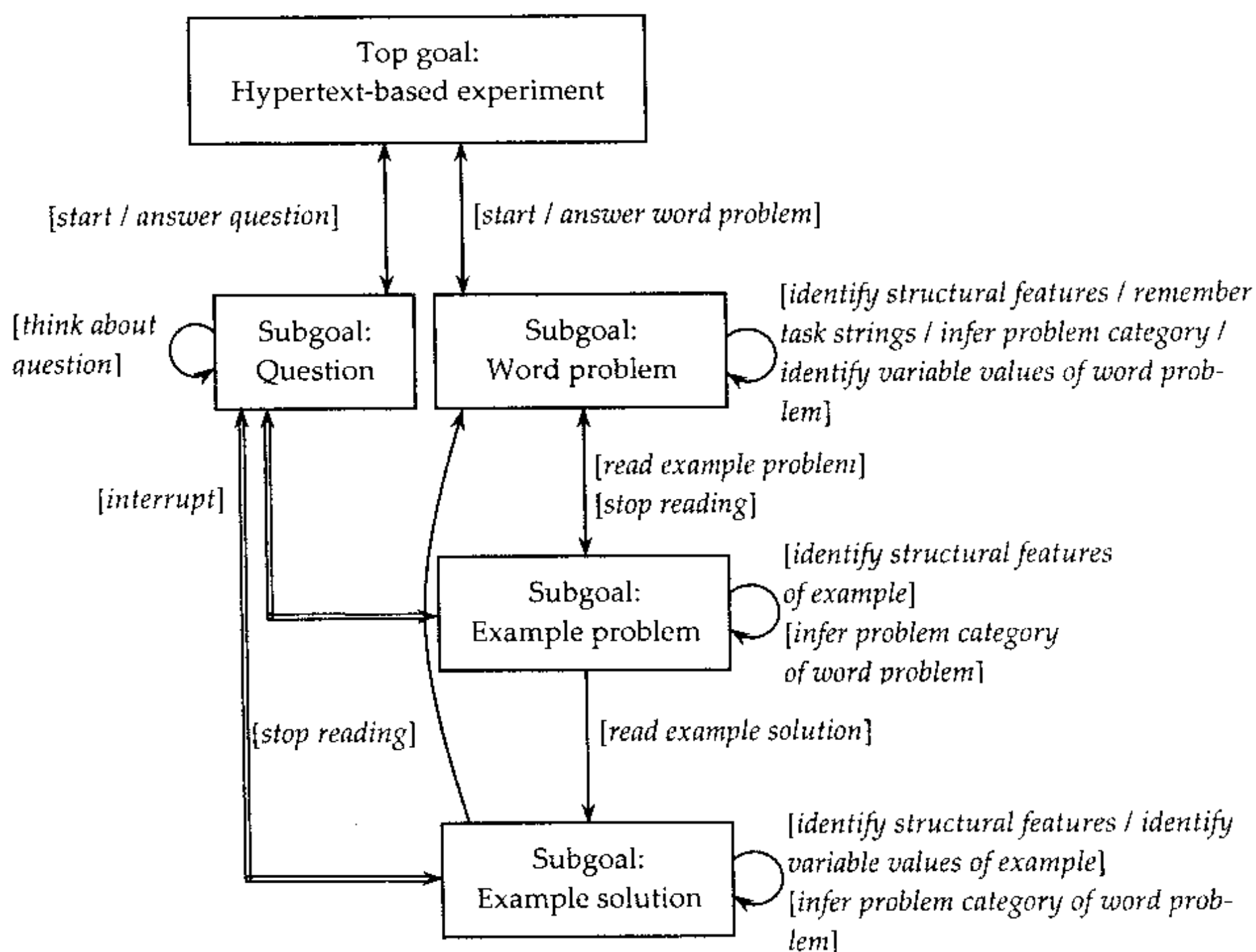


Figure 6. Overall symbolic structure of the ACT-R model

### Modeling the mathematical problem-solving task

The mathematical problem-solving task consists of three combinatoric word problems that have to be solved by identifying the appropriate problem category (defined by three structural features) and the values of two variables. In accordance with the experimental manipulation of task difficulty, the model simulates the accomplishment of easy, as well as of difficult, word problems. The model starts by executing a production rule that sets a subgoal to solve one of the three word problems [*start word problem*].

Each word problem is represented by means of a chunk of the chunk-type "math-task", whose slots allow for encoding the individual proposi-

tions contained in the problem description, as well as the problem solution. A math-solution chunk – that is a slot filler of the math-task chunk – represents details of the problem solution, i.e., the abstract structural features of the problem, its problem category, and values for the variables.

It is assumed that the structural features of easy word problems can immediately be inferred when starting with the processing of the word problem and can thus be represented directly [*identify structural features of word problem*]. However, in the case of difficult word problems, the problem interpretation in terms of identifying the problem's structural features will be more ambiguous. This may necessitate the additional representation of individual propositions entailed in the problem description [*remember task strings of word problem*]. Therefore, the representation of a difficult word problem will tend to be more complex in terms of the number of slots used for task representation than the representation of an easy word problem. As a result, a larger number of task-relevant information units needs to be activated in working memory. Therefore, the initial representation of a difficult word problem is characterized by a higher level of intrinsic cognitive load than the initial representation of an easy word problem.

Following this initial task representation, the model needs to identify the problem category and the variable values of the word problem. In order to acquire the knowledge that is necessary to infer this information, the model selects one of the example problems that are provided in the hypertext environment [*read example problem*]. It is assumed that reading an example problem results in encoding its structural features [*identify structural features of example*]. Since the problem category of each example is explicitly mentioned, a match between the structural features of an example problem and the word problem currently tackled can be used to infer the problem category of the current word problem [*infer problem category of word problem*]. Note that a prerequisite for this match is that the representation of the word problem is part of the goal of studying an example problem. Additionally, information about the solution of the example problem can be retrieved for study [*read example solution*]. Studying example solutions is a process of particular importance for task accomplishment, because it enables the verification of inferences about structural features of an example [*identify structural features of example*] and the use of these inferences to verify the problem category of the word problem to be solved [*infer problem category of word problem*]. Furthermore, example solutions may be used to infer how the appropriate variable values can be determined. This process is based on a subsymbolic representation of associations between variable values and cues in the example [*identify variable values of example*]. These processing steps assumed for example study can be executed in a more or less comprehensive way, yielding different strategies of example processing. In order to account for strategic differences in the example study, the model may skip processing steps. To illustrate this point, two different strategies will be described in the fol-

lowing section that represent two extreme values on the continuum from simple to elaborated example-processing strategies.

**Elaborated example-processing strategies.** An elaborated strategy would be to study all example problems – especially their solutions – thoroughly. This involves identifying each of the three structural features for every example problem and acquiring subsymbolic knowledge about associations between variable values and cues in the example. An elaborated strategy of example processing presupposes that the description of the example problem and aspects of the example solution are activated in working memory simultaneously. As a consequence, this strategy is characterized by a high degree of intrinsic cognitive load and a considerable number of chunk retrievals. For these reasons, the application of an elaborated processing strategy imposes high demands with regard to cognitive resources and processing time. However, as has been shown by empirical findings from worked example research (Chi, Bassok, Lewis, Reimann & Glaser, 1989; Renkl, 1997), this type of elaborated example processing can be expected to result in a good problem-solving performance.

**Simple example-processing strategies.** Simpler strategies of studying examples are characterized by omitting steps of example processing. For instance, only a subset of the worked examples provided may be retrieved, structural features of an example may only be partially inferred, cues that allow the determination of variable values may not be acquired, or descriptions of example problems and aspects of their solutions may not be activated in working memory simultaneously. In this case, only restricted knowledge resources will be available for solving the word problems, thus, their solutions will rely heavily on guessing. As a result, substantial decreases in problem-solving performance will be expected. However, since simpler strategies are characterized by a smaller number of productions to be executed, there should be a considerable speed-up in task performance. Additionally, fewer example-related details need to be activated in working memory, resulting in a lower level of intrinsic cognitive load. Thus, severe restrictions of cognitive or time resources may lead to the application of this strategy, as the implementation of a more resource-demanding strategy may be impeded.

At any time during example study, the model may stop reading and engage more directly in solving the current word problem [*stop reading*]. If, up to now, example study yielded no information with regard to the problem category of the current word problem, the model will guess one of the possible problem categories [*infer problem category of word problem*]. Subsymbolic knowledge that results from studying the example solutions is used to infer the values of the variables  $n$  and  $k$  in the word problem [*identify variable values of word problem*]. Subsequently, the model will proceed to solve the remaining word problems.

### *Modeling the question-answering task*

In the abovementioned experiment on hypertext-based learning and problem solving, subjects were instructed to solve a mathematical problem-solving task first and to perform a question-answering task later on that contained three questions. However, the performance in the latter task was not of real interest, because the question-answering task only served to induce a competing goal during the first task. Accordingly, the accomplishment of the question-answering task is modeled in a very simplified and superficial way by three production rules that simulate the initiation of question-answering activities [*start question*], thinking about a question [*think about question*], and answering it [*answer question*].

### *Modeling volitional action control*

The most important component of our ACT-R model is responsible for modeling the coordination and interference between the mathematical problem-solving task and the question-answering task, i.e., to simulate the management of multiple goals. This component is made up of three basic ideas that deal with (1) activation mechanisms for the cueing of pending goals, (2) a representation format for goals that enables the execution of task-superordinated processes, and (3) an executive production rule for task interruption and goal management.

**Cueing of pending goals.** In order to allow for adaptive volitional action control, a cognitive system must be able to flexibly respond to situational changes. However, the ACT-R architecture emphasizes the importance of goal maintenance with its conception of the goal stack according to a last-in-first-out principle. In order to counteract this potential drawback of ACT-R, Altmann and Trafton (2002) propose the removal of the goal stack from the cognitive architecture in favor of a goal representation that is based on ordinary working-memory mechanisms related to activation. In our modeling approach, we leave the goal stack intact, but appreciate the idea of using activation mechanisms for the control of multiple goals.

For instance, we assume that the cueing of pending goals is an important process for flexible action control, i.e., whenever a suitable opportunity for the implementation of a pending goal arises, this should lead to an increased activation of its representation in memory. Within our ACT-R model, this means that hyperlinks in a worked example, which are related to a pending question-answering task, may act as cues that activate the representation of the competing task in memory. This is because propositions of the example problem are slot fillers in the goal-chunk of reading an example problem and, therefore, these propositions are sources of activation that spread activation to associated chunks. This process can be easily implemented in the model by using the ACT-R mechanism of spreading activation.

**Enabling the execution of task-superordinated processes.** However, a heightened state of activation in memory is not yet sufficient for a goal in the ACT-R architecture to guide the system's behavior, because, in ACT-R, only goals that are on top of the goal stack control information processing. Thus, additional executive processes are necessary in order to ensure that activated pending goals can get access to the system's executive resources. As these processes need to be able to insert and delete task goals in the goal stack, they are implemented by means of superordinated executive production rules for scheduling processes that do the basic computations involved in performing a task. In this context, *superordinated* means that executive production rules need to be able to fire irrespective of the task that is currently pursued, i.e., the current goal. The distinction between task processes on the one hand, and superordinated executive production rules on the other, resembles the modeling of multiple-task performance in EPIC (Meyer & Kieras, 1997a; Rubinstein et al., 2001).

In order to implement this approach in ACT-R, we introduced a chunk-type *intention* as a super-type in the type hierarchy that subsumes all possible goals that may guide behavior by being the top goal of the stack. This super-type intention can be used as the goal specification in the condition-part of *executive* production rules, so that these may fire whenever a chunk of the super-type intention is the current goal of processing. In order to enable executive production rules to resolve conflicts between activated goals, they need to have access to information on the goals' current status of accomplishment. For this reason, we endowed every goal-chunk of the super-type intention with a so-called *status-slot*, whose filler-chunk indicates whether the goal's status is *current*, *pending*, or *solved*. This conception is similar to Meyer and Kieras' idea (1997a) of explicitly representing information on task progress by means of notes placed in working memory. Additionally, goal-chunks of the super-type intention are provided with slots that allow for the representation of past conflicts that the goal was involved in.

**An executive production rule for task interruption and goal management.** Finally, we introduced an executive production rule *interrupt* that detects whether there is a *pending goal* with a sufficiently high level of activation to compete with the *current goal* for execution. The interrupt-production resolves the conflict between these goals by deciding between continuing to work on the current task or switching to the competing task. This conception is similar to Anderson and Lebiere's idea of a "high-priority production rule" (1998, p. 40):

IF            the goal is to do any task  
                 and one hears "fire"  
THEN        change the goal to escape the fire

However, the interrupt-production does not automatically switch to another goal, but rather tries to achieve a balance between maintenance and switching based on activation mechanisms. That is, if there is a conflict between a

current and a pending goal, the interrupt-production selects the goal with the higher activation level for further processing (cf. Altmann & Trafton, 2002). The structure of the interrupt-production is as follows:

(p interrupt

IF the goal is an intention with status "current" and there is another intention with status "pending"

THEN change the goal to the most active of these intentions and set its status to current and the status of the other intention to pending and note in both intentions that a conflict situation has occurred)

The execution of the interrupt-production will lead to a goal switch if the activation level of the pending goal is higher than that of the current goal. In this case, the formerly "pending" goal becomes the "current" goal and vice versa, i.e., the current goal is actually replaced by a competing task. These changes in the goal stack automatically cause changes in the activation pattern in working memory, because different current goals activate different chunks in memory by spreading activation. Additionally, both goal-chunks are augmented by encoding the information that a conflict between these two goals has occurred. This information may be used in order to enable the system to resume the suspended task after the interleaved task has been completed (cf. Altmann & Trafton, 2002). However, an inevitable side effect of tracking this conflict information is that it leads to a more distributed pattern of activation and extraneous cognitive load. This results from an increased number of filler-chunks of the current goal – some of which represent information on a competing goal – due to the execution of the interrupt-production. Since the source activation of the goal-chunk is divided up between more filler-chunks, every chunk associated with these filler-chunks will get less activation than before the interrupt-production was executed. Additionally, information may become activated that is related to a competing goal, i.e., extraneous cognitive load increases.

Thus, if the execution of the interrupt-production leads to goal switching, then this will result in (1) a modification of the goal stack, (2) the activation of different chunks than before, and (3) a more distributed activation pattern. However, in the case of goal maintenance, only the latter event occurs. That is, a conflict situation will be tracked whenever the interrupt production is executed, leading to a more distributed pattern of activation and extraneous cognitive load. Thus, even if there is no change regarding the goal stack, this altered activation pattern may prevent chunks from being retrieved from memory after the execution of the interrupt-production, as their activation levels now lie below the retrieval threshold.

To sum up, we introduced three basic ideas for simulating processes of volitional action control, which consist of the situational cueing of pending goals, the enabling of task-superordinated processes, and an executive production rule for task interruption and goal management. These ideas use

assumptions inherent to the ACT-R architecture and, furthermore, they fit nicely into existing approaches to action control and goal management (e.g., Altmann & Trafton, 2002; Anderson & Lebiere, 1998; Meyer & Kieras, 1997a; Rubinstein et al., 2001). In the next paragraphs, we will illustrate how the ideas work together to model distraction effects due to goal competition in a high-level learning and problem-solving task.

### *Modeling distraction effects due to goal competition*

A run of our ACT-R model starts with reading a worked example in order to acquire knowledge that helps to solve one of the three word problems as the current goal. At this point in time, the current goal may not only contain propositions encoded from the example problem, but it also entails a representation of the word problem the system currently attempts to solve.

In the conditions with goal competition, an example problem page contains mathematical information, as well as hyperlinks that lead to additional information about attractiveness and mate choice. These hyperlinks are encoded during reading, become part of the current goal, and thus, spread activation to associated chunks in declarative memory. If the associative strength between an encoded hyperlink and a question-answering task in declarative memory is sufficiently high, this may result in a large amount of context activation received by this question-answering task. Thus, the question-answering task may be cued by reading hyperlinks in worked examples, whereby cueing depends on the difficulty of the test problems.

In the case of difficult test problems, the current goal of example reading contains a large number of slots needed for representing details of the difficult test problem (i.e., high intrinsic cognitive load). Therefore, spreading activation will be rather weak when reading examples in order to solve difficult test problems. In the case of easy word problems, however, there are only a few filler-chunks needed for goal representation (i.e., low intrinsic cognitive load) and therefore, each of them may spread a high amount of activation to associated chunks. As a result, the probability that a pending question-answering task becomes activated above threshold by associated hyperlinks is much higher for easy test problems than for difficult ones.

If the activation level of the pending goal exceeds the retrieval threshold, the interrupt-production may fire in order to decide which of the two competing goals should be further pursued. This decision will be made according to the relative activation of the competing goals, with the more active one winning the competition. Independently of whether the execution of the interrupt-production results in goal switching or goal maintenance, the extraneous load imposed on the cognitive system will increase due to the representation of the goal conflict. This increase in extraneous cognitive load reduces the capacity of each of the goal's filler-chunks for activating associated chunks. Thus, conflict monitoring may prevent the system from deploying elaborated example-processing strategies, which presuppose many si-

multaneously activated chunks in working memory. Therefore, simpler, but error-prone processing strategies have to be applied, explaining higher error rates in the problem-solving task, as well as the decrease in time demands. Figure 7 provides a schematic flowchart illustrating the emergence of distraction effects in the condition with goal competition and low task difficulty.

Following this goal conflict, the model continues working on the current goal, i.e., either the mathematical word problem or the question-answering task. The interrupt-production may fire again whenever there is a pending goal that is sufficiently activated.

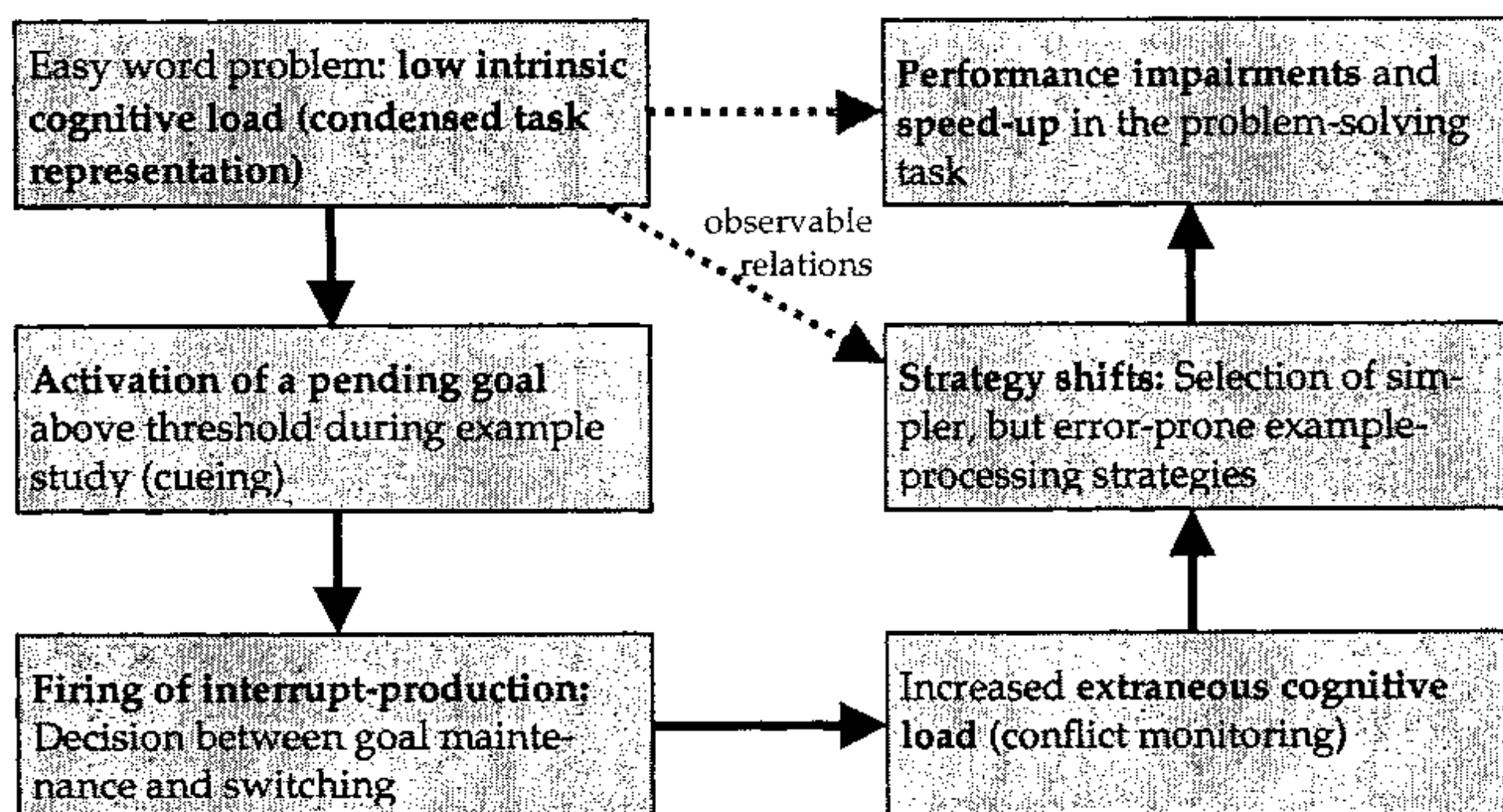


Figure 7. Schematic flowchart illustrating the emergence of distraction effects in the condition with goal competition and low task difficulty

### *Comparing data and model*

Our ACT-R model was intended to account for several findings obtained in the experiment on distraction effects in hypertext-based learning and problem solving. The conditions under which distraction effects occurred can be summarized as follows:

- First, distraction effects occurred when task-irrelevant information that was related to an explicit pending goal was provided.
- Second, the occurrence of distraction effects was moderated by task difficulty as these effects could be observed only in the case of low task difficulty.
- Third, active distraction behavior (i.e., active retrieval of task-irrelevant information) was not a necessary prerequisite for performance impairments due to goal competition.

Distraction effects due to goal competition comprised:

- Performance impairments in terms of higher error rates in the problem-solving task
- Reduction of learning and problem-solving time (speed-up)
- Resource-adaptive strategy shifts towards simpler, but at the same time, more error-prone processing strategies (e.g., less time spent on processing example solutions)

In the following section, the data from 40 runs of the ACT-R model will be evaluated against the empirical pattern of results. For the model, the same materials were used – represented as declarative memory chunks – as in the experiment. The simulations of the ACT-R model were based on the experimental 2x2-design with the independent variables *task difficulty* (easy vs. difficult) and *goal competition* (with vs. without competing goal). The simulation data were generated by executing 10 runs for each of the four conditions. For every run, we registered the error rates for the mathematical word problems (problem-solving errors in %), the total time demands per run (in seconds), as well as the total number of executed productions per run (number of cycles). In order to generate variance in the simulation data, we increased the noise parameters *activation noise*, *permanent activation noise*, and *expected-gain noise* to 0.1/0.1/1 (default values: 0). Furthermore, the retrieval threshold was lowered to -1 (default value: 0) in order to strengthen the relevance of context activation for chunk retrieval. Subsymbolic learning mechanisms were disabled. The results of the simulations are presented in Table 1.

Table 1. Simulation data: Problem-solving errors, time demands, number of cycles, and time per cycle (standard deviations) as a function of task difficulty and goal competition

	Easy problems		Difficult problems	
	Without goal competition	With goal competition	Without goal competition	With goal competition
Problem-solving errors [%]	34.44 (9.73)	55.56 (19.07)	53.33 (11.48)	56.11 (14.69)
Total time demands [sec]	1212 (195)	882 (932)	1015 (46)	1184 (78)
Total number of cycles	190 (23)	253 (191)	176 (12)	174 (16)
Time per cycle [sec]	6.36 (0.44)	3.19 (0.50)	5.77 (0.20)	6.83 (0.34)

This pattern of simulation data very much resembles the empirical results with regard to problem-solving performance and time demands.

**Problem-solving performance.** An ANOVA (*task difficulty*  $\times$  *goal competition*) for problem-solving errors showed a main effect for task difficulty ( $F(1,36) = 4.69$ ;  $MS_e = 201.39$ ;  $p < .05$ ), a main effect for goal competition ( $F(1,36) = 7.08$ ;  $MS_e = 201.39$ ;  $p < .05$ ), and a significant interaction ( $F(1,36) = 4.17$ ;  $MS_e = 201.39$ ;  $p < .05$ ). Specific contrasts indicated that the effect of goal competition could be traced back completely to differences in the conditions with easy problems ( $t(18) = 3.12$ ;  $p < .01$ , two-tailed), whereas there were no performance impairments due to a competing goal in the conditions with difficult test problems ( $t(18) = .47$ ;  $p > .60$ , two-tailed). Thus, the ACT-R model could simulate the empirical results for performance and support the assumption of difficulty-related distraction effects very well, i.e., performance impairments due to goal competition were stronger for easy problems than for difficult ones.

**Time demands.** Regarding the time needed for completing a run, we found the same speed-up pattern that could be observed in the empirical data, i.e., a reduction of learning and problem-solving time in the condition with easy test problems and goal competition. This speed-up was also true for the simulation data, as can be seen in the total time demands for a run of the model. However, the time measures used in the experiment and in the simulation were not directly comparable: in the experiment, we differentiated between time spent on relevant and irrelevant information pages, whereas in the simulation, we merely obtained the overall time demands that equal the sum of both measures. Since there were two counteracting tendencies in the condition with easy test problems and goal competition, namely the speed-up for processing relevant information, as well as greater time demands for processing task-irrelevant information, only a slight overall speed-up is to be expected. This can explain why the interaction between task difficulty and goal competition was only close to statistical significance ( $F(1,36) = 2.72$ ;  $MS_e = 228905.38$ ;  $p = .11$ ; main effects: both  $F$ s  $< 1$ ).

**Processing strategies.** The empirically observed performance impairments and the speed-up due to goal competition were traced back to resource-adaptive strategy shifts. This interpretation is in line with the simulation data, which showed a different pattern for the condition with easy test problems and goal competition as compared to all other conditions. For easy problems with goal competition, a more cursory processing takes place, which is indicated by less time demands and a larger number of processing cycles at the same time. This implies the execution of rather simple production rules with only a few specifications in the condition-part. A comparison of the mean time needed to complete a processing cycle in the condition with easy test problems and goal competition with the other experimental conditions by means of specific contrasts revealed that a large number of simple production rules were deployed in this condition (all  $t$ s  $> 15.00$ , all  $p$ s  $< .001$ , two-tailed). In our model, there are two types of production rules that are sufficiently undemanding to account for this data, namely the interrupt-

production and production rules that implement simple example-processing strategies.

To summarize, the empirically obtained effects of goal competition and task difficulty on processing strategies and performance could be simulated meticulously by our ACT-R model.

#### 4. Summary and conclusions

In this paper, we presented an ACT-R model that simulates effects of goal competition and task difficulty on processing strategies and performance in a high-level learning and problem-solving task. This model is able to explain a couple of findings that were obtained in a hypertext experiment where subjects had to perform the same tasks that were used for modeling:

First, the model explains how task-irrelevant information may cue pending goals and how this goal cueing may result in goal competition. This explanation is based on activation mechanisms inherent to the ACT-R architecture, as well as on the assumption of a task-superordinated executive production rule that handles task interruption and goal management.

Second, we could explain why distraction effects depend on the current task difficulty, i.e., why goal competition due to the cueing of pending goals is more likely to occur for easy tasks than for difficult tasks. This moderating effect of task difficulty is based on the degree of *intrinsic cognitive load* that is imposed onto the cognitive system by the representation of easy and difficult tasks. In the case of difficult tasks, the task representation is complex and thus results in high intrinsic cognitive load. Therefore, spreading activation to associated chunks will be rather weak. In the case of easy tasks, however, the intrinsic cognitive load is low, because the task representation is rather condensed. Therefore, each filler-chunk of the goal-chunk may spread a high amount of activation to associated chunks. As a result, the probability that a pending goal becomes activated above the retrieval threshold and interferes with the performance of the current task is much higher for easy test problems than for difficult ones.

Third, the model explains why effects of distraction occur independently of whether subjects actually retrieve task-irrelevant information related to a competing goal. This explanation claims that goal competition results in the firing of an executive control production that decides between goal switching and goal maintenance. However, this interrupt-production will initiate a monitoring of the conflict regardless of the result, leading to additional *extraneous cognitive load* that is responsible for effects of distraction.

Fourth, the model reflects different effects of distraction that have been observed empirically, namely an increase in error rates for the current task, a speed-up, and strategy shifts towards less sophisticated, but at the same time, more error-prone processing strategies. In the simulation, these effects

are traced back to the increased level of extraneous cognitive load due to goal competition and a resulting resource-adaptive strategy-shift.

The issue of goal maintenance and goal switching in multiple-task performance – in adaptation to situational opportunities, task difficulties, and other relevant factors – that we studied empirically and computationally in this paper is one of the central problems of *volitional action control*. Accordingly, our findings corroborate hypotheses that have been derived from the volitional framework PART, which analyzes control demands of everyday actions on an abstract functional level. To elaborate on how the volitional mechanisms and variables postulated by PART may be implemented by cognitive structures that eventually have to put these processes of volitional action control into operation, we explored two approaches to connect the volitional framework of PART with cognitive concepts: The first approach was to use concepts from *Cognitive Load Theory* to reinterpret the competition between current and pending goals in more cognitive terms. The other approach was to construct *intertheoretical links between PART and the ACT architecture* within the structuralist view of theories. Both approaches proved helpful to elaborate on the cognitive foundations of volitional action control in a systematic and comprehensive way and were useful to guide our cognitive modeling efforts. The resulting cognitive model that combines volitional and cognitive concepts demonstrates the usefulness of the proposed *top-down research strategy* that starts with a comprehensive high-level framework – in order to identify and classify important issues of action control from a unified perspective – and proceeds by filling in the cognitive details of different control processes step by step – in order to refine the general framework.

The fundamental processing mechanisms used in our cognitive model – namely activation mechanisms and executive control productions – are very much in line with current experimental and computational approaches to analyzing elementary executive control processes in the domain of simple choice reaction time tasks. Cognitive models of successive or simultaneous multiple-task performance in this domain (e.g., *task-switching procedure*, *psychological refractory period procedure*) unisonously rely on these processing mechanisms irrespective of the cognitive architecture they are based on (e.g., EPIC, ACT-R). On the one hand, this consistency provides further support for our approach of modeling volitional action control. On the other hand, our model demonstrates that the computational approaches that have been useful for the analysis of elementary processes of action control can likewise be applied successfully to the explanation of more complex volitional processes.

Thus, we consider our modeling approach to be a fruitful bridging of the conceptual and explanatory gap that exists between volitional control demands in real-world, with multiple-task performance on the one hand and experimental task-switching and PRP effects on the millisecond scale on the

other. Our model allows for scaling up findings on elementary processes, as well as for providing a cognitive foundation for volitional frameworks that analyze control demands of everyday multiple-task performance on an abstract functional level – without elaborating how these control demands may be met by cognitive mechanisms.

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