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The Dynamic Process of Polytelic Problem Solving: A Model and First Results

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***Abstract*—Based on previous work, we present a stage model for problem solving with conflicting goals (polytelic problem solving). That model predicts (a) a specific stage sequence, (b) specific strategic reactions due to failures, and (c) conditions for rumination. Tests of the model predictions are based on categorized think-aloud protocols. *N* = 20 subjects worked on a complex ecological microworld that required a series of 20 interdependent decisions with either goal independence or goal conflict. Qualitative results from think-aloud protocols and from decision times show (a) that peak episodes can be identified where failures happen, (b) that failure experiences during problem-solving and rumination occur in parallel, and (c) that adaptive problem solving leads to a more careful style of intervention after the first failure. The discussion addresses issues of model building and model testing as well as the connection between goal conflicts and complex problems.**

***Keywords*—complex problem solving, goal conflicts, motivation, process model, strategy**

I. Introduction

There is little doubt that solving problems poses a challenge to humans of all ages. Struggling with a problem means to pursue a goal, not yet knowing how to achieve it [1]. Complex problems share additional characteristics: They are broad in scope and involve intricate links among distant entities, which make the connections appear blurred, not obvious at all. While we take a rest and possibly rethink our goals, due to dynamic changes one obstacle can disappear and another one shows up. Likewise, a minor difficulty left unattended may turn into great concern. Finally, what makes an unfamiliar situation tricky is "polytely" [2], derived from the Greek "poly" (many) and "telos" (goal), meaning a multitude of goals.

Goals within a problem structure usually do not stand apart, but are linked to each other according to one of three relational types: goal independence, goal compatibility, or goal interference [3]. For pairs of two goals each, the relational types can be defined as follows: In case of goal independence, goals can be pursued and achieved separately from one another. Goal compatibility refers to contexts in which achieving goal A increases the probability of achieving goal B at the same time (synergy goals). Goal interference – most interesting to our study – occurs if two goals cannot be achieved simultaneously without considerable extra effort or cannot be achieved simultaneously at all. Successful actions towards goal A will decrease the probability of reaching goal B as well. In an extreme specification, goal A would be the precise negative mirror image of goal B, making combined success logically impossible. We will refer to this type of conflict situation as goal antagonism.

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Our work focuses on problem solving in the context of such polytelic conflicts with goal antagonism. Extending earlier studies [4] we aimed to model and empirically test changes in motivation, related cognition, and actual strategic behavior during its continuous process over time, from a first encounter with a problem up to its final solution. From a methodological point of view, we used a computer-simulated scenario where subjects have to make a sequence of interdependent decisions under conditions of uncertainty and will receive stepwise feedback about the consequences of their interventions [5].

A. *A Process Model of Polytelic Problem Solving*

Process models of problem solving have a long tradition [6-10]. The typical stage model consists of a sequence of four to six stages, typically labeled as *problem identification*, *exploration*, *strategy application*, and *reflection* upon the achieved results. The exact psychical processes, however, remain unconsidered. Our own model seeks to enrich this linear chain – the upper arrow line in Fig. 1 – by adding the four psychological core domains *motivation*, *stress experience*, *thoughts*, and *strategies* to each stage.

Our assumption is that during each step in a complex problem solving activity, each of the four above mentioned core domains is involved, yet to a different degree. That way, we specify the more general stage models by giving reference to basic psychic processes. Our idealized process runs as follows: (a) *Problem with goal conflict*. This is the starting point for our model: A situation exists with a goal conflict for which no routine solution is available. The acting person becomes stuck. (b) *Exploration*. The first approach towards the problem is to define it precisely, figuring out what is 'wrong' so far, and what should be the desired outcome. In this phase, cognition is the most prominent domain, i.e., analyzing the given situation and developing a first strategy. People will make use of their common sense knowledge and any prior expectations or associations with the semantic framing of the problem since this is the only available

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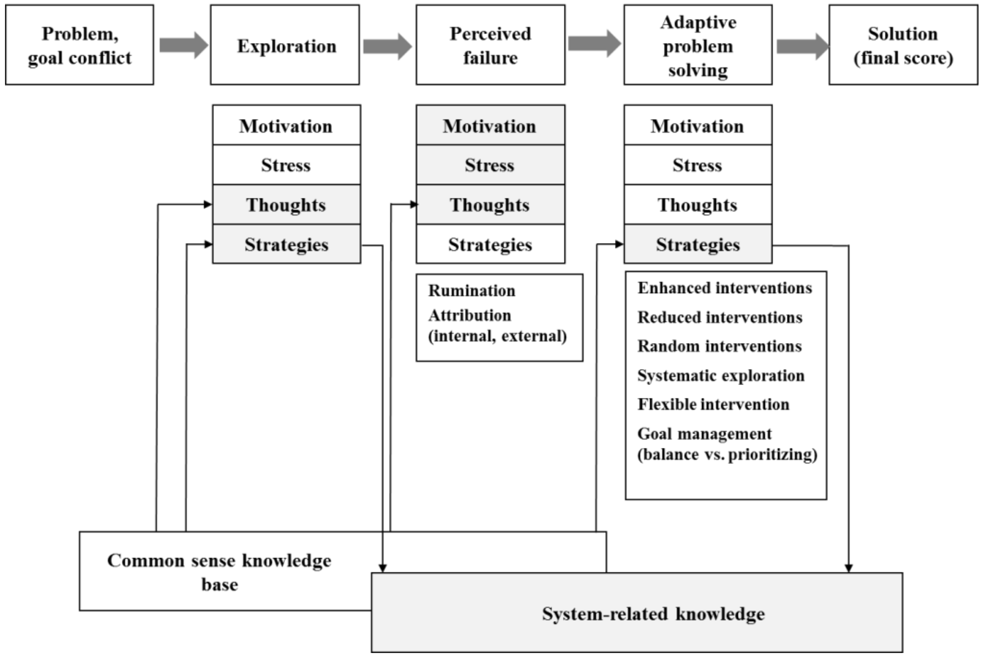

Figure 1. Stage model of complex polytelic problem-solving. At any time, motivation, stress experience, related thoughts, and strategies will be involved, but the respective impact is highest in phases with grey background.

information at that early stage. (c) *Perceived failure*. Once the first interventions are carried out, problem solvers receive feedback concerning the outcome. As earlier experiments showed, in polytelic problems immediate success is impossible by definition [4]. At least one of two conflicting goals has to be abandoned. For this reason we hypothesized this phase to be centered around the perception of failure, which is marked by heightened stress and declining motivation. Thoughts imply rumination about potential causes ("why did I fail?") and its sources ("did I fail or is it due to the situation?"). Strategies to cope with the setback are not active until the next step. (d) *Adaptive problem solving*. This phase can manifest itself in different ways: in an particularly systematic approach towards the problem, in arbitrary randomness, or in passive resignation, for example. People may make use of the insights they gained about the situation this far. Their prior common sense knowledge has turned to a base of system-related knowledge to some extent. We did not expect that only one type of reaction is suitable for all problem solvers. Instead we aimed to track strategic changes from an individual perspective, i.e., by comparing a person's behavior prior to a failure episode with the behavior afterwards. (e) *Solution*. The ending point in this process model is settled by the status achieved after a fixed time or a fixed number of solution steps. The term "solution" should not be read as "best solution" because a compromise might be seen as a suboptimal solution if one uses different optimization criteria [11].

Several theoretical influences have been considered in this model. The relation between conflict and the feeling of being "stuck" in a problem goes back to field theory [12]. Dörner [8, 13] highlights that complex, polytelic problems in general tend to evoke overstrain, lowering the self-perceived expectancy of success. Passive rumination as a consequence of unattained goals is the focal theme of the Martin and Tesser model [14, 15], see also [16, 17]. Strategies of complex problem solving come into play from at least two different traditions: cognitive functionalism and mood-dependent cognition. Cognitive functionalism distinguishes between hypothesis-driven and data-driven strategies [18, 19]. The most promising approach to manage a complex problem would be to translate one's a priori knowledge into a specific hypothesis about the situation at hand, carry out appropriate interventions, observe the resulting effects, decide whether these effects are in line with the predictions, and then update one's system-related knowledge. Heuristic approaches on the other hand yield less precise knowledge. Studies on mood-dependent cognition show that positive mood facilitates the heuristic style whereas negative mood can trigger the thoughtful, systematic solution [20]. As we expect negative feelings due to the perceived failure in the conflict situation, adaptive problem solving could be directed preferentially to a systematic testing of hypotheses in this case.

B. *Aim of the Study*

The aim of the current study was to look for first empirical evidence supporting this model. With the help of a computer-simulated complex problem scenario and with the use of think-aloud data we investigated the suggested processes in terms of their time sequence, i.e., whether the order of the problem-solving steps matched the expectation. Our data analysis was carried out with specific regard to the link between perceived failure and strategy changes. Also, we explored if ruminating thoughts occur most frequently paired with low motivation and the negative feelings of stress, and what kind of thoughts that would be.

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II. Method

A. Participants

20 subjects (17 female) volunteered for the experiment, mostly students of psychology and social sciences, recruited at the Department of Psychology at the University of Heidelberg, Germany. The average age within the sample was 24.35 years (*SD* = 5.29). Participants received either 5 Euros or course credit for participation. None of the subjects had prior experience with multiple-goal computer scenarios as used in this study.

B. Design

Goal relation was manipulated between subjects in a two-level one-way ANOVA design. 10 participants worked on a computer simulation with independent goals (as a control condition), the other 10 worked on conflicting goals. The participants were assigned randomly to the two experimental conditions.

C. Computer-based Scenario

Participants' main task was to explore and control the computer-simulated task *Schorfheide-Chorin*. This was programmed in AgentSheets 1.6X [21], a java-based visual programming environment. The name of the scenario is derived from a biosphere reserve in North-Eastern Germany. Biosphere reserves resemble nature conservation areas. However, the aim is to combine sustainable ecology with the social and cultural development of a rural area. Inspired by educational material [22], information of the environmental conservation association [23] and visitors' guidance [24, 25] we designed a polytelic conflict scenario within Schorfheide-Chorin. According to the cover story, problem-solvers took the role of local politicians in the biosphere reserve. Doing so, they dealt with (a) the demands of protected nature and (b) the promotion of tourism. These two parallel goals (*nature* and *tourism*) could be affected by a list of nine different interventions each. Examples were "setting up breeding station for sea-eagles" (nature intervention) and "refurbishing hotels" (tourism intervention).

Interventions differed in their efficacy to promote the two goals with some interventions being counterproductive. Participants needed to test the items from a list of potential interventions in order to find the most successful combination. In a sequence of 20 interdependent steps they selected interventions by mouse-click, confirmed their choice, and observed the resulting feedback scores. Then again, they chose a combination, and so forth. The starting score was 200 points on the side of nature and tourism each. The global aim was to get the highest possible scores on each goal. While the cover story and user interface looked exactly the same for all subjects, the relationship between nature and tourism depended on the experimental condition. There was no relationship in the case of goal independence, but a mutual negative effect in the condition of goal conflict: Gains in the goal "nature" went together with equally high losses in tourism and vice versa [4].

D. Speech Recording

A digital voice recorder provided recordings of participants' think-aloud activities during the task. Transcripts were written by means of the *Talk in Qualitative Social Research* procedure [26]. It was marked in the protocol when a subject finished an intervention and proceeded to the next step in the scenario problem.

E. Procedure

Participants gave their written informed consent to the study. Confidential treatment was highlighted. Subjects were assured that their original speech data would be deleted after transcription and that eventual identity-revealing information would be omitted. The think-aloud procedure was practiced in a five-minute introductory task with a simple one-goal scenario unrelated to the main task. Subjects were encouraged to verbalize everything that came to their mind while working on the task. They rated their current motivation and stress experience in standardized questionnaires. Then they worked on the scenario for 20 intervention steps. This phase of problem solving and concurrent thinking aloud took 20 to 25 minutes on average. The session concluded with post-experimental assessments of stress and motivation, knowledge acquisition, socio-demographic variables, and a debriefing.

F. Dependent Measures

A set of standardized quantitative questionnaires was applied to check for initial and final motivation [27], stress level, acquisition of system-related knowledge, and habitual action control [28]. The chosen problem-solving interventions, resulting outcome states, and decision times were measured electronically. Most important for the current analyses were the codings on the transcripts. These were classified, counted, and analyzed with regard to the solution process.

III. Results

A. Manipulation Check and Measures of Control

The measures for habitual action-control and the socio-demographic factors were distributed evenly across the two conditions. Under the condition of goal conflict, participants ran down the initial score of 200 points to a mean score of M = – 3.3 (SD = 50.89). In contrast, the independent goal condition finished with an average of M = 205.05 (SD = 34.89). Thus, the manipulation of pre-programmed failure and conflict worked as intended. Due to the small sample size, the standardized control measures allowed for coarse descriptive comparisons only. The trends were in line with findings reported earlier [4]: Goal conflicts implied less system-related knowledge, slightly decreased expectancy of success, and heightened stress as compared to the control condition with independent goals.

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B. *Code System and Coding Procedure*

The qualitative content analysis of think-aloud protocols was based on 20 transcripts, one per participant. The average length was about 2400 words (about 8 pages), yet marked differences appeared, the shortest protocol being less than 1200 words, the longest consisting of over 5000 words. All texts were fragmented into sections of two to three pages. These sections were selected randomly for the analysis.

Coding was done with the aid of MAXQDA2 [29], a software for marking and counting categories in text data. A code defines a single meaningful unit in the text, the corresponding category is a larger set or class of similar units. In our study codes could either be single words, passages of one or two sentences, or – most frequently – several words, a clause within a sentence. Speech breaks and fillers ("yeah", "uh", "erm") were not interpreted. We started with a guideline of *a priori categories*. These categories were derived from the process model before running the experiment and included all keywords from Fig. 1. We identified category-compatible bits of speech, differentiated categories for ambiguous information, and subsumed rarely mentioned entities under broader categories. We favored exclusive categories but accepted some overlaps, i.e., allocating information to more than one category (e.g., rumination in combination with common sense knowledge). The outcome was an elaborate, empirically adapted guideline including examples and differential conditions of how to classify the think-aloud data. The final systematics contained 2940 codings altogether, nine global categories, and 16 subcategories (see Table 1).

One third of the marked verbalizations (33.6%) dealt with the subjects' manipulating items from the checklist (categories C, D, E, and F). Close to another third (29.7%) were statements related to thoughts about possible, future or past problem-solving activities. These were summarized under the term *rumination* (G). The remaining classes for the last third of verbalizations were *observing conditions and trends* (A), *evaluation* (B), *knowledge* (H), and *goal management* (I). The coding system proved valid in terms of inter-rater reliability and substantial matching with the a priori categories. Besides complete coding of *all* protocols through the first author, a random subset of ten protocol sections was given to a second independent rater. She applied the coding guideline and assigned 333 selected passages (11.3% of the total codings) to the existing categories. Agreement between the first and second rater was determined per sub-category if possible, else per category. We calculated the index *AC1* [30, 31], i.e., the agreement (share of cases classified the same by both raters) in proportion to the maximum possible agreement. Compared to Cohen's Kappa [32], *AC1* takes into account the number of categories and the estimators of the marginal probabilities. Taking Landis' and Koch's [33] conventions as a reference, nine of the 18 categories displayed almost perfect agreement (*AC1* from .84 to 1.00). The poorest, but still fair agreement (*AC1* = .30) was found for the rare categories *hypothesis-driven strategies* (C1) and *striving for balance* (I1). The remainder values ranged from *AC1* = .58 and *AC1* = .77, meaning substantial or nearly substantial agreement.

In comparing the empirical coding system with our expectations we assessed whether categories were (a) clearly consistent, (b) consistent but rare, (c) consistent and differentiable, or (d) not initially predicted. All categories concerning the actual problem solving behavior turned out to be clearly consistent. Spontaneous comments on goal management, though identified, were low in number. Protocols indicated that the bulk of participants stuck to the introductory text that suggested forwarding both tourism *and* nature. Only eight subjects explicitly referred to goal balance or goal prioritizing, and this occurred as late as in the final

TABLE I. CODING SYSTEM DERIVED FROM THINK-ALOUD DATA

Category (Percentage) *Subcategory and Examples*	***Coding Frequency***	***AC1***
A) Observing conditions and trends (6.7%) "I lost twenty-one points"	198	.93
B) Evaluation (14.7%)	433	
B1) Negative evaluation (ineffectiveness): "the sea-eagles in the beginning didn't help"	249	.84
B2) Positive evaluation (effectiveness): "that's better"	184	.86
C) Systematics of interventions (7.2%)	213	
C1) Hypothesis-driven strategy: "suppose I merely improve the quality of food it should turn out that..."	26	.30
C2) Explorative (data-driven) strategy: "have a look what happens next"	187	.88
D) Readiness to intervene (8.3%)	244	
D1) Restrained interventions: "better avoid too much all at once"	194	.86
D2) Expansive interventions: "the more the better"	50	1.00
E) Variability of interventions (13.5%)	396	
E1) Routines: "continue to grant subsidies to farmers"	332	.93
E2) Flexibility: "let's change my strategy"	64	.58
F) Interventions without giving reasons (4.6%) "simply extend the visitor season"	136	.87
G) Rumination (29.7%)	874	
G1) Prospective rumination: "what can I do to improve nature?"	453	.77
G2) Retrospective rumination: "nature dropped, I wonder why"	235	.66
G3) Helplessness: "I don't know, I feel there's little I can do"	186	.86
H) Knowledge (13.2%)	388	
H1) Common sense knowledge base: "I suppose with the guest houses renovated and the food improved tourist will feel comfortable and attracted"	308	.59
H2) Knowledge on goal relations: "seems totally incompatible to me, as if I cannot push the two of them, just one, if at all"	80	.77
I) Goal management (2.6%)	76	
I1) Striving for balance: "get it to a fairly equal level"	14	.30
I2) Prioritizing: "focus on nature and change nothing but that"	17	.65
I3) Maintaining goals: "now, in no way I must ruin what I have achieved for nature"	45	.65
Total (100%)	**2940**	

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steps of the task. The theoretical concept of rumination allowed for three substantial empirically based subsets: *prospective rumination* (G1), *retrospective rumination* (G2), and *helplessness* (G3). We had not predicted a distinct category named *observing conditions and trends* (A), yet as a supplement to the exploration phase it seemed easy to handle.

C. Comparing Coding Proportions for Goal Antagonism vs. Goal Independence

An analysis of coding frequencies sought to ascertain whether certain categories would be more prominent in the experimental conflict condition compared to the control condition. To control for the impact of protocols different in length we divided the number of codings within a special category by the total number of codings obtained from the same individual. *U*-test comparisons showed that participants from the conflict condition, on average, had higher shares of negative evaluations, $U = 43.00$, $p < .05$, lower shares of positive evaluations, $U = 22.00$, $p < .05$, and less routines, $U = 18.00$, $p < .05$. Also, they tended to mention “goal relation” more often, $U = 28.50$, $p = .11$, and ruminated more. Albeit mainly in descriptive terms, the results corroborate and extend the manipulation check above.

D. Locating and Interpreting Peaks of Failure and Rumination Within the Solution Process

Committed to the genuine aim of the article, we evaluated think-aloud codings under three leading questions. (1) Do distinct phases of failure and heightened rumination exist? (2) Provided such peaks are identified, do perceived failure and rumination coincide? (3) Relying on the same precondition, will failure and rumination ensue strategic changes, i.e., adaptive problem-solving? The method for answering these questions is to apply the sequence of twenty intervention cycles as a timer that indicates coincidence or not. Code frequencies of relevant categories are counted for each cycle, arranged on a timeline and visually displayed.

(1) *Locating peaks*: (a) To identify perceived failure we added up coding frequencies of the categories negative evaluations and helplessness. (b) Rumination in this analysis was the sum of retrospective rumination and prospective rumination. (c) A third related indicator was the time spent on each step. The cycle (out of the 20) holding the highest frequency was marked as a peak unless the value was below two. Further peaks were marked if coding frequencies continuously increased or rose by at least two units in a sudden “pop out”. To grant maximum objectivity, this procedure was carried out by two independent raters. They agreed by .86, .84, and .79 for the three constructs of failure, rumination, and decision time, respectively.

Five out of ten subjects in the conflict condition did not reveal any distinct failure experience at all. Their comments seemed too scarce or too evenly distributed to match the outlined criteria. The other subjects showed two ($n = 2$) or three ($n = 3$) episodes corresponding to failure. These occurred initially in the first third or first half of the task (step 4 to step 12) with four to eight steps between the peaks. Increased rumination was observed for all participants except for two who had verbalized little during the whole task. For low-verbalizers (see participant #17 in Fig. 2, left side), peaks of decision time occurred in the very first step, reflecting the demands of general orientation. High verbalizers (see participant #04 in Fig. 2, right side) revealed peaks of decision time during later stages as well, but even more impressive is the high coincidence between failure experience and rumination along with increased decision times.

(2) *Simultaneous occurrence of failure and rumination*: Simultaneous occurrence was indicated if peaks of rumination and decision time were either located in the very same step as the failure peak (n) or in the adjoining steps ($n – 1$; $n + 1$). We computed a ratio measure Q_{syn} to measure the extent of overlaps (p_{syn}) in proportion to the total number of peaks (p_{total}) according to the following formula:

$$Q_{syn} = 2 * p_{syn} / p_{total} \quad (1)$$

$Q_{syn} = .50$ is found if every second peak of failure coincides with a peak of rumination. Our data revealed Q_{syn} ratios of .47 for the combination of failure and rumination, .45 for the combination of failure and decision time, and .61 for the combination of rumination and decision time. This means a moderate extent of matching.

(3) *Adaptive problem-solving after perceived failure*: This explorative analysis was conducted for the five participants who showed distinct phases of failure experience in the conflict condition. For each relevant strategy, we computed N_{diff} as the difference between the number of units prior to the failure peak N_{before} (step $n – 2$; $n – 1$) minus the number of units at the peak step and immediately afterwards N_{after} (step n; $n + 1$) according to formula (2):

$$N_{diff} = N_{before} – N_{after} \quad (2)$$

The algebraic sign (plus or minus) of N_{diff} indicates whether a strategic approach has become more or less frequent after the failure experience. To figure out the relative significance S_{rel} of a strategic change, we applied a subject’s individual baseline N as a benchmark (how often a strategy type has been coded in total for that very person). Also, we took into account how likely two codings would happen to occupy adjoining steps in a random distribution over 20 steps. Altogether, S_{rel} displays the binomial probability of obtaining the actually observed number of codings N_{after} or a number greater than that:

$$S_{rel} = B\,(x \leq N_{after}; 1/10; N) \quad (3)$$

Tentatively we assumed that changes with $S_{rel} \leq .20$ would be worth reporting. The following strategies were analyzed by means of N_{diff} and S_{rel}: restrained vs. expansive interventions, routines, flexibility, hypothesis-driven strategies

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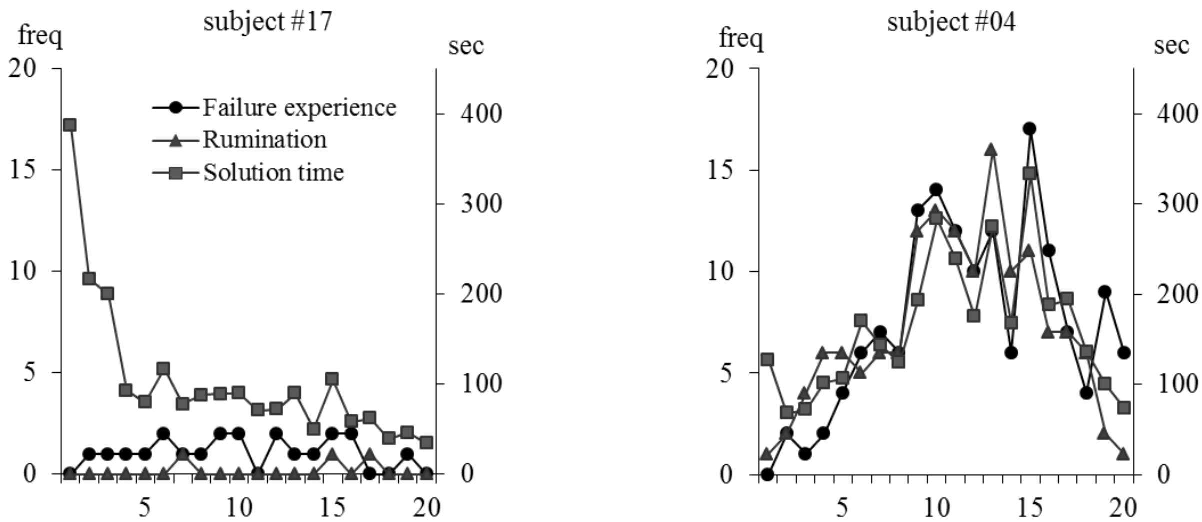

Figure 2. Decision time in seconds (“sec”, right axis) and counted instances of perceived failure and rumination in think-aloud protocols (“freq”, left axis) mapped along the time axis of 20 intervention cycles in the computer-simulated scenario.

as coded from the protocols plus the electronically recorded number of actual interventions per step. Consistent with our expectations, four out of five participants reduced the number of interventions at their first failure peak, yet only for one person this effect met our preset criterion of significance (S_{rel} = .10). There was no such trend regarding the second peak of failure. All participants verbally addressed the category *reduced interventions* during failure episodes, however, not clearly more often than otherwise. Codings of routine strategies were not contingent with failure reports, either. Instead, individual variation was high. The remaining strategies, finally, were too low in their baseline to yield systematic patterns.

IV. Discussion

The study at hand gives a first insight into the process of solving complex problems with two conflicting goals. In addition to pointing out the rather straightforward finding that negative evaluations and ruminative thinking accrue from conflicts, we took a closer look at different stages within the solution process. Provided that participants were sufficiently engaged and verbalized intensively enough, their think-aloud protocols revealed two or three episodes of marked failure during an about thirty-minute interaction with a computer-simulated conflict problem. Perceived failure went parallel with ruminative thinking. To objectify strategic changes triggered by the failure experiences was obviously beyond the scope of this study. Nevertheless, the results are basically in line with our predictions.

The striking parallel between rumination and perceived failure triggers the assumption that the failure might come first and then comes the rumination. But one has to be careful with such considerations – besides the fact that correlation does not imply causal relations, it could be exactly the other way round: due to intensive ruminations, the existence of failures becomes evident. The precise form of the relationship has to be explored by another experiment.

Recommendations for consecutive studies include larger sample sizes and a more detailed investigation of individual approaches to a conflicting problem. The linear time frame based on a time axis could be refined towards a model of interconnected feedback-loops. Such loops are postulated in psychological theories that relate to artificial intelligence and neural networks like PSI [34]. A person’s reaction to a specific emotional or motivational experience could be mapped together with its consecutive behavioral strategy as a unit of analysis. Such linked couples of experience and behavior could be observed in terms of neural facilitation – whether they grow stronger or fade out over time. So far, cognitive architectures have paid little attention to the specific field of cognitive and motivational conflicts. Conflict resolution by means of rumination is not yet implemented.

A general remark concerns the robustness of the conflicts under consideration. Interviews from real-life settings and social situations, e.g., disaster management, could supplement the method for ecological validity and conflict experience among personal goals. Research from Huber [35] demonstrates the importance of real-life settings for the choice of strategies. In the laboratory, incentives, punishment, time pressure, especially captivating cover stories, and a high fit between the cover story and the participants’ habitual interest could help establish further the computer-simulated paradigm as a usable research instrument – not merely on the cognitive part of complex problem solving, but also on the side of conflict experience and goal struggling.

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