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

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Part VI

Discussion and Future Work

Chapter 16

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The research that was presented in this thesis explored the role of attention, situation awareness and functional state in human performance. Limitations in these aspects of human cognition can cause degrading performance, especially when circumstances are demanding. As stated in the introduction, the motivation of this thesis was to simulate or overcome such limitations in demanding environments by the use of agent systems.

The agent systems that were proposed in this thesis used computational models of attention, situation awareness and functional state for simulation of human performance. The purpose of these systems was to either provide support in case of performance degradation, or represent human-like performance within an opponent to allow for simulation-based training of realistic situations. Validation was performed for most of the agent systems, either against human data or by using expert evaluations. This provided a strong argument for the effectiveness of the agents to simulate human-like behaviour, or support human performance.

In this section, an overview is given on what research aspects are addressed in the different chapters that were presented in this thesis. Also, the outcomes of the research are discussed in the light of the three research questions as put forward in the introduction. Finally, the contributions of this thesis are discussed by considering existing research, and directions for future work are given.

1. Research Overview

In Chapter 1, three research questions were outlined and the research methodology was explained. These aspects were used to create an overview of the research that can be found in this thesis. In Table 1 it is shown which research aspects were addressed in the different chapters. The table contains the following elements:

- *Performance aspect:* this column contains the relevant aspects of human performance on which the chapter focused.
- *Research Question:* here references are given to the specific research questions that were addressed in the chapter:
    1. How can the role of functional state, attention and situation awareness on human performance be represented by models?
    2. How can models of human performance be applied to agent-based support models to allow for effective support?
    3. How can models of human performance be used for simulation of human-like agents, to be used in serious games that allow for training opportunities?
- *Evaluation:* this column states what kind of evaluation is applied to the proposed agent model in a chapter. Evaluation of the model could be done in three different ways. Firstly, it could be investigated whether the model described realistic human behaviour, often done by comparing it with human data (*data*) and in some cases by analysis of simulation patterns (*sim*). Secondly, in case of agent support, human experiments could be performed to investigate whether the

support was effective (*effective*). Thirdly, the results of the model could be evaluated in light of expert opinion (*experts*).

Table 1. Overview of research addressed in the different chapters

Chapter	Performance Aspect	Research Question	Analysis
2	**Functional State**	**1**	**Data**
3	**Functional State**	**2**	**Data**
4	**Functional State**	**1**	**--**
5	**Functional State**	**2**	**--**
6	**Attention**	**2**	**Effective**
7	**Attention**	**1, 2**	**Data**
8	**Situation Awareness**	**1, 3**	**Data**
9	**Situation Awareness**	**3**	**Experts**
10	**Situation Awareness**	**3**	**Experts**
11	**Situation Awareness**	**1, 2**	**Sim**
12	**Attention/FS**	**1, 2, 3**	**Data**
13	**SA/FS**	**3**	**Sim**
14	**FS**	**2**	**Effective**
15	**SA/FS**	**3**	**Experts**

Next, a discussion of the research is presented considering the contribution to one of the three research questions.

1.1 Research Question 1

How can the role of functional state, attention and situation awareness on human performance be represented by models?

This thesis showed models on functional state, attention and situation awareness. To design these models, the relevant concepts and relations for the given areas were explored. In this section, the main findings on the design of these models are outlined.

1.1.1 Functional State. With respect to functional state, many different aspects were found that are involved in determining the human's state and performance. In this thesis, a complex dynamic model of functional state was presented that incorporated the cognitive energetical framework as well as the different influences of personality on task performance and experienced pressure. The model was validated using an experimental approach and parameter tuning techniques showed that the model can be used to adequately predict human performance.

Also, it was investigated whether a less complex model of functional state could also be used to predict task performance. Here, the cognitive energetical framework was combined with the input of task load for prediction of human performance. By comparison of the outcome of this model with human data, it was concluded that the model was able to predict a realistic task performance. Which of the two models can best be used depends on the circumstances. If a situation arises where not all characteristics of a person are known and a quick prediction of human performance needs to be made, a simpler model can be more useful. On the other hand, when there is time to tune the complex model to the person performing the task, the complex model is able to simulate more aspects of the person's state.

1.1.2 Attention. The model of attention that was proposed in Chapter 6, aimed at predicting bottom-up attention. This is done on the one hand through a saliency map of features in the environment. On the other hand, the model uses the human's eye movement information as input to determine the human's current attention distribution. As an output, the model estimates to what locations a person directs the attention for the given task and environment. Application of the model within an agent-based support system resulted in effective manipulation of attention. This shows that the proposed model provides an adequate representation of attention.

In addition, the attention model was used in combination with parameter tuning techniques that allow for personalization of the proposed model. The tuned model was compared with the regular model by comparison of the estimated attention distributions with the real human attention distribution as measured through humans performing a demanding task. The results indicated that indeed the tuning of parameters provides added value to the attention model.

1.1.3 Situation Awareness. In Part 4, it was identified that an adequate model of situation awareness can be designed by taking into account the three levels of situation awareness (i.e., perception, comprehension, projection). In addition, aspects of working memory and long-term memory were found to be relevant for inclusion within a model of situation awareness. The model that was presented in Chapter 8 shows the importance of memory in maintaining situation awareness and it confirms the need for a regular update of information from the environment.

To be able to represent knowledge in long-term memory, a model of situation awareness was proposed that uses a human's mental model. Within this mental model, a person's knowledge on certain states that belong to a specific task environment can be represented. This allows, for example, for modelling situation awareness in novices as well as experts. As in the latter case, the relations between beliefs in the mental model will be more developed, less information is needed to update the expert's situation awareness. In addition, research is presented that allows for learning of the connection strengths between beliefs in the mental model. This shows that it is possible to use a mental model within a model of situation awareness, even though initially the person's exact available knowledge within long-term memory is unknown.

1.1.4 Integration. Regarding the integration of models and the interaction between them, the most relevant relations between the separate human performance aspects were investigated. Especially functional state was found to have an important influence on both attention and situation awareness. Therefore, models of attention and situation awareness were coupled to the model of functional state.

Considering the integration of the functional state model with the attention model, the experienced pressure was identified as one of the important influences to the amount of available attention. Indeed, it was shown that a model of attention that uses as input the experienced pressure was more effective in estimating attention. When looking at situation awareness, an approach was taken that allowed for the modelling of strategic updating of situation awareness. The amount of effort that can be contributed to updating situation awareness was varied. It was found that less adequate contribution of effort to the update of situation awareness leads to less adequate decision making.

1.2 Research Question 2

How can models of human performance be applied to agent-based support models to allow for effective support?

In this thesis, a number of agent-based support systems have been proposed. The systems were able to reason through the relevant performance model and based on this determine the appropriate support to be given at a specific point in time. An important feature of the presented support agents is that they are generic and can adjust their exact goal depending on the requirements of the task and the environment. Also, in most cases validation of (part of) the agent system was performed using human data, which serves as evidence for the effectiveness of the support system.

In Chapters 3 and 5 support agents were shown that base their specific support on one model of human performance, namely that of functional state and attention respectively. In the former case, the agent reasons through the proposed functional state model and takes a person's effort, exhaustion and performance as input. The agent can be specialized by specific choices based on the task and its characteristics in order to reason in a number of ways about the situation and required support for the human. By using experimental data on human performance, the agent was found to be able to predict human performance resembling that of real humans.

In the latter case, the dedicated support agent was designed to make use of a prescriptive model and a descriptive model. Based on requirements of the task that indicate where attention should be and on the model that estimates where attention really is, the agent determines what support should be given. In the validation study it was found that the attention manipulation provided by the support agent was given a positive evaluation and improved task performance.

Also, a generic agent framework was presented to allow for personal assistance during a human's task execution. The proposed agent framework consists of different components which perform effective reasoning, dependent on the purpose of the task and the characteristics of the person performing the task. The agent is able to load a specific model from the library of models, in this case illustrated for a model of functional state. Furthermore, the agent can determine the exact type of support by reasoning through the dedicated model and knowledge on possible support mechanisms.

The importance of agent-based support systems that are well adjusted to the human performing the task was stressed in Chapter 11. The agent that was presented in this chapter adjusts the type and level of support given to the state of the human. More specifically, a balance is found for keeping a human's exhaustion at a maximal level and the engagement to the task at a minimal level. By continuously monitoring these two states and adjusting the amount of support accordingly, it was shown that more optimal agent support can be given.

1.3 Research Question 3

How can models of human performance be used for simulation of human-like agents, to be used in serious games that allow for training opportunities?

In this thesis, it was investigated what aspects of human performance can best be applied within human-like agents for serious games. It was found to be important that human-like agents are able to represent the stages of information processing, from information acquisition to decision making. For the development of human-like agents, situation awareness was taken as a main component that affects behaviour in these stages. In addition, the agent's ability to update situation awareness was extended with a model of decision making as to be able to simulate the actions that resulted from the agent's judgment of the situation.

Furthermore, research stressed the importance of the ability to represent different personalities within agent systems. The models that were presented are able to do this, through the availability of parameters that can be adjusted in order to simulate agents that display humans who differ in their personal characteristics. This difference can either be represented in the agent's strategy for information acquisition (Chapter 7), in the agent's expertise or in its working memory capacity (Chapter 8). Also, an agent was presented that is able to simulate a person's contribution of effort towards different aspects of situation awareness (Chapter 12). Finally, the possibility of team decision making was shown in Chapter 15, where multiple agents in a team could make a decision based on their situation awareness.

To show that the models can be used for simulation of human-like behaviour, multiple case studies were developed. These case studies focused on the behaviour of human-like opponents in combat flight training simulations. Experts judged the outcome of the simulated case studies and evaluated that it represented realistic behaviour as compared to real fighter pilots. As there are many parameter values involved in implementing knowledge for a case study, a learning method was presented that was able to learn these specific parameter values. This evades the process of setting the parameter values manually and allows the agent to learn the domain knowledge needed to simulate the desired behaviour.

2. Discussion of research contribution

In this section, the research contribution of the work that was presented in this dissertation will be discussed in the light of the existing literature on informal and formalised computational agent models of human performance. When looking at human performance in its broadest sense, from the literature different models can be identified. These models range from predicting academic performance (Zyphur et al., 2007) to predicting a person's driving behaviour (Salvucci, 2006). However, not many models exist that are useful for the purpose presented in the current research. In this section, a discussion is given on the existing models considering (one of) the three aspects of human performance that were investigated in this research. The models are compared with the models that were proposed for this thesis and evaluated on their usefulness within agent systems for simulation and support of human performance.

2.1 Functional State

Two models of functional state have been proposed in this thesis. The models aim to predict performance and effort by taking as a base the cognitive energetical framework (Hockey, 1996). While a graphical representation has been given of this model in Veldman & Jansen (2003), the framework has not been formalized before. The advantage of the use of the cognitive energetical framework is that it enables to estimate the human state dynamically, taking into account the past effort contribution and performance. This allows for modelling the build-up of concepts such as exhaustion and experienced pressure over time.

In the literature, other models of functional state can be found. However, they often do not have such a dynamic nature. For example, models exist that predict the amount of cognitive load from characteristics of the task. Wickens (2002) predicted the mental workload and performance of humans functioning in a multi-task environment by identifying the resources necessary for the task. Based on the amount of conflict between types of resources and the time required to perform a task, the total amount of workload was determined. Also, Neerincx et al. (e.g. 2003) present a model that estimates the cognitive load of a given task by looking at the switch costs, time occupied and level of information processing necessary for the task.

In addition, the advantage of the functional state models is that they address multiple aspects of the human's functional state. This is especially apparent in the more complex model presented in Chapter 2, which takes into account aspects such as a person's experienced pressure, personality and expertise. Models that have been presented previously often focus on one specific aspect of functional state, such as fatigue (Dawson & Fletcher, 2003; Gonzalez et.al., 2011). Wilson and Russell (2003) do aim to model the functional state by taking the human's psychophysiological state into account as input to a neural network that classifies the level of workload. However, the model is not able to relate the human's psychophysiological measurements to specific aspects of functional state, that result from accumulation over time such as exhaustion and experienced pressure.

When looking at agent-based support systems, literature can be found on automation that adapts the support to a human's workload. However, often in such cases the estimation of a human's workload is based on data from the environment. In Stuiver et al. (X) and Byrne & Parasuraman (1996) support is given based on a human's physiological response during task execution and Kaber & Reilly (1999) estimate workload by using a secondary task. Although it is useful to have real-time information on human functioning, ideally such data should be combined with a model to obtain a more complete overview of functional state and the accumulation aspects of it.

2.2 Attention

In this thesis, bottom-up attention is modelled by using a saliency map that incorporates the saliency of features in the environment, as well as the human's current eye movements. Several other models have been proposed that show that it is possible to simulate attention allocation based on a saliency map, calculated from features of a stimulus, like luminance, colour and orientation (Itti & Koch, 2001; Parkhurst et al., 2002; Verma & McOwen, 2010). Also, le Meur et al. (2006) combine the saliency map with more complex characteristics of bottom-up attention such as contrast sensitivity and visual masking. A drawback of these models is that they are often not dynamic in the sense that they do not take the attention distribution over time into account. The models predict a human's attention to static pictures, while especially for simulation of attention in dynamic circumstances, the influence of changes in the environment is important.

Also, much is known on the features that guide attention (Theeuwes, 1994; Itti & Koch, 1998). However, few attempts have been made to design a support system with the purpose of directing attention to the most salient location. Automated attention guidance has been investigated, by providing either a tactical cue (Sklar & Sarter, 1999), a visual cue to a relevant location (Horrey et al., 2006), or changing the saliency at a location (Veas et al., 2011). However, this automated cueing is merely based on features of the task (i.e., threat of an object), or features of the environment (i.e., saliency of a location), and not on the human's actual distribution of attention. In contrast, the attention support system presented in this thesis makes use of the descriptive attention model to obtain an estimation of the human's attention distribution and combines this with the prescriptive model to determine the location to where attention should be manipulated.

2.3 Situation Awareness

The presented research on situation awareness contributes to the existing literature on situation awareness as it aims to model in a formalised computational manner the most relevant concepts as defined informally in the psychological literature. The models were equipped with prominent concepts, such as working memory and mental models. Also, the three key stages within situation awareness as defined by Endsley (1995), perception, comprehension and projection, were modelled. In addition, personal characteristics were identified that strongly influenced the updating of situation awareness, such as expertise

(Schriver et al., 2008) and working memory capacity (Johannsdottir & Herdman, 2010). These aspects have been taken into account within the proposed models.

Other computational models have been proposed for Situation Awareness, also in dynamic environments. For instance, So and Sonenberg (2004) create a computational model for situation awareness for defining pro-activeness of behaviour. In their model, they also use the model of Endsley as a basis and they incorporate beliefs with certainty factors. However, the differences between novices and experts in this reasoning process are not explicitly taken into account. This has been done in the model of situation awareness as proposed in this thesis.

As mentioned in the introduction, BDI models (Rao and Georgeff , 1995) in general can also be seen as models for Situation Awareness, as most of these models incorporate the formation of beliefs based upon observations, and can create a projection for the future to decide which intention to pursue. These models do however not explicitly incorporate all the criteria shown to be important in Situation Awareness, such as the ability to distinguish between experts and novices and the influence of working memory.

One particularly interesting field is the domain of *situated agents* which are "artificial systems capable of effective, rational behavior in dynamic and unpredictable environments" (Kinny and Georgeff, 1991), for which the crucial problem faced is "to ensure that the agent's responses to important changes in its environment are both appropriate and timely" (Kinny and Georgeff, 1991). Within these approaches however, the emphasis is mainly on selection of appropriate actions, given that beliefs have been formed, and not so much on creating an adequate model of the world such that decisions can be based on a more accurate description of the situation. When looking at the literature in Psychology, modelling the part concerning the perception and judgment of the situation is crucial to enable good responses (Randel and Pugh, 1996).

Furthermore, earlier systems have been investigated for the purpose of giving support based on a human's situation awareness. In Feng, Teng & Tan (2009) an agent system is described that supports the decision making of humans performing a task, depending on their awareness of the context. Also, in the field of adaptive automation, systems can be found that provide automation dependent on the situation awareness. However, the situation awareness is measured by looking at psychophysiological measurements (Pope et al, 1995) or subjective evaluation, instead of model-based prediction, which would be a more accurate way of giving support.

2.4 Integration

Few models have been designed that allow for an integrated representation of multiple aspects of human performance. Wu and Liu (2007) do aim to model the effect of workload on measurements of human performance, but do not integrate concepts such as attention and situation awareness. In another example from the literature, effort and situation awareness are incorporated in a model that predicts attention of humans functioning in demanding environments (Gore et al., 2009; Wickens et al., 2009). Although the model does look into relevant aspects of attention, the effort and the situation awareness component are not very complex. For example, the effort refers only to the effort that is needed to move attention to a location and no other relevant aspects of functional state (i.e., motivation, exhaustion) are considered.

3. Directions for Future Research

In this thesis human performance models on attention, functional state and situation awareness were explored to design agents for the purpose of either performance support or simulation of human-like behaviour. Although the current research reported is extensive, more effort is needed for a complete elaboration of human performance models and agent systems.

The model integration that was done focused mainly on extending the models of attention and situation awareness with components of the human functional state. Although the literature showed that this was an important interaction, additional integration can be done in the future. For example, the interaction between attention and situation awareness was not explicitly taken into account. More specifically, an agent system equipped with situation awareness uses some aspects of top-down attention, involved the selection of observations. However, the agent could simulate this selection more accurately by using additional knowledge on bottom-up attention.

In addition, more research should be done on the integration of models within agent support systems. The personal assistant agent that was shown in Chapter 14 was able to load a model from an existing library of models. This library needs to be extended with multiple models to allow for the integration of different aspects of human performance. This way, the support agent can improve human performance in a wide range of situations and tasks.

The human-like agents that where proposed were able to provide realistic behaviour. However, future research would be useful to further investigate the application of such agents within real training systems. For this, different agents that are equipped with different models need to be applied within opponents in a training simulation. Evaluation of these agents can be done by looking at the behaviour of humans learning a task through such a simulation. By both analysis of their learning curve or subjective evaluation of their preference, the effectiveness of different human-like agents can be investigated.

Finally, further research should be done considering the investigated support agents, in order to determine their effectiveness in real-life circumstances. Although the proposed agents have been found effective for improving human performance in experimental settings, real-life situations have different characteristics which might influence the dedicated agent support. For example, it is possible that sensory input is less reliable for humans on board of a naval warfare ship when they are walking around. The current support agents do incorporate aspects such as reliability, but they should be investigated to check whether they can estimate and improve performance of humans functioning in realistic environments.

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