# When the Going Gets Tough: Exploring Agent-based Models of Human Performance under Demanding Conditions

van Lambalgen, R.M.

2012

***document version***
Publisher's PDF, also known as Version of record

***citation for published version (APA)***
van Lambalgen, R. M. (2012). *When the Going Gets Tough: Exploring Agent-based Models of Human Performance under Demanding Conditions*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

# Chapter 11

# Design of an Optimal Automation System: Finding a Balance between a Human's Task Engagement and Exhaustion

**This chapter appeared as:**

Klein, M., and Lambalgen, R. van. *Design of an optimal automation system: finding a balance between a human's task engagement and exhaustion.* In: K.G. Mehrotra, Mohan, C., Oh, J., Varshney, P., Ali, M. (Eds.): IEA/AIE 2011, Proceedings of the 24th international conference on Industrial engineering and other applications of applied intelligent systems conference on Modern approaches in applied intelligence. Part II. Lecture Notes in Artificial Intelligence, vol 6704, pp 98-108, Springer Verlag Berlin, Heidelberg, 2011.

# Design of an Optimal Automation System: Finding a Balance between a Human's Task Engagement and Exhaustion

**Michel C.A. Klein[1], Rianne M. van Lambalgen[1],**

1 Vrije Universiteit Amsterdam, Department of Artificial Intelligence
De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
{m.c.a.klein, r.m.van.lambalgen}@vu.nl

**Abstract.** In demanding tasks, human performance can seriously degrade as a consequence of increased workload and limited resources. In such tasks it is very important to maintain an optimal performance quality, therefore automation assistance is required. On the other hand, automation can also impose additional demands on a person monitoring the system and it will likely reduce the person's awareness of the situation. Therefore, automation should be adapted to the human's state in order to keep the human in the loop. In this paper an agent model is proposed that calculates a person's workload and engagement to an automated task. Based on this agent model, an intelligent support system can provide different types of automation and aims at adapting to the human state such that an optimal balance is found between exhaustion and task engagement.

*Keywords.* Agents, Cognitive Modeling, Adaptive Automation,

## 1. Introduction

Human task performance can degrade over time when demanding tasks are performed. Such degradation can for instance be caused by available resources being exceeded [1]. However, high effectiveness and efficiency levels are of particular importance for critical tasks. In such cases, automated assistance to support humans in effective and efficient task execution is often required. However, while humans take advantage of such systems in that it reduces their workload, these systems can also have negative effects on human functioning. Automation induced complacency causes a person to rely on an automated system, even when that system is not always flawless [2]. In addition, automation reduces a person's picture of the environment, often referred to as situation awareness [3]. A reduction in situation awareness may lead to human error, especially when automation does fail. Parasuraman defines levels and stages of automation that all have a different effect on a person's situation awareness and human functioning [4].

To overcome disadvantages of automation, it is important to adapt automation to the state of the human [5]. Existing systems often adapt their level of automation throughout a specific task either to the person's workload [6] or situation awareness [7]. Also, automation can be adapted by analysis of the human's state through psychophysiology ([8], [9], [10]). For an extensive review on adaptive automation, see [11]. The system that is proposed in this paper also aims at providing adaptive automation, but as opposed to previous systems it integrates both workload and situation awareness (referred to as task engagement) in the model of a human's state. This way, advantages of automation (in reducing workload) as well as disadvantages of automation (in reducing awareness) are taken into account. The design of the system is based on the agent-paradigm: the human and its behavior and states are explicitly described in a formal way, as a separate entity, as is the interaction between the human and its environment. This agent model is then used to decide on the effect of specific actions on the human. Within the agent model theories of automation ([4], [5], [6]) and operator functional state ([12], [13]) are used to calculate the effects of a specific level of automation on both a person's engagement to the task and the human's functional state (i.e. exhaustion and performance). This allows the support system to choose the optimal support level at each point in time and to find the balance between a reduction in exhaustion on the one hand and maintenance of a person's engagement on the other hand.

In this paper, first a theoretical background on human automation and human workload is given in Section 2. Section 3 describes the agent model and in Section 4 simulation results are presented for different types of automation. Section 5 explains how support can be given using the agent model, which is illustrated by an example. Finally, a discussion of the work is given in Section 6.

## 2. Theoretical Background

Parasuraman ([4]) defines 4 possible types of automation that are applied to 4 stages of information processing: *information acquisition*, *information analysis*, *decision and action selection* and *action implementation*. Within those 4 types of automation, different levels can be distinguished, ranging from no automation to very high automation. Depending on the specific type and level of automation, each system has different consequences to a person's workload, situation awareness and performance. Decision automation can decrease a human's awareness, which impairs human performance in case the automation fails. Therefore, decision automation should be set at a low level, especially in demanding circumstances such as air traffic control. On the other hand, both automation of information acquisition and information analysis allow the human to stay involved with the task and thus are beneficial to a human performing a task.

Other effects of the level of automation are that on a person's workload. A high level of automation reduces the workload of the person performing the task. However, a high level of automation also induces monitoring demands, which in turn increases workload. Workload is influenced by the demands of the task, which determine the effort a person has to give to the task for an optimal performance. A high workload may lead to exhaustion, caused by a depletion of resources when the person generates effort to the task (see [13]). Such a mechanism is also common in sports and exercise, where each person has a critical point that determines a person's basic level at which effort can be contributed without getting exhausted [14]. In [12] a model is presented that explores these relationships between demands, effort, exhaustion and critical point (also referred to as a human's functional state)..

In addition to the type and level of automation, awareness of the operator can also be influenced by the level of self-agency. The concept of self-agency is found in literature on consciousness and can be defined as 'the feeling that one causes one's own actions and their outcomes' ([15], [16]). Normally, self-agency is present when a task is consciously performed. However, research points out that self-agency can also be evoked by priming of the outcome of an action just before the outcome itself emerges ([17]). This is especially useful when humans are supported by high level information. In this case, such priming leads to an increased awareness of the human to the task even though it is performed by the system.

## 3. Agent Model for Human's Task Engagement and Exhaustion

To design a system that can intelligently decide on the optimal form of automation, it is necessary to create a dynamic model that describes the interaction between the system, the environment, and the human agent. The overall agent model is depicted in Figure 1 and is composed of three main components: the system, the world and the human (or operator). Within the system component, the possible actions of an intelligent support system in order to provide support are represented. The world contains information on the environment and output of both the support system and the operator. Furthermore, in the operator component concepts and relations on operator states are defined. In this section, first the three components explained in more detail. Secondly, a computational specification of the model is provided, in which formulas are given for the calculation of the values for different concepts.

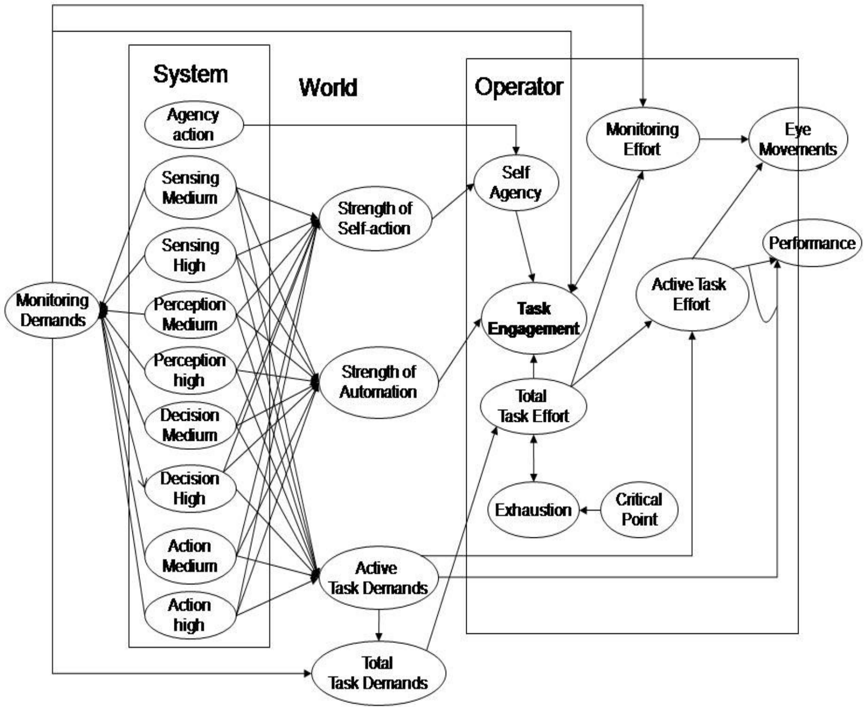

**Figure 1.** Agent Model

## 3.1 Model Components

**System.** The actions that the support system performs can be divided in two different sorts of actions: *actions for automation* and *actions for agency*. Actions for automation define the different levels and stages of automation the support system can adapt to provide support, based on [3], [4]. All actions for automation affect one of the 4 stages of information processing: sensing, perception, decision making or action. Furthermore, within each stage, the support system can perform a low automation action or a high automation action. Each automation action affects the strength of self-action, the strength of automation, the active task demands and the monitoring demands in the world. In addition, the agency action can be performed by the support system in order to increase task engagement. This function is based on literature on consciousness which states that support can be given to increase a person's awareness of performing a specific task ([16], [17]). If task engagement is low given the automation actions of the system, agency action can be performed by the support system to overcome this decrease in task engagement.

**World.** The world contains the characteristics of the environment as well as the output of the system and the operator. On the side of the operator, eye movements and task performance can be reflected in the world. On the side of the system, firstly *active task demands* and *monitoring demands* are distinguished, where the former represents the demands of performing the task that is left after automation and the latter represents the demands of monitoring the automated task. Both forms of demand influence the total effort generated by the operator at a specific point in time. Secondly, the *strength of automation* is determined by the automation action of the system. Finally, the system's automation action also influences the strength of self action, which indicates the extent to which operators feel themselves to be responsible for performing the task. Both strength of automation and strength of self action influence the person's task engagement.

**Operator**. In the operator component, knowledge of concepts and relations is represented used by the support system to determine task engagement and exhaustion. The world component serves as input for the task engagement, the self agency and the total task effort generated by the operator. A simplified model of operator functional state based on ([12]) is used to determine the level of exhaustion with the total generated effort and a person's critical point (a person's basic cognitive abilities). Furthermore, the total task effort is split up into a monitoring effort level and active task effort level. Task engagement is determined by the strength of automation, strength of self-action and the monitoring effort. The output that can be measured based on the states of the operator are eye movements and task performance.

## 3.2 Formal Computational Model

To determine the interaction of the human, the system and the world, a formal model had been developed that specifies the effect of specific types of support on the exhaustion and engagement of a human. In this formalization, all concepts have a value between 0 and 1. In order to distinguish between the different types of support, it is assumed that for each variant of automation it is defined what the effect is on:

- the strength of automation (**SoA**)
- strength of self action (**SSA**)
- active task demands (**AT_D**)
- monitoring demands (**M_D**).

An example of such a specification is given in Table 1 in the next section, where a simulation based on the model is presented. The total strength of automation (SoA) and the total strength of self action (SSA) are determined by averaging the effect of all automation actions; to determine the total active task demands (AT_D) and the total monitoring task demands (M_D) the demands that result of the individual automation actions are summed up.

Total task demands (**TT_D**) represent the sum of the active task demands and the monitoring demands.

$$\mathbf{TT\_D} = \mathrm{AT\_D} + \mathrm{M\_D} \qquad (1)$$

The demands of the task and the exhaustion of the operator together determine how much effort the operator generates in total. The parameter *ex_speed* determines the influence on exhaustion.

$$\mathbf{TT\_E} = \mathrm{TT\_D} * (1-(\mathrm{Ex}(t-1)*\mathit{ex\_speed})) \tag{2}$$

The total effort is distributed between the active task and the monitoring task according to the priority that is given to either active task effort (**AT_E**) or monitoring effort (**M_E**) (note that prior_m should be 1-prior_at and the other way around).

$$\mathbf{AT\_E} = \begin{cases} 0 & \mathit{if\ TT\_E = 0} \\ \mathrm{AT\_D}-((\mathrm{TT\_D}-\mathrm{TT\_E})-\mathrm{M\_D}) & \mathit{if\ (TT\_D-TT\_E)*(1-prior\_m)>MD} \\ \mathrm{AT\_D}-((\mathrm{TT\_D}-\mathrm{TT\_E})*(1-\mathrm{prior\_at})) & \mathit{else} \end{cases} \tag{3}$$

$$\mathbf{M\_E} = \begin{cases} 0 & \mathit{if\ TTE = 0} \\ \mathrm{M\_D}-((\mathrm{TT\_D}-\mathrm{TT\_E})-\mathrm{ATD}) & \mathit{if\ ((TT\_D-TT\_E)*(1-prior\_at)>AT\_D} \\ \mathrm{M\_D}-(\mathrm{diff}*(1-\mathrm{prior\_m})) & \mathit{else} \end{cases} \tag{4}$$

The engagement to the task (**TE**) depends on the Strength of Automation, the Self Agency and the effort that is given to the task.

$$\mathbf{TE} = \begin{cases} w1*(1-\mathrm{SoA})*\mathrm{SSA} + w2*1 + w3*\mathrm{AT\_E}/\mathrm{AT\_D} & \mathit{if\ M\_D=0} \\ w1*(1-\mathrm{SoA})*\mathrm{SSA} + w2*\mathrm{M\_E}/\mathrm{M\_D} + w3*1 & \mathit{if\ AT\_D=0} \\ w1*(1-\mathrm{SoA})*\mathrm{SSA} + w2*1 + w3*1 & \mathit{if\ AT\_D=0\ and\ M\_D=0} \\ w1*(1-\mathrm{SoA})*\mathrm{SSA} + w2*\mathrm{M\_E}/\mathrm{M\_D} + w3*\mathrm{AT\_E}/\mathrm{AT\_D} & \mathit{else} \end{cases} \tag{5}$$

The formula for exhaustion (**Ex**) is temporal as it takes into account the person's exhaustion at the previous point in time. *Ex_parameter* determines the influence of effort (related to the critical point) on exhaustion.

$$\mathbf{Ex}(t+\Delta t) = \begin{cases} \mathrm{Ex}(t) + (\mathrm{Ex})*\Delta t*(\mathrm{TTE}-\mathrm{CP})/\mathrm{CP} * \mathit{Ex\_parameter} & \mathit{if\ TTE<CP} \\ \mathrm{Ex}(t) + (1-\mathrm{Ex})*\Delta t*(\mathrm{TTE}-\mathrm{CP})/\mathrm{TTE} * \mathit{Ex\_parameter} & \mathit{if\ TTE>CP} \end{cases} \tag{6}$$

## 4. Simulations

To illustrate the working of the model, a number of simulations have been performed in which the effect of different variants of automation on a person performing the same fictitious task is compared. In the simulations, the effect of a specific type of automation is investigated on two variables, namely *exhaustion* and *engagement*, assuming that the system would give continuous support for a long period of time (in this case 100 time steps, where $\Delta t=0.5$).

*Table 1.* Values that determine effects of automation

| Automation Action | | Strength of Automation | Strength of Self Action | Active Task Demands | Monitoring Demands |
|---|---|---|---|---|---|
| Sensing | Off | 0 | 1 | 1 | 0 |
| | Medium | 0.1 | 0.5 | 0.5 | 0.5 |
| | High | 0.4 | 0 | 0 | 1 |
| Perception | Off | 0 | 1 | 1 | 0 |
| | Medium | 0.4 | 0.8 | 0.5 | 0.5 |
| | High | 0.7 | 0 | 0 | 1 |
| Decision Making | Off | 0 | 1 | 1 | 0 |
| | Medium | 0.8 | 1 | 0.5 | 0.5 |
| | High | 1.0 | 0 | 0 | 1 |
| Action | Off | 0 | 1 | 1 | 0 |
| | Medium | 1.0 | 0 | 0.5 | 0.5 |
| | High | 1.0 | 0 | 0 | 1 |

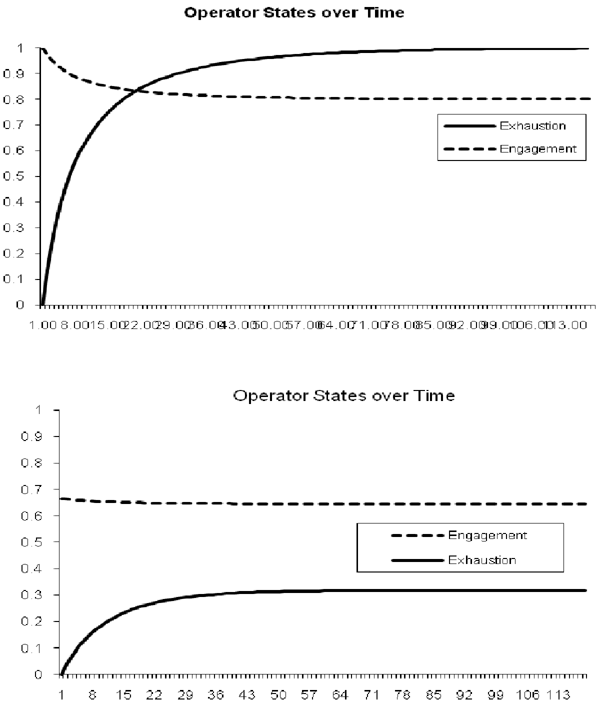

**Figure 2a, b.** Exhaustion and Engagement over time in a system without automation (left) and a system with high sense and high perception automation (right).

In order to execute the model, it is required to specify the effect of different types of automation on the task demands and the strength of self-action and strength of automation. These values are task specific. In the experiments, four different types of support are considered, i.e. support on *sensing*, support on *perception*, support on *decision making* and finally support on *action*. The latter two are highly dependent on each other, as action support always requires decision support. Each of the automation actions can be off, medium active, or high active. In Table 1, it is specified what the effect of each support action is on the factors described before. Here, the assumption is that the effect of automation on Active Task Demands and Monitoring Demands is independent of the specific type. On the other hand, the effect of the automation action on strength of automation is strongly dependent on the specific type of automation; sensing and perception automation is relatively more 'lightweight' as compared to the decision making automation (e.g. [4]).

*Table 2.* Simulated combinations of automation.

| Combination | Automation |
|---|---|
| 1 | No Automation |
| 2 | Only medium Sensing automation |
| 3 | Only high Sensing automation |
| 4 | Only medium Perception automation |
| 5 | Only high Perception automation |
| 6 | Only medium Decision automation |
| 7 | High decision automation and high action automation |
| 8 | Medium Sensing and Medium Perception automation |
| 9 | Medium Sensing, Medium Perception and Medium Decision automation |
| 10 | High sensing, high perception, high decision and high action automation |

The parameter values in this simulation were as follows: ex_speed=0.2; ex_parameter=0.5; prior_at=0.8; prior_m=0.2. w1=0.7; w2=0.1; w3=0.2. The operator's critical point was set to 4.4.

The pattern of engagement and exhaustion over time are shown in Figure 2 a and b, for the case that there is no automation and the case of medium sense and medium perception automation respectively.

In both figures it can be seen that the exhaustion and engagement reaches a stable situation after some time, however, with different value for the variables of interest. Since each specific type of automation leads to some stable values for exhaustion and engangement, it is also possible to compare these end-situations directly. This shows the eventual effect of a specific type of support directly. Therefore, 10 different combinations of support were compared by simulation, in a somewhat increasing level of complexity; the different combinations are listed in Table 2. Figure 4 shows the person's engagement and exhaustion for the different combinations of types and levels of automation listed in Table 2.

As can be seen in Figure 3, exhaustion is highest in the system without any automation and lowest in the fully automated system. In addition, engagement is also relatively low for combination 7, which has a high decision automation and high action automation.

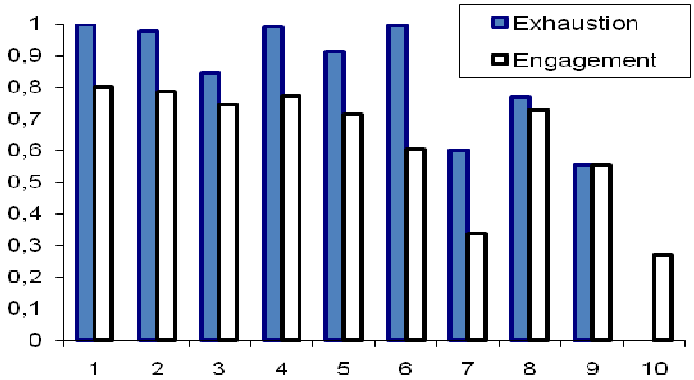

**Figure 3.** Engagement and Exhaustion for 10 different combinations of automation

## 5. Support Framework

This section presents how the model introduced in Section 3 can be used within a intelligent support system to reason about the most appropriate type of support for a human, taking both the engagement and the exhaustion into account. To do so, the support system uses the information presented in Table 1, to obtain the knowledge about the effect of different types of support on the task demands, the strength of automation and the self agency. In addition, the system makes use of a preference value for the optimal balance between exhaustion and engagement. This preference value is task specific, as more critical tasks might require relatively higher engagement than enduring tasks, for which a lower exhaustion is important.

Based on this knowledge and the model, the support system can calculate the *reduction* in exhaustion and engagement for the upcoming period for all different types of support, compared with the scenario in which no support is given, i.e.

$$\mathbf{Ex_{diff\_x}(t)} = \mathrm{Ex}_{no\_support}(t) - \mathrm{Ex}_{support\_x}(t) \qquad (7)$$
$$\mathbf{TE_{diff\_x}(t)} = \mathrm{TE}_{no\_support}(t) - \mathrm{TE}_{support\_x}(t)$$

for all different types of support_x, where $\mathrm{TE}_{support\_x}$ is the task engagement when a specific variant of support is given (similar for $\mathrm{Ex}_{support\_x}$).

To decide on the optimal balance between exhaustion and engagement, both values can be combined into a single value using a formula with a weighting mechanism, e.g.

$$\mathbf{F_x(t)} = w1 * \mathrm{TE}_{diff\_x}(t) \,/\, w2 * \mathrm{Ex}_{diff\_x}(t) \qquad (8)$$

In this function, a high task engagement and a low exhaustion both contribute positively to the combined value (*w1* and *w2* are weighting factors). Alternative formalizations are also possible, e.g. based on a weighted sum of the TE and (1 – Ex).

The system will choose the most optimal type of support (i.e. with the highest value for the combination function) until the time point that it is predicted that a different type of support will result in a better balance. At that time point, a new simulation is started, in which it is predicted what the additional effect of all variants of support is, compared with the type of support given until then, i.e.

$$\begin{aligned} \mathbf{Ex_{diff\_y}(t)} &= \mathrm{Ex_{support\_x}}(t) - \mathrm{Ex_{support\_y}}(t) \\ \mathbf{TE_{diff\_y}(t)} &= \mathrm{TE_{support\_x}}(t) - \mathrm{TE_{support\_y}}(t) \end{aligned} \tag{9}$$

for all types of support_y, and support_x the current type of support.

**Example scenario.** To illustrate the approach, simulations are performed using the agent-model described in Section 3 and the reasoning in the support framework as described above. For the example scenario, a task is considered for which the effects are described in Table 1. In addition, the engagement and exhaustion are assumed to be equally important: formula 8 is used with weights $w1 = w2 = 1$. All other variables in the simulations have the same value as in Section 4.

First, the system compares the effect of a specific variant of support with giving no support. Figure 4 shows the value of the combination function for all different variants of support listed in Table 2. It can be seen that up to time point 22, the line with small dots (support variant 3, *high sensing automation*) is the most effective type of support. Figure 5 shows the same simulation up to time point 22, but from time point 23 on the support system compares all variants of support with support variant 3. It can be seen that until the end of the simulation the line with the thick dots is the highest. This represents variant 4, *low perception automation.* Consequently, the intelligent support system would generate high sensing support up to time point 23, and then would switch to low perception support.

Note that in the example no "agency actions" (i.e. actions that would increase the self-agency) are considered. Using those actions, it might be possible to influence the engagement directly, without implementing a lower level of automation (which would increase the task demands).

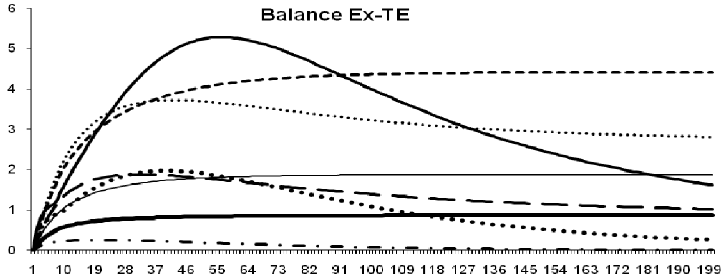

**Figure 4.** Simulated balance between reduction of exhaustion and engagement compared with no support (line with thin dots is support variant 3).

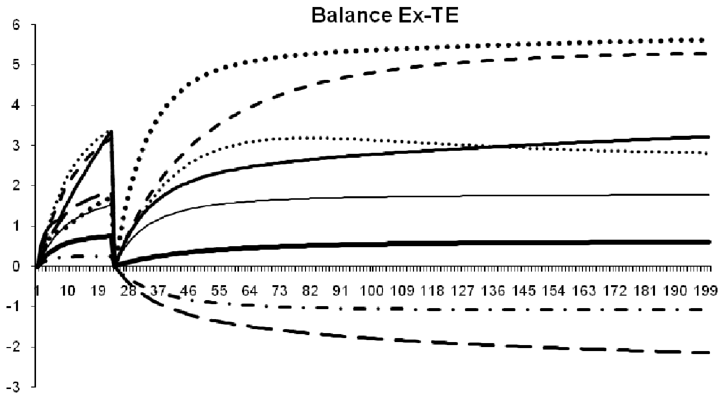

**Figure 5.** Simulated balance between reduction of exhaustion and engagement compared with support variant 3 from timepoint 23.

## 6. Discussion

In this paper, an agent model and a framework for an intelligent support system is presented to decide on the optimal type of automation, taking both the task engagement and the exhaustion into account. The model is generic and can be used for different tasks. This requires a specification of the effect of the support actions on both the task demands and the strength of automation and the self agency. The specification of these effects is not trivial because it requires quantification for the effect of all actions on different aspects, but part of this specification can be based on actual measurements of demands.

The approach has been illustrated with an example scenario. In this scenario, no agency actions are assumed, and a constant balance between the importance of task engagement and exhaustion is assumed. However, it could be that the importance changes over time. The framework can cope with such situations as well. This will result in a more varied behavior of the support system. For example, if the task is very critical at a specific point in time and the operator is too exhausted to perform, automation should be kept constant. When the critical task is performed, the task should be given back to the operator such that the operator's engagement can be kept optimal.

## References

1. Posner, M. I., and Boies, S. J. Components of attention. *Psychological Bulletin* 78, 1971, 391-408.
2. Rovira, E., McGarry, K., & Parasuraman, R., 2007. Effects of imperfect automation on decision making in a simulated command and control task. *Human Factors 49 (1), 76-87.*

3. Endsley, M.R.,1999. Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics 42(3), 462-492.*
4. Parasuraman, R., 2000 Designing automation for human use: empirical studies and quantative models. *Ergonomics 43(7), 931-951.*
5. Parasuraman, R., 1997. Humans and automation: Use, misuse, disuse, abuse. *Human Factors 39,* 230-253.
6. Kaber, D.B., & Endsley, M.R., 2004. The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. *Theoretical Issues in Ergonomics Science 5(2), 113-153.*
7. Parasuraman, R., Barnes, M., & Cosenzo, K, 2007. Adaptive automation for human-robot teaming in future command and control systems. *The International C2 Journal 1(2) 43-68.*
8. Wilson, G.F., & Russell, C.A., 2007. Performance enhancement in an uninhabited air vehicle task using psychophysiologically determined adaptive aiding. *Human Factors 49 (6), 1005-1018.*
9. Byrne, E.A., Parasuraman, R., 1997. Psychophysiology and adaptive automation. Biological Psychology 42 (5), 249-268.
10. Prinzel, L.J., Freeman, F.G., Scerbo, M.W., Mikulka, P.J., Pope, A.J., 2003. Effects of a psychophysiological system for adaptive automation on performance, workload, and the event-related potential P300 component. *Human Factors 45(4),* 601-614.
11. Parasuraman, R., & Wickens, C.D. (2008). Humans: still vital after all these years of automation. *Human Factors 50 (3), 511-520.*
12. Bosse, T., Both, F., Lambalgen, R. van, and Treur, J., An Agent Model for a Human's Functional State and Performance. In: Jain, L., Gini, M., Faltings, B.B., Terano, T., Zhang, C., Cercone, N., Cao, L. (eds.), Proceedings of the 8th IEEE/WIC/ACM International Conference on Intelligent Agent Technology, IAT'08. IEEE Computer Societypress, 2008, pp 302-307.
13. Robert, G., & Hockey, J., 1997. Compensatory control in the regulation of human performance under stress and high workload: a cognitive-energetical framework. *Biological Psychology 45,* 73-93.
14. Hill, D.W. (1993). The critical power concept. *Sports Medicine*, vol.16, pp. 237-254
15. Wegner, D.M., 2004. Précis of The illusion of conscious will. *Behavioral and Brain Sciences 27*, 1-46.
16. Aarts, H., Custers, R., & Marien, H., 2009. Priming and authorship ascription: when nonconscious goals turn into conscious experiences of self-agency. *Journal of Personality and Social Psychology 96(5),* 967-979.
17. Custers, R., & Aarts, H., 2005. Positive affect as implicit motivator: on the nonconscious operation of behavioral goals. *Journal of Personality and Social Psychology 89 (2),* 129-142.