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

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Part I

Introduction

Chapter 1

Introduction

Introduction

1. Motivation

Air traffic control, naval warfare and air combat fighting are examples of domains where high demanding tasks have to be executed. For an optimal performance on such tasks, humans have to process a great amount of information. Unfortunately, processing can be impaired due to limitations in human cognition (Wickens & Hollands, 2000). For example, a person cannot spend an unlimited amount of time and effort on a task. Also, humans cannot distribute their attention to every piece of information in the environment. These limitations often lead to bad performance or errors in decision making, which have significant negative consequences, especially in high-risk environments such as the ones listed. Also, the fact that humans constantly need to maintain a high task performance may lead to stress, which in turn influences human functioning (Gaillard, 1993).

To aid humans in their task performance and to overcome limitations in human cognition, automated systems can be of help. On the one hand, systems can contribute support in case of performance degradation. As these systems need to interact with humans, it is important that they take into account characteristics of human functioning. This way, they serve as an extension of human cognition, not a replacement. On the other hand, automation can be used to provide training for people that have to perform well in demanding circumstances. Human-like agents that serve as opponents or team mates in training simulations need knowledge of human performance. This allows them for simulation of performance resembling that of human opponents or team mates in real-life situations. By training with such human-like opponents, humans can learn to handle the opponents' or team mate's unexpected behaviour as caused by human performance limitations. This will increase their task performance when having to deal with a real opponent.

This thesis is aimed at an exploration of computational modelling of human-like performance which is applied to (1) the design of agent systems that improve human functioning in demanding circumstances, and (2) human-like virtual agents in simulation-based training. For this purpose, human performance models that represent aspects of human cognition when performing a task, are created and analysed. Such models can be applied to agents that perform a specific task, in order to display human-like behaviour that represents that of a person with specific characteristics. Also, support agents can be designed that reason based on such models of human performance in order to predict performance degradation and to select the appropriate support when necessary.

Amongst the aspects that are involved in human performance under demanding conditions, important ones are a human's functional state, attention and situation awareness (e.g. Ma & Kaber, 2005; Parasuraman et. al., 2009; Wickens, 2002). A human *functional state* represents the dynamic state of a person during task execution, which includes personality, cognitive load and stress (Hockey, 2003). The functional state of a human influences the amount of effort a person can and will contribute to a task. Secondly, *attention* needs to be directed to the optimal location(s) in order to obtain good performance. Especially in dynamic tasks this is difficult, since attention needs to be directed to many locations at the same time. Therefore it is important to investigate a human's attention distribution when looking at human performance. In turn, attention contributes to *situation awareness*, a third important aspect of human performance. Situation awareness refers to a person's picture of the environment and is an important predecessor of decision making (Endsley, 1995). Adequate knowledge of the current situation and its temporal projections to the future leads to optimal decisions and to an optimal performance quality.

2. Research Questions

Given the above motivation three important research questions were investigated in the research reported in this thesis:

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?

3. Background

In this section, a background is given on the relevant concepts to be considered in line of this thesis. The three aspects of human performance are explained. Also, this background stresses important characteristics of human performance models for their application within agent systems.

3.1 Human Performance

Many interpretations of human performance exist. One can consider human performance by only looking at the output of a task. This often results in measures of speed or accuracy (Wickens & Hollands, 2000). On the other hand, a broader way of defining human performance is to consider the underlying human information processing that is responsible for human behaviour while performing a task. This thesis focuses on three aspects of such human information processing: a human's functional state, attention, and situation awareness, aspects all contributing much to human performance. Here, a more detailed explanation is given on these concepts and their influence on humans performing a demanding task.

3.1.1 Human Functional State. The Functional State of a human (or operator) represents a combination of factors involved in task execution that influence the human's cognitive and physiological state. In Hockey (2003, pg. 3) it is defined as:

"The variable capacity of the operator for effective task performance in response to task and environmental demands, and under the constraints imposed by cognitive and physiological processes that control and energise behaviour."

The advantage of studying a human's functional state to analyse human performance is that it allows for the possibility to take into account metrics of human performance other than the outcome of the task. Although the functional state does consider task performance, it also focuses on the emotional and physical state in determining human performance. Someone can obtain 100% accuracy on a task, but if the person is completely exhausted upon finishing the task, human performance is not as desired. Also, as personality plays an important role in the functioning of a human, it is important that models of human performance are able to simulate persons with different personal characteristics. In models on functional state, aspects such as motivation, perfectionism and cognitive capabilities can be incorporated.

Since models of functional state incorporate multiple aspects of human performance, agent systems that use such models should also be able to adapt to multiple aspects of human task execution. This way, agents that are aimed at simulating performance for a human-like training can adapt their behaviour according to the requirements of a specific training. Also, support agents that are able to adjust their goal can support specific aspects of the human functional state. For example, in tasks that require a high performance for a short amount of time, it is important that support is directed at maintaining the effort contribution to the task. However, if a task needs to be executed for a long time period, it is of importance that support is aimed at keeping the person's experienced pressure within boundaries. This is important both from a task perspective (experienced pressure will influence task performance), but also from a person's perspective, since too much experienced pressure may produce long-term stress effects.

Ideally, agents systems that focus on human performance should use sensor information on human performance in combination with models on human functional state. Changes in a human state will result in changes in the human's body. Thus, the use of psychophysiology, such as heart rate, heart rate variability and eye blink activity allows an agent to obtain additional information on the human functional state (Wilson & Russell, 2007). Agents systems that combine sensors from the environment with human performance models are able to obtain an even more complete overview of a human and the task performance. Together with knowledge on the human's personality, this will result in appropriate agent systems that are tailored to a situation and to an individual.

3.1.2 Attention. When looking at a visual scene, our attention shifts rapidly from one location to the other in order to process the available information. Typically, the direction of a person's attention is influenced by top-down and bottom-up processes (Pashler et.al., 2001). Top-down attention is goal-directed and depends on the task at hand or the intentions and expectations of the observer. For example, when someone is looking for one's car in the parking space, attention is guided top-down. The person's attention is directed towards the specific features of the car and the expectations about the location at which the car is believed to be parked. On the other hand, bottom-up attention is elicited by features of the objects in the environment. Whether a location draws bottom-up attention depends on the saliency of the features at that location. Salient features will pop-out of the scene: a green triangle pops out amongst red circles and a flashing object pops out amongst static objects.

Attention is an important element of human information processing. It has a strong contribution to human performance, considering that only information that a person attends to can be used for further analysis and decision making. Unfortunately, a human's attention is limited in the sense that attention can not be directed to each part of all available information. An example of this is the phenomenon called change blindness, which shows that people are often unable to detect changes in an object or scene (Simons and Levin, 2005). Considering the crucial role of attention in human performance, it is important to be incorporated within the type of human-like agent systems addressed here. When agent systems take into account attention in their simulation of performance, this will result in more human-like behaviour. For this, the situational aspects of a training environment should serve as an input for the attention model. This allows for a realistic attention distribution, and for the simulation of errors in performance as caused by limitations of human attention.

In addition, to overcome the limitations in attention and thereby improving human performance, agent systems that direct a human's attention to an important location are very useful. Especially in demanding circumstances this will be of help, as experienced stress in humans narrows their field of attention (attentional tunnelling; Williams, 1988). For an optimal support of a human's attention, the agent systems should be able to estimate a person's current attention distribution. This can be done with the use of models on attention. Also, a person's eye movements reveal a great deal on the location of attention. Ideally, models should combine information on eye movements with information on features of the environment, in order to provide a complete overview on the human's attention distribution. This information can be used within agent systems in order to compare the estimation of a human's attention to the optimal attention distribution and to give support when necessary.

A possible way for agents to give support towards a better attention allocation for the current situation is the manipulation of features in the environment. When looking at bottom-up attention, previous research shows that attention can be elicited by the contrast with stimuli at other locations Itti and Koch, 2001; Levitt and Lund, 1997). Also, attention will be directed to locations or objects that abruptly change luminance or form (Theeuwes, 1995; Turatto and Galfano, 2000). The possibility to change features in the environment allows for a real time improvement of human performance.

3.1.3 Situation Awareness. Situation Awareness refers to the picture that humans have of the environment in which they are functioning. Endsley (1988) has defined it as: *"the perception of elements in the environment, the comprehension of their meaning and projection of their status in the near future"*. Here, perception refers to attaining the available information. For comprehension, interpretation of the perceived information is necessary, as well as the integration of multiple pieces of information. The ability of projection contributes to the ability to predict future events and anticipation to possible problems. Low situation awareness can be caused by problems in any of these three aspects, which will lead to problems in decision making and less optimal performance. For example, a lack of situation awareness when driving a car can result in missing a traffic sign and turning left at a point where it is not allowed.

The importance of the ability to maintain situation awareness is especially apparent in dynamic environments. As elements in such environments change rapidly, a person's situation awareness should also often be updated. If someone needs to make a quick decision, but is not aware of how the situation has changed, this decision will be based on the wrong situation. This can have high consequences for performance. The effect of situation awareness on performance is reflected in a domain such as aviation, where many errors occur due to a lack of situation awareness (Durso and Sethumadhavan, 2008).

Considering the importance of situation awareness in decision making, this aspect should be taken into account when looking at human performance in dynamic tasks. For example, virtual agents that are able to update their situation awareness and base their decisions and actions accordingly, will display realistic behaviour. When agents with such human-like performance serve as opponents in a training simulation, this will allow for optimal learning circumstances and increase performance in real-life situations. Several factors that are involved in a person's ability to maintain situation awareness can be considered for the design of human-like agents. For example, a person's working memory capacity is seen as an important aspect involved in reasoning on a specific situation (Endsley, 1995). Also, expertise influences a person's ability to obtain a good picture of the environment (Schriver et.al., 2008).

Furthermore, the environment in which humans function has a large influence on their situation awareness. Nowadays, humans often interact with automated systems, which can impose challenges for situation awareness when badly designed. Also, when humans rely on automation to perform a task, they will feel less need to update their own situation awareness (Parasuraman, 2000). This will result in less optimal human task performance when the system fails. Therefore, agent systems designed to support humans in their interaction with the environment need to consider situation awareness in order to prevent an otherwise inevitable decrease of human performance.

3.1.4 Interaction. When looking at the cognitive concepts described in the previous sections, it is important to realize that not only the concepts alone have a strong influence on human performance, but also the interaction between them. For example, attention is necessary for good situation awareness while at the same time situation awareness directs a person’s (top-down) attention to a specific location (Endsley, 1999),. In addition, effort as determined by the human functional state is an important prerequisite for an optimal attention distribution and good situation awareness (Kahneman, 1971; Wickens, 2002). Also, a suboptimal human state, such as a high level of experienced stress can influence both attention (by a decrease in the amount of attention available) and situation awareness (by using less information from the environment; Dirkin, 1983, Endsley, 1995).

Ideally, these types of interaction should be considered in the design of agent systems. Systems that use integrated models are able to obtain an even better representation of human performance as compared to systems that consider single aspects separately. This way, a more realistic simulation of behaviour within human-like agents provides for optimal training circumstances. Also, with the use of integrated models, agent systems can be designed that give optimal support, thereby improving performance of humans executing a task.

3.2 Human Performance Modelling

Now that the relevant aspects in determining human performance are explained, this section gives a background on the important considerations on human performance modelling for agent systems. Human performance models are aimed at representing a part of human cognition and use this for simulation of human performance in a specific task. From the literature, the models on human performance that are proposed differ in the dedicated purpose of the model and in the aspect of performance that is simulated. For example, some of these models focus at simulation of human performance in a specific task and environment, such as a model that predicts errors in pilot taxiway navigation (Lebiere et.al., 2008). While it is useful to predict performance for the dedicated task, such models are difficult to use within agent systems, since they usually can not apply to multiple scenarios.

When designing a model for its application within agent systems, the general nature of the model is important. That is, the model should be able to simulate human performance within multiple tasks in multiple environments. With use of a general model the agent has the opportunity to tailor support to each situation, where otherwise a new model should be used for each specific case. Also, the model should be general in the sense that it can be applied to persons with different personalities. Therefore it is important that a model contains personalized parameters that can be adjusted depending on the person performing a task.

This thesis focuses on models of human performance that represent the three aspects of human performance discussed in the previous section; attention, functional state and situation awareness. The design of a general model on either one of these concepts is not trivial, especially considering their dynamic nature. When looking at previous research, other models have been proposed. For example, models on attention can be found that use a saliency map to predict a person's bottom-up attention based on the features in the environment (Itti & Koch, 2001, Parkhurst et.al., 2002). Also, computational models have been proposed that are able to estimate the amount of workload from characteristics of the task to be performed (Wickens, 2004; Neerincx, 2000). The estimation of cognitive task load is important in determining a person's functional state. Furthermore, several models exist, that focus on one of the aspects important for situation awareness, such as memory (O'Reilly, 2006) and belief updating (Rao and Georgeff).

However, more general models need to be designed that can be both tailored to characteristics of the environment and tailored to the characteristics of the person performing a task. Also, the complexity of functional state, attention and situation awareness, asks for models that can represent all important aspects involved in these concepts. Another important characteristic of models that are to be applied within agent systems is that the agent should be able to combine a model with sensor information on the environment. Considering that the context is relevant in determining a human state and performance, sensor data can provide important additional information. This requires models that allow for integration of model concepts with sensor data from the environment. Using models that meet these important requirements, optimal agent systems can be designed that will maximize human performance and minimize errors in task execution.

4. Research Methodology

In this section, an overview is given of the research methodology that was used to answer the research questions addressed in this thesis. This methodology allows for a good representation of human performance and allows for models to be used for agent support or simulation of human-like behaviour.

4.1 Obtaining background knowledge

The motivation for the design of models on human performance was derived from problems identified from real-life circumstances. This is often done in close collaboration with persons who have experience with human task performance in dynamic tasks. Also, the knowledge available from literature is used to identify the problem space. The combination of expert opinions and psychological literature serves as a base for identification of aspects required for a good representation of human performance in demanding tasks and of important qualifications of agent support systems.

4.2 Design of informal model

When the topic and the purpose of the model are availabe, the important concepts are identified by using psychological literature. Much research has been conducted on human performance in demanding tasks, especially in the field of attention, workload and situation awareness. However, there are not many papers that address all aspects of a problem in a given situation. Therefore, the most important concepts and relations were identified from different pieces of available literature. These are used in order to make a schematic overview of the specific aspect of human performance (for an example, see Figure 1). Eventually, with the available knowledge, an informal model is created that gives a representation of the dedicated concepts and relations between them.

4.3 Formalization

After designing an informal model, the model needs to be formalized to allow for a formal representation of states within the model. This representation can be used within agent systems for simulation of human behaviour. The models that are presented in this thesis are mostly formalized by using mathematical formalization methods. In order to do this, first the numerical range of all concepts is specified. Then, the exact influence to a given concept is represented by a mathematical relation. This relation includes all inputs to the concept, combined with parameters to determine the precise impact of an input.

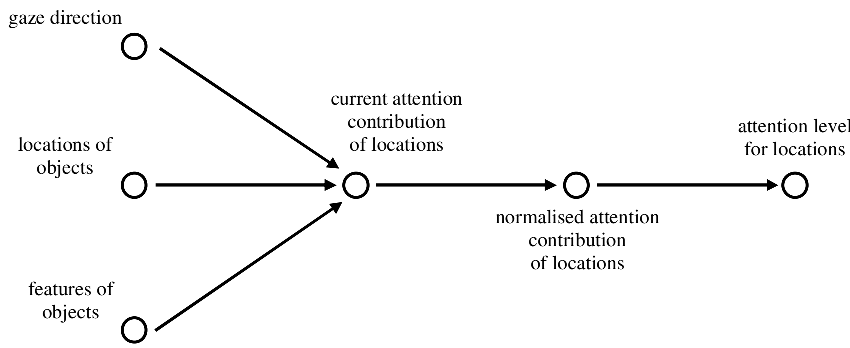

Figure 1. Example of a schematic model (taken from Chapter 6)

4.4 Simulation/Verification

By using the formalization of a model it is possible to represent states of a human performance model in terms of numerical values. Consequently, simulations can be performed to obtain more knowledge on the behaviour that follows from the formalization. Typically, such a simulation starts with the determination of parameter values that result in a realistic pattern of human behaviour. For an evaluation of realistic human behaviour patterns, first properties are formulated on the desired characteristics of behaviour. This is done by either consulting expert opinions or by analysis of the available literature on the topic, and by formalizing the type of patterns found. By systematically varying the input values to the model, the defined properties can be checked. One way of checking the properties is by performing a formal verification. In this thesis, formal verification is done with use of the Temporal Trace Language (Bosse et. al., 2007), that is able to check for temporal patterns of human behaviour.

4.5 Agent System Design

In order to apply the human performance models, it should be possible to reason on the basis of these models. Therefore, agent systems have been designed that take a human model as input and apply them to a specific context or task, depending on the purpose of the system. In case of agent systems that are designed to display human-like behaviour, the model is used to simulate the dedicated behaviour, which is executed by the agent system. On the other hand, within agent support systems, human performance models are used to predict performance for a given task and conditions. In case of performance degradation, the agent will use the human model to determine the exact support that should be given.

4.6 Human Experimentation

Human experimentation is a method that can be used to validate agent systems against human data to determine their effectiveness. For example, when agent systems are designed to give support, validation will provide information on whether the support really did improve a human's performance. The experiments are designed such that a comparison can be made between performance with and without a support agent. Other experiments can be designed for validation of agent systems that serve as human-like opponents in training simulations. A good experimental method to evaluate such systems is to look at how well humans learn a specific task when training with the system.

Also, the method of human experimentation is used to test and improve human models. The performance data that results from human experimentation allows for the tuning of parameters of a given human performance model. This means that a person first performs a given task. After this, the parameters in the model are adjusted (by means of a tuning algorithm) such that the simulated data best represents the person's behaviour. This way, the models can adapt to the characteristics of the person performing the task.

5. Overview of this Thesis

The parts that follow contain the research papers that are relevant to answer the research questions of this thesis. Most chapters were previously published in peer-reviewed journals or conferences, and, where applicable, references to the publications are given.

In each part, different aspects of human performance are addressed, except for the current part and the final part that gives a discussion of the work. Part 2, 3 and 4 present research on functional state, attention and situation awareness, respectively. Part 5 focuses on the integration and the interaction of models within agent systems. In this section, a brief overview is given on the contents of the chapters that are presented in the different parts.

Part 2 focuses on the human functional state. Two models on functional state are shown that have been designed in the light of this thesis. The two models can both be applied in different situations. On the one hand, a complex model is designed that considers many aspects of human functional state, including personality and expertise. On the other hand, the second model is more general and therefore allows for the design of agent systems that can easily be tailored to the purpose of the task. Both models have been validated using human data. In addition, this part presents psychological research that aims at exploring the aspects of human functional state that are important for human performance, such as personality and psychophysiological measurements (i.e. ECG, eye blink). Agents can integrate this external information with models on functional state to be able to contribute adequate support given a person performing a task.

In Part 3, a model of attention is addressed. The model design is described and an agent system is presented that takes the prediction of this model into account. In combination with features from the environment and the goal of the task, the agent gives support on the desired human attention distribution. Validation has been done on both the model and agent system. Results prove that it is possible to represent a human's attention distribution and that the agent system can effectively manipulate attention to the optimal location. In addition, this part applies a technique of parameter tuning to the attention model. This shows that the attention model can be tailored to the characteristics of the person performing the task.

Part 4 addresses situation awareness. Research is presented that investigates how humans select important information, either through sensing or through memory. Based on human data, a model is designed that predicts how and when a person selects information. In addition, this part proposes an agent that can represent the three stages of situation awareness. The agent makes use of a person's mental model on the situation that contains beliefs and connections between them. Techniques are shown with which an agent can learn those belief connections. Finally, an automated system is presented that takes into account a person's situation awareness while at the same time minimizing exhaustion.

In Part 5, integration of the models on the different aspects of human performance is addressed. Several models that were presented in Parts 2 to 4 are combined to provide a more complete representation of human performance. Attention and functional state are coupled, as are situation awareness and functional state. Also, a general support agent is proposed that makes use of a library with different models in order to load the appropriate model when necessary.

The thesis concludes with Part 6, where a general discussion is given on human performance modelling. The results of the presented research are evaluated in the light of the research questions that were addressed in Section 2 of this chapter. Also, Part 6 looks at directions for future research that are necessary in order to keep improving human performance models to allow for effective agent systems.

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