Volitional Action Control in Multiple-Task Performance: Modeling Effects of Goal Competition and Task Difficulty in ACT-R

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Abstract

In this paper we present a cognitive-modeling analysis of processes of volitional action control in multiple-task performance. We simulated experimentally obtained effects of goal competition and task difficulty on processing strategies and performance in a high-level learning and problem-solving task within the ACT-R architecture. Beyond the model's capacity for explaining the empirical pattern of results, the fundamental processing mechanisms used for modeling, i.e., activation mechanisms and executive control productions are in line with current explanations of elementary executive control processes. Thus, we consider our modeling approach to be a solution to fill the gap between volitional control demands in real-world multiple-task performance and experimental findings on elementary executive functions.

Elementary Executive Control Processes

In recent years, research on action control in multiple-task situations in the fields of experimental cognitive psychology and cognitive modeling has yielded promising insights (see Monsell & Driver, 2000, for an overview). With regard to modeling, mainly two approaches were proposed for analyzing the management of component tasks in multiple-task performance. First, *activation mechanisms* have been proven useful to represent aspects of task coordination and task interference. Second, *executive control productions* have successfully modeled processes that act on task-related processes by enabling, preventing, and directing them. There are two ways to handle component tasks in a multiple-task situation, namely either *simultaneously* or *successively*.

Simultaneous Task Procedures

In simultaneous processing, people are required to perform two different tasks at the same time as in the psychological refractory period (PRP) procedure where two choice reaction time tasks have to be performed with a temporal overlap. If this overlap is short enough performance impairments on the second but not on the first task will result. However, the total time required to complete both tasks is often less than the sum of times for performing both tasks separately.

Meyer and Kieras (1997) simulated these findings in an EPIC model by introducing *executive production rules* that schedule and control a set of task-specific rules by monitoring task progress and by inserting and deleting task goals as well as strategy notes in working memory.

Successive Task Procedures

Successive processing requires the ability to alternate between different tasks and is often studied in the *task-switching paradigm* where subjects either repeatedly have to perform the same task or to alternate between different tasks. Typically, alternating task sequences result in temporal switch costs in terms of a prolonged response time compared to task repetition.

In their ACT-R model, Altmann and Gray (2000) simulated switch costs mainly as a result of proactive interference from previous tasks that may impede performance on a current task. The authors proposed *active inhibition* and *automatic decay* of memory elements as mechanisms that in combination may counteract proactive interference. According to this view, a memory element can be inhibited by an encoding process that increases the activation of a competing element. Additionally, the activation of an unused memory element decreases over time because of automatic decay.

Rubinstein, Meyer, and Evans (2001) proposed an EPIC model of task switching with two complementary sets of production rules. *Task processes* are used for performing the component tasks involved in multiple-task performance. *Executive control processes* coordinate the execution of various task and subtask procedures.

Because activation mechanisms as well as executive control productions have been shown to influence task switching, Sohn and Anderson (2001) combined both approaches in their ACT-R model. An activation-based *task repetition* mechanism increases the activation of a task representation. An executive control process for *task preparation* reconfigures the cognitive system in accordance with an upcoming task.

The Issue of Scaling Up

The current research as it is reflected in the above mentioned cognitive models yields promising results with regard to the study of multiple-task performance. However, these results may be confined to the microscopic world of simple choice reaction time tasks. For this reason, it remains unclear whether theoretical constructs and computational mechanisms that have been useful in thinking about elementary control processes might be applicable to everyday multiple-task behavior. First, real-world tasks may be better analyzed on a coarser temporal grain size because their time demands are not comparable to microscopic tasks. Second, further executive functions may be relevant for the coordination of more complex tasks that need to be integrated into a comprehensive theoretical framework. Third, energetic, dynamic, or motivational aspects of action control may be much more relevant.

Volitional Action Control

In the remainder of this paper, it will be examined whether the mechanisms that have been used to analyze elementary processes of action control are suitable to explain more complex control processes. To do so, we first introduce a comprehensive framework of volitional action control that allows deriving empirical hypotheses on effects of goal competition and task difficulty in multiple-task situations. Second, we outline how this framework can be connected with cognitive concepts relevant for the analysis of executive functions. Third, we sketch an experimental study that was conducted to test the proposed hypotheses (cf. Gerjets, Scheiter, & Heise, 2002). Fourth, we present an ACT-R model that simulates our findings on complex control processes by using the above mentioned computational mechanisms.

A Framework of Volitional Action Control

In the following, we use the term "volitional action control" to refer to abilities that are traditionally ascribed to a hypothetical "will power". For instance, will power comes into play when we need to maintain goals over time and in the face of competing goals. As a comprehensive framework for the analysis of volitional action control we use a condensed and precise version of the rubicon theory of action phases (Heckhausen, 1991) called PART (Pivotal Assumptions of the Rubicon Theory; Heise, Gerjets, & Westermann, 1997).

PART's broad framework integrates general cognitive, motivational, and volitional principles of goal-directed action. The framework is guided by an analysis of control demands at the level of everyday actions and deals with issues of goal setting and implementation on a rather abstract functional level and thus without elaborating how these control demands may be met by cognitive mechanisms of information processing.

The theory describes actions from a time-sequential perspective as an idealized sequence of four phases (Figure 1). In the *predecisional phase*, the goal alternative with the highest expected value will be chosen as the current goal to pursue. In the *preexecutive phase* goal-related activities are planned that will be executed when a suitable opportunity occurs. In the *executive phase*, the focus lies on regulating effort investment and persistence in goal accomplishment, both of which depend on a variable called goal strength and determine performance. After goal accomplishment or disengagement in the case of failure the *postexecutive phase* starts in which the attained outcome is evaluated.

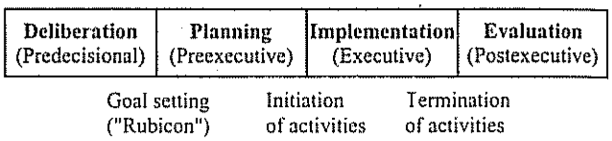

Figure 1: Action phases in PART

In multiple-task situations, conflicts between different actions may occur. In our work we focus on conflicts between a *current goal* (i.e., a Task 1 in its executive phase) and a *pending goal* (i.e., a Task 2 in its preexecutive phase). When situational opportunities for implementing a pending goal arise, its goal strength may be increased leading to a competition between this goal and the current goal.

The theory allows for deriving several empirically testable hypotheses for this situation from which we chose the following two for experimental investigation.

- *Distraction due to competing goals.* The performance of a currently executed Task 1 will be impaired if a suitable opportunity for the implementation of activities related to a pending Task 2 occurs. This prediction results from the assumption that an opportunity to implement Task 2 increases its goal strength. Impairments of Task 1 will be reflected in error rates or reaction times. This is expected in the case that Task 1 is maintained as well as in the case that it is suspended in favor of the pending Task 2, i.e., in the case of goal switching that takes place only if the goal strength of Task 2 exceeds the one of Task 1.
- *Difficulty-related volitional protection.* Performance impairments due to goal competition should be more severe for a low than for a high level of task difficulty of a currently executed Task 1. This prediction results from the assumption that an increasing level of task difficulty for Task 1 leads to an increase of its goal strength. This influences the balance between the goal strengths of Task 1 and Task 2 in favor of Task 1 and thus decreases the distracting effect of the pending Task 2.

Cognitive Foundations of PART

In order to restate these assumptions on conflicts between a current and a pending goal in more cognitive terms, we use concepts from *Cognitive Load Theory* (Sweller, van Merrienboer, & Paas, 1998). This theory distinguishes between *mental effort* as the amount of cognitive capacity that is allocated to accommodate task demands and *cognitive load* that is imposed by these task demands on the cognitive system. Cognitive load is caused by processing task-related information (*intrinsic* and *germane workload*) as well as by processing task-unrelated information (*extraneous workload*). However, only the latter one is responsible for performance impairments because it reduces working memory capacity available for performing a current task. It can be hypothesized that an opportunity for the implementation of a pending goal activates information related to that goal in memory and thus, increases extraneous workload for the current goal. As a consequence, simpler processing strategies might be selected to accomplish the current goal which may be less resource demanding but at the same time less effective (Schunn & Reder, 2001). These assumptions may allow for a more cognitive explanation of our first hypothesis on *distraction due to competing goals*.

Our second hypothesis on *difficulty-related volitional protection* can also be related to Cognitive Load Theory by assuming a *first-come-first-serve principle of working memory allocation* (cf. Gerjets & Scheiter, in press). A current goal with a *low level of difficulty* may be accompanied with low levels of intrinsic and germane cognitive load and thus leaves working memory resources that can be claimed by either extraneous or germane cognitive load. Without goal competition these resources may be used to implement rather sophisticated processing strategies to accomplish the current goal. Conversely, goal competition in multiple-task situations may impose extraneous cognitive load that prevents the utilization of sophisticated strategies. However, working on a current goal with a *high level of difficulty* may be characterized by high levels of intrinsic and germane cognitive load and thus, may not leave enough working memory resources available for being distracted (i.e., for extraneous cognitive load).

Empirical Findings on Conflicts between a Current and a Pending Goal

We tested our hypotheses in a series of experiments with a complex hypertext-based learning and problem-solving task (see Gerjets et al., 2002, for details).

Materials and procedure The subjects' main task (the current goal) was to solve three probability word problems by identifying the correct problem category and two correct variable values. Subjects were instructed to solve the problems as fast and as correctly as possible using information provided in a hypertext environment which they could browse freely. Six problem categories from probability theory were explained and illustrated by worked-out examples with interesting cover stories related to attractiveness and mate choice. Each example was presented on two pages, one containing the *example problem* and one containing a step-by-step *example solution* that explicitly mentioned three structural features defining the problem categories. All information was available during the whole experiment.

Design and dependent measures As independent variables two different levels of difficulty of the word problems (*easy vs. difficult problems*) and two levels of goal competition (*with vs. without goal competition*) were introduced. Both variables of the resulting 2x2-design were varied between subjects (N = 68). In accordance with preliminary studies we manipulated the level of task difficulty by using larger numbers for the difficult problems and by stating them in a less familiar way than the easy problems. We assumed that this manipulation would affect the intrinsic cognitive load imposed onto the cognitive system when representing the problem. This is because the problem situation in difficult test problems is harder to understand and thus harder to represent than in easy test problems for which the important structural features can be extracted more easily. For difficult test problems the problem interpretation, i.e., identifying structural features is more ambiguous so that it may be necessary to additionally represent individual propositions of the problem description. Therefore, the representations of difficult word problems will tend to be more complex than those of the easy word problems.

In the *conditions with goal competition* we introduced a pending goal 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 consisted of answering three questions about attractiveness and mate choice that were presented briefly at the beginning of the experiment. Subjects were instructed to work on the problem-solving task first and to postpone thinking about the question-answering task until they finished the three word problems. As suitable opportunities to execute activities related to the pending goal we included information about attractiveness and mate choice in the hypertext environment. To make this information available during the first task, the examples illustrating the problem categories contained hyperlinks to access this information. In the *conditions without goal competition* no competing goal was induced. Subjects were only instructed to work on the problem-solving task.

As dependent variables, we obtained the percentage of errors for the three word problems (performance measure) as well as several time and frequency parameters (process measures) that were determined by means of log file analyses. In particular, the total amount of time spent on relevant information pages was computed.

Results and discussion Overall, the average error rate in the problem-solving task was 35.41 %. Comparing

the conditions with and without goal competition yielded a significant main effect of goal competition on error rates. As expected in our first hypothesis, subjects with competing goal showed worse performance in the problem-solving task than subjects without competing goal This was true regardless of whether the subjects with competing goal displayed active distraction behavior, i.e., retrieved irrelevant information pages in the hypertext environment, or not.
Additionally, a main effect of task difficulty demonstrated that the manipulation of task difficulty was successful. In accordance with our second hypothesis on difficulty-related distraction effects, the influence of the competing goal 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 problems whereas there where no performance impairments due to goal competition in the conditions with difficult problems.

In the next step we analyzed time spent on relevant information. The average time across all conditions was 1212 seconds There was no main effect for task difficulty, but a main effect for goal competition as well as an interaction. Subjects who worked on easy problems under goal competition spent less time on relevant information pages than subjects in the respective condition without goal competition. There was no comparable speed-up due to goal competition for subjects working on difficult problems.

Taken together, our data showed no distraction effects in terms of performance impairments or a speed-up with regard to the studying of relevant information under high levels of task difficulty. However, for easy problems goal competition led to an increase in error rates as well as to a decrease in time investment This pattern of results fits nicely into the refinements of our hypotheses based on the Cognitive Load Theory. The processing of task-unrelated information in the case of easy problems and goal competition may have increased extraneous cognitive load, and thus may have led to the selection of simpler processing strategies This *resource-adaptive strategy shift* would explain the performance impairments and the speed-up in the condition with easy problems and competing goal. Further evidence for this idea resulted from more detailed analyses of log file data which showed that subjects in this condition are characterized by a cursory processing especially of example-solution pages. Studying these pages intensively, however, was identified as a resource-demanding strategy suited to improve performance

We further examined this empirical pattern of results in an ACT-R model of volitional action control that uses the elementary control processes introduced at the beginning of this paper to simulate high-level effects of goal competition and task difficulty.

Modeling Volitional Action Control in ACT-R

Our ACT-R model was developed to cope with the same materials and tasks as subjects in the experiment. The model's overall structure is made up of three components that simulate either the problem-solving task or the question-answering task or model volitional action control itself (Figure 2).

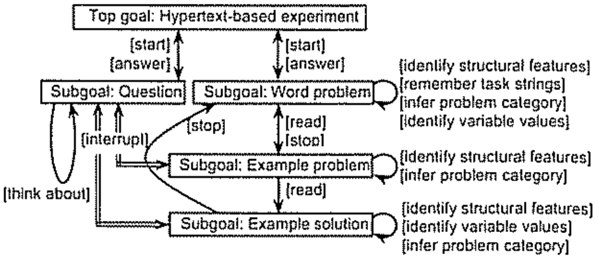

Figure 2: Symbolic structure of the ACT-R model

The three word problems of the *problem-solving task* are solved one after another by identifying the problem category and the values of two variables The processing of a problem starts with an initial problem representation. This representation is rather condensed for a low level of task difficulty, but more ambiguous and complex in the case of high task difficulty in order to account for the fact that difficult problems are harder to understand. As a result, the initial representation of a difficult problem is characterized by a higher level of intrinsic cognitive load (i.e., increased number of chunks simultaneously activated in working memory) than the initial representation of an easy problem.

Information on identifying problem categories and variable values in probability theory that is needed in order to solve a problem can be acquired by studying example problems and their solutions. Examples can be studied more or less comprehensively depending on the example-processing strategy deployed. When using the *sophisticated strategy* implemented in our model all example problems and their worked-out solutions are studied thoroughly. This is realized by executing complex production rules that rely on the simultaneous activation of descriptions of example problems and their solutions in working memory. Thus, applying a sophisticated strategy results in a high degree of intrinsic cognitive load which in turn imposes high demands with regard to cognitive resources and processing time. On the other hand, the *simple strategy* in our model omits steps of example processing, e.g., only example problems are studied but not their solutions. This strategy is simulated by executing rather simple production rules that may even fire when only descriptions of example problems are activated in working memory, but not their solutions. As a result of applying a simple strategy, not all relevant information will be acquired so that performance impairments are to be expected when solving the word problems. However, when using a simple strategy there will also be a considerable speed-up in task performance and a lower level of intrinsic cognitive load. Thus, severe restrictions of cognitive resources or time that impede the implementation of more resource-demanding strategies will lead to the application of a simple strategy in our model.

The accomplishment of the *question-answering task* is simulated in a very simplified and superficial way because it serves only for inducing a competing goal.

The management of multiple goals is simulated by a model component that is responsible for *volitional action control*. On basis of the above mentioned theoretical considerations and empirical findings, we assume that processes that are illustrated in Figure 3 produce the empirically observed distraction effects (i.e., performance impairments and speed-up in problem solving as well as strategy shifts to simple strategies when working on easy problems under goal competition).

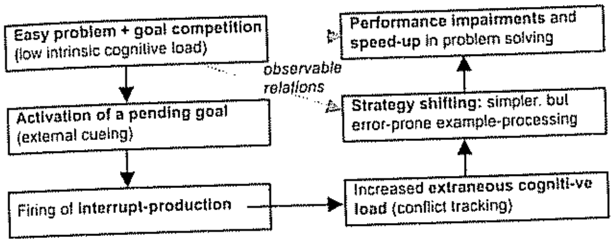

Figure 3: Emergence of distraction effects

We simulated these processes by relying on three ideas: (1) the situational cueing of pending goals, (2) a specific task-representational format for goals that enables task-superordinated processes, and (3) an executive production rule for task interruption and goal management.

(1) When working on easy problems intrinsic cognitive load is low and thus working memory capacity is available that allows for additional processing. This may lead to the encoding of hyperlinks within the examples that are related to a pending goal. By using ACT-R's capability for spreading activation, these hyperlinks serve as external cues that activate the pending goal's representation (cf. Altmann & Trafton, 2002). (2) However, in order to allow this pending goal to guide behavior additional task-superordinated executive processes are necessary that are able to fire irrespectively of the task that is currently pursued. We implemented this prerequisite in ACT-R by introducing a chunk-type 'intention' as a super-type that subsumes all possible goals that may guide behavior. The chunk-type 'intention' contains slots to track the implementation status (e.g., current, pending) of goals. Executive processes have access to that information and can use it when resolving goal conflicts (cf. Meyer & Kieras, 1997). Additional history-slots are used to track past conflicts that the goal was involved in. (3) Finally, we introduced an interrupt-production that implements task-superordinated executive processes of resolving goal conflicts. The interrupt production may fire whenever multiple chunks of the chunk-type 'intention' are activated. If a pending goal becomes activated by situational cueing while a current goal is pursued the interrupt-production selects the goal with the highest activation value for further processing (cf. Altmann & Trafton, 2002). This approach simulates the goal selection process in PART that is guided by the competing goals' strengths. Regardless whether there is a goal switch or not, the conflict situation between the two goals will be stored in the goals' history slots. As a result the extraneous cognitive load increases and leads to a more distributed pattern of activation so that chunks from declarative memory may be harder to retrieve because of low activation levels.

Comparing Data and Model

The model's simulations were based on the same 2x2-design that was used in the experiment with the independent variables *task difficulty* (easy vs. difficult problems) and *goal competition* (with vs. without goal competition). We added some activation and expected-gain noise to the system and executed 10 runs for each condition. Dependent measures were error rates for the word problems, total time demands for completing a run as well as the number of executed productions per run.

The ACT-R model was able to capture the empirically obtained pattern of results very well. With regard to the simulated *problem-solving errors* (Figure 4), an ANOVA (*task difficulty* x *goal competition*) 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 ($F(1,36) = 4.17$; $MS_e = 201.39$; $p < .05$). The effect of goal competition could be traced back completely to differences in the conditions with easy test 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 finding of difficulty-related distraction effects could be simulated.

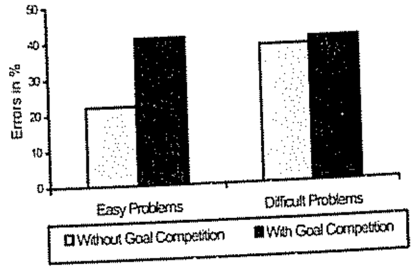

Figure 4: Simulated error rates as a function of task difficulty and goal competition

Regarding the *time needed for completing a run* (Figure 5) we found the same pattern as in the empirical data, i.e., a speed-up when solving easy problems under goal competition. However, time data from experiment and simulation were not directly comparable because the simulation runs comprised not only processing of task-relevant bus also of task-irrelevant information.

Most interestingly, the model revealed strategy shifts in the condition with easy problems and competing goal, as it was assumed on basis of the experimental data. The model not only simulated the speed-up in this condition but also displayed an increased number of *processing cycles* indicating a more cursory processing based on rather simple production rules. Two types of productions in the model are sufficiently simple to account for this data, namely the interrupt-production and productions that implement simple example-processing strategies without studying example-solution pages.

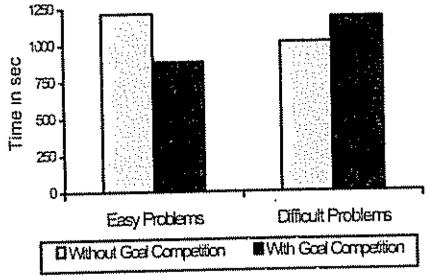

Figure 5: Simulated total time demands as a function of task difficulty and goal competition

Finally, it is important to note that the described pattern of results is not dependent on actual goal shifting which is in line with predictions on basis of PART as well as with the experimental data. Distraction effects occurred in our model whenever competing goals became activated and thus the execution of control processes was initiated, regardless of whether a pending goal overrode the current goal or not.

Summary and Conclusions

In this paper, we outlined an ACT-R model of volitional action control that is based on mechanisms which have proven useful for modeling elementary control processes in multiple-task performance, namely activation mechanisms and executive control productions. However, our model simulates effects of goal competition and task difficulty on processing strategies and performance for complex learning and problem-solving tasks of a much coarser temporal grain size. The model is able to capture the following experimental findings.

First, distraction effects occur when task-irrelevant information related to a pending goal is available. Distraction effects comprise performance impairments, a speed-up in time as well as resource-adaptive strategy shifts towards simpler but at the same time more error-prone processing strategies. Second, the occurrence of distraction effects is moderated by task difficulty as these effects could be observed only in the case of low task difficulty. Third, active distraction behavior (i.e., actively retrieving task-irrelevant information related to a pending goal) is not a necessary prerequisite for performance impairments due to goal competition.

Thus, we consider our modeling approach to be a solution to fill the conceptual and explanatory gap that exists between volitional control demands in real-world multiple-task performance on the one hand and experimental task-switching and PRP effects and their respective simulations on the other hand. 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 level without elaborating how these control demands may be met by cognitive mechanisms of information processing.

Acknowledgments

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