Using cardiovascular measures for adaptive automation
Stuiver, Arjan

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 13-08-2019
CHAPTER 1 - INTRODUCTION

Introduction

An inspiring new phase in the study of human-computer interaction has arrived with adaptive automation. In this field, technological systems are developed that adapt to the needs and demands of the human operator (Duric et al., 2002). The main goal of adaptive automation is to design systems that include both the human operator and technical systems, in which the support system serves to take over tasks from the human operator where and when needed. Support systems have been proposed for use in air traffic control rooms, in the car and in other control rooms such as military operation and emergency vehicle dispatch centres. The overall approach used in these proposals is based on the idea that the whole system (human and machine) functions best if workload is kept at an optimal level. Several methods have been put forward how to assess mental workload in this context and how to create reliable indices. One approach is to use psychophysiological measures, or more specifically cardiovascular indices for the assessment of mental workload. In this thesis the strengths and weaknesses of some of the currently available cardiovascular measures and analysis methods are investigated and a description is given how these methods may be improved in terms of sensitivity and usefulness for adaptive automation by describing a new approach that focuses on short term (40-60 seconds) responses to changes in task demands.

Adaptive Automation

In literature on adaptive automation, adaptive systems are suggested to provide a solution to the restrictions of traditional automated systems (Scerbo, 1996; Parasuraman and Riley, 1997; Hoogeboom and Mulder, 2004; Miller and Parasuraman, 2007; Mulder et al., 2009). In traditional automation, a machine agent executes task functions that would otherwise be carried out by a human operator and this might have many advantages over manual labour (Parasuraman and Riley, 1997). These advantages include increased capacity and productivity, reduction of human errors, reduction of manual workload and fatigue, and more precise and quicker handling of routine operations (Wiener, 1989; Wiener and Curry, 1980). On the other hand, automation changes the role of the operators; often reducing them to passive monitors who need to remain vigilant while monitoring a highly reliable system.

The effect of traditional (full) automation on the human role in previously mental demanding tasks creates a whole set of new problems. These are referred to as 'out of the loop' problems, revealing themselves as increased boredom, reduced situation awareness, manual skill erosion, and late detection of automation failures (Wiener, 1989; de Waard et al., 1999; Endsley and Kiris, 1995). The
solution that adaptive support systems provide is to keep involved the human operator as much as possible in the task and only to automate (sub) tasks if and when support is really needed by the human operator. To achieve such an optimised situation, the adaptive system must first assess when support is really needed.

Several strategies have been suggested for triggering adaptive support automatically (Parasuraman et al., 1992). Rouse (1988) stated: 'The level of aiding, as well as the ways in which human and aid interact, should change as task demands vary. More specifically, the level of aiding should increase as task demands become such that human performance will unacceptably degrade without 'aiding'. One way to initiate adaptations in a machine environment is to use operator's preferences. An operator could simply 'command' extra assistance when he or she thinks support is required, which has the advantage that support will always be experienced as correct and timely. A drawback might be that the operator is not always aware of whether assistance is needed and the need to activate assistance might actually increase workload temporarily. Scerbo (2001) labels systems where the operator is in control of when assistance is initiated as adaptable systems, in which 'the human always maintains authority to invoke or change the automation'. In contrast, 'in adaptive systems, the authority over invocation is shared' according to Scerbo. In the latter approach, the adaptive system assesses when support is needed, usually based on the current operator's functional state. A working definition of operator functional state is given by Hockey 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' (Hockey et al., 2003). This approach has been applied in our lab in the so-called Operator Status Model developed in a project called COMPANION funded by the Dutch government (B. Mulder et al., 2008). The goal of COMPANION was to develop better co-operation between a man-machine interface and the human operator, based on the human's (physiological) state. Our model developed from the COMPANION concept is called the Operator Status Model (OSM). Within the OSM, data acquisition, pre-processing, analysis and status decision-making are implemented, forming a generic system for adaptive automation. A short description of the development of the OSM will be given below, more details can be found in chapter two of this thesis.

For the European FP7 (7th Framework Programme for Research and Technological Development) project HILAS a first implementation of the OSM was made (Hoogeboom and Mulder, 2004). The prototype was tested in simulated test flights by one of the consortium partners (ELBIT). The OSM approach was further developed in PerAda’s REFLECT project (FP7-215893). The REFLECT project aimed to develop concepts for pervasive adaptive systems. A prototype of the OSM was built for the project using heart rate as input. It uses a data acquisition module, a pre-processing module to detect artefacts, and an analysis module to compute the operators' heart rate and to derive variability measures. With the OSM we were able to give an indication of workload while a test-driver was driving.
in a Ferrari on the open road. As initial adaptive response of the system, the workload estimation was used to suppress phone calls during high workload periods.

![Figure 1: Schematic overview of the Operator Status Model](image)

In the Operator Status Model (see Figure 1, Hoogeboom and Mulder, 2004, ©Hoogeboom, NLR) the operator’s functional state is derived from physiological indicators such as heart rate, blood pressure, respiration and other physiological measures (Hoogeboom and Mulder, 2004). This information is combined with information about task performance, which is taken from the active applications. Together, physiological and task performance measurements form the basis for the index of operator functional state. Such measures about the derived functional state can subsequently be applied to affect the Human Machine Interface in such a way that the present functional state can be changed towards an optimal state. In this way task support is used to improve task performance as well as the operators’ mental state.
Mental workload and effort

There are a few concepts in the literature on mental workload that require some explanation. In this thesis, cardiovascular measures, i.e. heart rate, blood pressure and their corresponding variability measures, are used as psychophysiological measures to study workload and mental effort. In general it can be said that increases in effort are strongly related to increases in mental workload. There is however not a one to one link between mental workload and effort since workload is also dependent on several other factors, such as motivation, fatigue, emotional stress and time related factors such as how much time is available and how much is required for a task. It is therefore important to clarify these concepts and their relationships (Mulder and Mulder, 1981; Brookhuis and De Waard, 2001; Mulder, 2009).

The concept of mental workload is used to describe how much of someone’s information-processing capacity is invested during task performance and how this is influenced by task demands. It is important to note that task demands are exclusively properties of the task itself; personal aspects are important when studying how a person deals with the task demands but are not part of the task demands. The amount of resources, a property of the operator, that can (voluntarily) be allocated to cope with task demands are considered scarce and when they are exhausted, task performance degradation is likely to occur (Broadbent, 1958; Kahneman, 1973; Posner, 1980; Wickens, 1984; Hockey, 1997; Gaillard and Kramer, 2000). Mulder (1986) has linked these capacity theories to the, with task demands associated, computational processes and energetical mechanisms occurring during task performance. Although we are looking at mechanisms that explain mental workload, this does not necessarily mean that these processes are always consciously monitored (Meijman & Mulder, 1992). There might be voluntary control over how much effort someone puts into a task but the underlying psychological processes and mechanisms seem mostly inaccessible for conscious monitoring.

With cardiovascular measures we study the (effects of the) energetical mechanisms that become active with the computational processes that take place during task performance. Based on the work of Pribram & McGuiness (1975), who describe three mechanisms that control processing capacity, Mulder (1986) makes a distinction in different energetical resources in the relation between computational processes and energetical mechanisms: arousal (related to input processes), activation (related to output, e.g. motor activity) and effort. He divides effort again in two forms: computational effort and compensatory effort. Computational effort is exerted when resources are used for information processing, which can be compared to the processing effort described by Norman and Bobrow (1975). Mulder (1986) associates computational effort with processes that require working memory. Compensatory effort is meant when resources are used to compensate for a mismatch between the desired and the current psychophysiological state, for example due to prolonged task performance or fatigue. Cnossen (1994) gave these two kinds of effort self-evident names, calling the first task related
effort and the latter state related effort. The latter form, state related or compensatory effort, has been described by Hockey (1986) in his state control theory in which he states that central executive mechanisms compare the current cognitive (psychophysiological) state to the desired state and allocate resources to return to the desired state when a difference is found.

When dealing with invested effort to meet task demands, it must be taken into account that the response to the imposed demands has a large voluntary component. Demands may change but a change in effort only follows if the person willingly changes his effort. Vice versa, effort may even change without any changes in task demands but solely on a person's own initiative. The possibility to respond in various ways to (changes in) demands is included in the state control theory of Hockey (1986) by taking strategy into account. With the same demand, changes towards a different strategy (e.g. being more reluctant to errors or feeling less time pressure) may result in a different level of effort investment. This does not mean that no relation can be found between demands and effort, but it must be kept in mind that this relation is mediated by strategy. Performance measures may be needed for detecting strategy changes and, for example, performance degradation can be a clue to an adapted strategy (Hockey, 1986).

**Mental Effort and Cardiovascular Measures**

Cardiovascular measures can be used to study the effects of mental effort and to create an index or indices for mental workload, which may then be used in adaptive automation, as described in the previous paragraphs. The cardiovascular response that is often found with increased mental effort is a pattern of increased HR in combination with decreased HRV (Mulder and Mulder, 1981; Veltman and Gaillard, 1998; De Rivecourt et al., 2008; Dijksterhuis et al., 2010), accompanied by an elevated blood pressure (BP), lowered baroreflex sensitivity (Mulder and Mulder, 1981; Reyes del Paso et al., 2004) and higher respiration rate (Wientjes, 1992). This response has been characterized as a defence reaction or a preparatory fight-or-flight response (Berntson et al., 1991; Jordan, 1990; Mulder, 1980). In other words, heart rate and blood pressure measures tend to increase while heart rate variability and blood pressure variability measures tend to decrease during periods of additional effort during task performance (Mulder, 1992).

Some authors have raised questions about the usefulness of current measures in (semi-)realistic work. Criticism has risen because contradictory results and inconsistencies have been found in the relationship between mental effort and effects in psychophysiological measures (Veltman and Gaillard, 1996; Sirevaag et al., 1993; Mulder, 1992; Wilson, 1992; Jorna, 1992; Porges and Byrne, 1992). Large parts of these inconsistencies are related to not completely understanding the conditions and circumstances of changed cardiovascular response patterns (Mulder et al., 2009). Despite these restrictions,
cardiovascular measures still receive much attention from researchers to be used as indicators of mental effort. There are two main reasons: firstly techniques for measuring improve and become less intrusive, making the use of cardiovascular measures in real world settings easier and more acceptable, a trend that has been going on since the onset of research into cardiovascular measures. The second reason is that within well-defined settings, cardiovascular measures have given clear and consistent results (Hockey, 1997; Parasuraman and Wilson, 2008; Ting et al., 2010; Byrne and Parasuraman, 1996; Gevins and Smith, 1999; Haarman et al. 2009). Inconsistent results have been found in situations in which it is not exactly known what is happening to the entire system. This is why effort should be invested into the development of more sensitive measures by looking how the system as a whole works and creating measures that focus on the part that is sensitive to mental effort related to computational processes.

It is important to realize that the cardiovascular system not only reacts to effects of mental effort, but e.g. also works to stabilize blood pressure in general. For task situations this has been described as a compensatory reaction of the short-term blood pressure control system (baroreflex, e.g., Mulder et al., 2004, Van Roon et al., 2003). When blood pressure increases over time in periods with increased effort, the blood pressure control system will react by trying to compensate for the elevated blood pressure. Typical effects are a lower heart rate (less beats per minute means less pressure) and increased heart rate variability. The response to mental effort over a longer period of time is often a combination of a defence reaction, followed by a compensatory response of the short-term blood pressure control system. An explanation for the divergent findings may therefore be that studies in general focus on effects of mental effort associated with computational processes, whereas the measures are both sensitive to effects related to momentary computational effort and the on-going compensatory processes of the baroreflex. In other words, the measures do not only depend on the changes due to mental effort but also reflect other influences that may differ between studies, in particular the effects of the short-term blood pressure control system (Mulder et al., 2009; Van Roon et al., 2004).

Objectives of this thesis

The first objective of this thesis is to further clarify the relationship between task-related mental effort and cardiovascular responses. With that knowledge new methods for assessment of mental workload will be developed or current methods can be refined. Prolonged periods of increased effort usually result in an on-going increase of blood pressure. This is because prolonged mental effort strongly activates the sympathetic system and therefore provokes an increase of blood pressure. When high mental effort continues for more than five or ten minutes, short-term blood pressure regulation (baroreflex) counteracts these effects (Mulder et al., 2009). This means that the initial heart rate and heart rate variability effects are strongly reduced after 10 to 15 minutes of task performance due to
increased short-term blood pressure control that counteracted these initial changes. This may be an important explanation as to why during long lasting effortful task performance contradictory effects of high task demands on heart rate (variability) are found. This is the main reason to introduce in this thesis a short-segment approach in which cardiovascular responses to specific task events are studied. Studying cardiovascular measures on a smaller time scale (30 to 60 seconds) creates an opportunity to better distinguish mental workload effects and compensatory effects of the blood pressure control system.

For years it was believed that heart rate variability measures needed to be based on time periods of several minutes or more. Task characteristics however, had been identified to change faster than that, therefore a need for (reliable) measures that could deal with shorter time segments existed. Using a new technique in this field using short moving windows with overlap De Rivecourt et al. (2008) found evidence for the usability of analysis periods of around 30 seconds for variability measures of heart rate. With these results an answer to the need for smaller analysis periods was getting closer. In De Rivecourt’s flight simulator study, changes in task demands were consistently reflected in short segments of data. Already in 1996 and later de Waard and colleagues linked the effects on short-term cardiovascular measures to specific events in which task demands changed in a driving environment (de Waard, 1996; de Waard et al., 2008). The results found using shorter analysis periods by De Rivecourt and De Waard are reasons to consider a short-segment approach for spectral analysis of heart rate and blood pressure variability in periods that were previously considered too short to give reliable results (Berntson et al., 1997). This leads to the main research question in this thesis: can we use the mentioned short-term approach as a basis and use the insights gained about the relationship between computational effort and cardiovascular measures to develop a better method for mental workload assessment? To be able to apply the insights gained in the relationship between computational effort and compensatory blood pressure control processes the method De Rivecourt and De Waard applied must be extended with blood pressure measures without which it is difficult to understand the relationship between these variables. To show the reliability and sensitivity of this short-term analysis approach, multiple studies in a simulated ambulance dispatch centre and a driving simulator are described and compared to each other. The question that these studies try to address is whether effects of changes of mental effort are sufficiently visible or present in the used cardiovascular measures despite the continuing compensating effects of the baroreflex.

**Organisation of the thesis**

In this section a short overview of the chapters in this thesis will be given. The theoretical and practical issues encountered in the sequence of data acquisition, artefact handling and data (pre-) processing are described in chapter two. The results of these processes are used to formulate suggestions how to
develop an operator status model, a generic system for operator workload assessment. In chapter three, time-on-task aspects during ongoing activation and the role of the baroreflex are the main topics. Based on the data of two separate experiments performed in a simulated ambulance dispatcher’s task the effects of continuous mental effort on the cardiovascular system are studied. This chapter addresses the question whether the long-term effects (15 minutes to hours) found in many studies can be explained by a baroreflex model and whether this knowledge can be used to formulate how to improve cardiovascular measures to become more sensitive to current effects of mental effort. The results of two studies are described, one carried out in an ambulance dispatcher’s task and one in a driving simulator. An interpretation of the results of both studies in terms of autonomic control, using a simplified simulation approach of a baroreflex regulation model is given. The insight in the effects of mental effort on the cardiovascular system described in chapter three is the basis for the development of the short-term approach that is described in chapter four. The results of two different experiments performed in a simulated ambulance dispatcher’s task are used to describe the sensitivity and diagnosticity of the short-term approach. To further test the usefulness and robustness of this short-term approach, in chapter five the short-term approach is applied to data collected in a driving environment. A lane switching task carried out by drivers in a driving simulator is used to study effort changes related to increases in task demands due to short-lasting occurrences of fog. In chapter six, finally, the results of the different studies and their implications for the field of mental workload and adaptive automation are discussed.