Using cardiovascular measures for adaptive automation
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CHAPTER 6 – DISCUSSION
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Introduction

In recent years, research on operator state assessment has frequently focused on developing advanced technology applications for adaptive automation. Many (working) environments are enjoying the benefits of advanced technology being introduced, such as Advanced Driver Assistance Systems in the car, new communication and display possibilities in control rooms, etc. There are multiple reasons why this automation technology should be adaptive to the individual or the situation. For example, overload (task demands are too high) may have a negative impact on safety and health. Controlling demands may not only prevent overload, or underload, but may also increase acceptance of the systems, ultimately making them more effective.

There are different approaches to operator state assessment, from focusing primarily on the task characteristics and task performance to focusing more on the individual by monitoring behaviour and (psycho-)physiology (Pope et al., 1995; Prinzel et al., 2000; Fairclough and Venables, 2006; Ting et al., 2010). This thesis focuses on the use of cardiovascular and related methods for operator assessment and adaptive automation. Cardiovascular measures are considered adequate candidates for the assessment of operator state, because they can be measured relatively easily and continuously, and if implemented correctly do not interfere (much) with the task the operator has to perform. They therefore ensure quite objective indications (independent of the task) of personal state, which can be an advantage when considering individual differences and the unique response of each individual to changes in task demand. On the other hand, sometimes it may be difficult to ensure that the effects found are really task related and not caused by other, distracting factors. An operator could for example be thinking about another stressful problem unrelated to the task, which might elicit a similar physiological response. In other words, a thorough understanding of the cardiovascular effects related to mental effort is needed to be able to use such measures in operator state assessment and subsequently in adaptive automation.

Long term effects

A lot of research has been performed to understand the relationship between cardiovascular measures and mental effort. It has been studied during laboratory tasks (Backs and Seljos, 1994; Mulder and Mulder, 1987), simulated work (Brookings et al., 1996; Veltman and Gaillard, 1998; De Rivecourt et al., 2008; Dijksterhuis et al., 2010) and during real work (Wilson, 1993; Roscoe, 1992; De Waard et al., 1995; Hankins and Wilson, 1998). Although most researchers have found cardiovascular responses that can be explained well within the context of the study and the task, sometimes different explanations are needed in other contexts or tasks. Actually, in most studies the results can be understood well in terms
of the cardiovascular control mechanisms holding for that specific situation and by interpretation of the effects in that specific context. It is clear that this makes the comparison of studies more complex and reduces possibilities for generalization. Some authors have pointed to these issues to pose the question how useful the existing cardiovascular measures are for operator state assessment in (semi-)realistic work if they require such context specific explanations. The implicit criticism has risen because apparently, or perhaps seemingly, contradictory results and inconsistencies have been found in the relationship between mental workload and effects in cardiovascular measures (Veltman and Gaillard, 1996; Sirevaag et al., 1993; Mulder, 1992; Wilson, 1992; Jorna, 1992; Porges and Byrne, 1992).

For example, in general, during effortful working periods a pattern is found of increased HR in combination with decreased HRV, compared to resting baselines or compared to conditions of lower workload. However, as stated in chapter three, the size of these effects depends strongly on the task load differences between conditions, the type of task and time on task (Mulder and Mulder, 1987; Backs and Boucsein, 2000; Althaus et al., 1998). The effects become less transparent and the interpretation of the effects more difficult due to varying overall task demands, little knowledge about current task characteristics, time on task effects and adaptivity of the short term blood pressure control system, (i.e. the baroreflex Mulder, 1992), to these changing task demands.

In chapter three we compared in two studies the effects of these mechanisms and described how the results of these studies are an interaction of the effects of these mechanisms combined. We found two characteristic, different cardiovascular patterns as a function of time-on-task for the two tasks. The differences between the two studies can be largely explained by looking at the effects on the baroreflex. In the first study, concerning the ambulance dispatcher’s task, blood pressure kept rising during the first half of the task and remained at a high level during the second half. Associated with the effects in blood pressure, the baroreflex sensitivity also kept increasing at first and then remained high, trying to compensate for the high blood pressure. One of the consequences of this baroreflex related response pattern is the lowering of heart rate during ongoing task performance. In the driving task a different pattern was found, blood pressure increased only from rest to task but did not continue to increase during the task. Associated with this pattern in blood pressure, the baroreflex sensitivity also only showed initial effects and remained constant after this initial period. As may be expected after seeing these two results, compensation for high blood pressure by lowering heart rate is not found in the driving study. As with previous studies reported in literature, the effects are well explainable, given the context and the task characteristics. More importantly, what can be concluded from the comparison made in chapter three is that by understanding the mechanisms of the baroreflex, these results are more predictable. We conclude that the effects of long lasting effortful task performance complicate the interpretation of effects of workload on cardiovascular measures, heart rate and heart rate variability especially. By differentiating between effects directly related to task demands and the compensatory effects related to the restorative processes of the short term blood
pressure system (baroreflex) taking place during prolonged periods of elevated mental workload, we are able to explain some of these effects.

Given this first conclusion, a second important conclusion can be drawn from the comparison made in chapter three: if we can develop measures that are less sensitive to the compensatory effects of the baroreflex and therefore more sensitive to effects of changes in task demand, we might be able to eliminate some of the problematic issues that some of the current cardiovascular measures show for operator state assessment. By developing methods that are less sensitive to the effects of the baroreflex, we may be less forced to interpret results in a very specific context and task, and find more consistent results between studies.

**Short term effects in the dispatcher’s task**

After identifying the difficulties with the current (long term) measures and the related task dependent factors, the question that needed to be addressed was: how to find suitable cardiovascular measures that are less dependent of these compensatory effects of the baroreflex. More specifically, how to increase their sensitivity to the effects of changes in task demands and decrease their sensitivity to effects related to baroreflex compensation mechanisms. To split the direct effects of demands and the effects of compensatory mechanisms, we developed a short-segment approach, described in detail in chapter four, in which cardiovascular responses to specific task events are studied. The approach is based on a time-frequency method in which the power in specified spectral bands is computed from small overlapping time segments, by using 30 second moving windows. Short segments of these data are then selected and related to specific events during an on-going cognitive task. The main hypothesis investigated in chapter four is whether the presented short-segment approach enables detection of changes that are due to invested cognitive effort, and not related to compensatory control.

We used a simulation of an ambulance dispatcher’s task to demonstrate this. The emergency calls an operator has to respond to during the task, are interrupting ongoing task performance and induces additional task load on top of the normal workload. The cardiovascular response to the interrupting phone calls can be considered as evidence for an effect of a short-term increase in cognitive mental effort. We found strong effects of workload on variability measures of heart rate and blood pressure, and some effects on heart rate and blood pressure.

The results of the two studies presented in chapter four seem to support the hypothesis that a distinction can be made between invested cognitive effort and compensatory control, by using a short-term approach. In both studies the expected decrease in variability during a short increase in task demands was found for heart rate variability and blood pressure variability (mid and high frequency
band). Mean heart rate, blood pressure and baroreflex sensitivity measures showed smaller or no effects, which could have been expected, as they are more related to the overall state of the cardiovascular system and less to immediate effects of changes in invested effort (Mulder et al., 2009). We conclude that studying cardiovascular measures on a smaller time scale creates the opportunity for a better distinction between mental workload effects and compensatory effects of the blood pressure control system, because the compensatory mechanisms work on a larger time scale.

An important conclusion that can be drawn when looking at the data from chapter four (and five) is that the effects of task demands from rest to workload (initial effects) can be found at any time during task performance when there is an increase in task demands. How large this response is, depends on the situation. During periods when overall demands are low a larger response is found. If overall demands are higher the response is smaller.

When demands are high, the response almost vanishes, which is probably a ceiling effect. In other words, participants experience less difference in mental workload before and after the increase as overall task demands are already high. From a physiological perspective we could say that the measures have lower sensitivity during the periods of high demand.

The effects of a short increase in demands during steady task performance are for a large part similar to the classical rest-task response, i.e. heart rate and blood pressure rise, heart rate variability and blood pressure variability decrease, and baroreflex sensitivity decreases as well. The effects seem to be represented most strongly in heart rate variability, whereas heart rate itself seems to be less affected. This is also reflected in the larger heart rate variability response in the ambulance dispatcher’s task, which is a typical mentally demanding task where time pressure plays an important role.

**Short term effects in the driving simulator**

The developed short term approach needed to be evaluated in a different environment to test whether this method could be applied more generally and whether it was indeed more sensitive to the effects of changes in task demands than to cardiovascular compensatory effects. A popular domain for adaptive automation, next to operator control rooms, is the automotive field. Driver support systems based on vehicle and/or driver data have been under development in recent years. The driving task seemed therefore an obvious area to evaluate the developed short-term method. Driving requires continuous attention and motor control from the driver. In the task that the drivers performed in our study (lane switching on command) central processing also played a significant role as participants had to decide how and when it was safe to change lanes. In general the driving task should be seen as a task with overall limited workload but with peaks at certain moments when drivers have to perform more than
just control tasks. These peaks can be used as input for the method developed here to give an overall impression of workload; they are the temporary increases in demands that are relevant for the method. In the study described in chapter five we manipulated traffic density between conditions to create different levels of workload demands and introduced fog on occasion to increase task load at that specific moment.

We found a clear decrease in heart rate variability and systolic blood pressure variability as a response to short lasting increases of task load due to fog. This decrease was only present in the low traffic intensity condition. The introduction of fog resulted in a number of effects; systolic blood pressure variability in both the mid and high frequency band and heart rate variability in the high frequency band were all reduced while driving in fog in the low traffic density conditions. No effects of fog were visible during the high traffic density conditions. These results support the expectations for heart rate variability and blood pressure variability to a large extent.

The absence of this effect in the high workload condition was similar to the results found in the previous ambulance dispatchers study described in chapter four and therefore also expected. However, we did find slightly different effects between the ambulance dispatcher’s task and the driving simulator study as well. The initial effects are stronger in the driving task, while no ongoing increase in blood pressure is seen, which is reflected in a quite different response pattern of the baroreflex. The baroreflex pattern clearly shows the initial rest–task differences (decrease) but remains at the same level during each of the two driving hours. In contrast with the ambulance dispatcher’s task where initial effects are smaller but where baroreflex sensitivity increases until the break and then remains at a high level. We argue that the main reason for this deviant response pattern is the difference in nature of the tasks. The ambulance dispatcher’s task, when compared to the driving task, requires more use of working memory and requires less motor activity. The driving task is a continuous control task and probably imposes low cognitive demands in general. In the ambulance dispatcher’s task compensatory processes of the blood pressure regulation system are continuously at work to try to bring the system back to normal levels. This is reflected in higher baroreflex sensitivity and lowered heart rate compared to the driving task. Time pressure and continuous workload are the reasons that the system does not succeed to reach the normal state, which means that the regulatory processes have to keep working. In the driving task, workload was probably lower and after compensating for the initial effects the system has reached acceptable levels for regulatory processes to be less pronounced, reflected in lower baroreflex sensitivity and lower heart rate, even comparable to resting heart rate.
Sensitivity

One might ask whether the short-term approach as presented in this thesis has resulted in more sensitive methods compared to common analysis methods. In the context of the tasks described in this thesis it seems that with the short-term approach smaller differences can be discerned. The results from the studies in chapter four and five support this claim. First of all, the absolute differences in variability values found in all studies in those chapters are smaller than generally found with the common long-segment approach, while effect sizes are relatively large and statistical effects clear. This gives an indication that small differences between conditions are consistent and can be detected with this approach, which is important for detecting task related effort changes at an individual level.

Comparing the sensitivity of the short term method with the long term method reveals that with the long term measures we were typically able to detect (statistically significant) differences of about 0.3 \( \log(MI^2) \) when comparing periods of 5 minutes of high and low workload (cf. Aasman et al., 1988; Mulder and Mulder, 1987; Mulder, 1992). On a logarithmic scale (as used in our approach) a reduction of 0.3 means reducing heart rate variability by half. Typical rest task differences are for example a decrease from 2000 MI\(^2\) to 1000 MI\(^2\). With the short-term method we were able to detect significant differences down to 0.1, with larger effect sizes than found in any of the long-term studies. Being able to detect small differences means that the measures respond in a more consistent way and therefore are more sensitive to different levels of task load. In other words, the results of the present two studies give an indication that current effects of changes in task load can be better distinguished with short-term measures than with long-term measures.

One further relevant finding was that the largest effects of workload manipulation were found in the conditions with low demand, indicating a kind of ceiling effect on variability measures. This was found in both the ambulance dispatchers’ study and the driving simulator study. It has been argued in the previous chapters that this finding gives an opportunity for detecting state dependent effort changes or that it can be used to detect or indicate situations of overload. This result is another promising aspect of the short-term approach for the development of adaptive driver support systems.

Conclusions

Based on the insights gained by the studies described in this thesis it can be concluded that the short-term approach is a good alternative for the classic heart rate variability approach. It has real added value when the goal is to detect immediate changes in workload. For the immediate effects the short-term approach seems to have even greater sensitivity than the long term methods. This increased
sensitivity can be really useful when looking at effects on individual level and on a short time scale of 30 seconds to a few minutes, which are both necessary when we want to apply the method in adaptive automation. Sensitivity to changes in workload is highest, or in other words the differences are best detectable, in periods of relative low workload with sudden clear increases in task load. In periods of high workload however, the lack of a response may indicate a ceiling effect on effort. Heart rate, blood pressure and baroreflex sensitivity levels may give additional information about such a high workload state in those situations, since they have been shown to be more related to physiological state than to immediate task load changes.

While describing and evaluating a short-term approach, the dependency between measures has been an important aspect in this thesis. To be able to understand the complex relation between task demands, workload and the effects these have on the operator and his task performance, looking at one aspect alone is not enough. Multiple measures are needed to increase understanding, but also to increase reliability, as already suggested at the beginning of this discussion. This thesis shows that there are quite a few cardiovascular and related measures that are informative with respect of either task load changes or state changes, such as heart rate variability in mid and high frequency bands, blood pressure variability in mid and high frequency bands, baroreflex sensitivity, respiration rate and respiration depth and heart rate. There are also several useful task related measures, such as speed, accuracy and task complexity, which are either informative with respect of performance or of task demands.

The analysis of the long-term approach and presentation of the short-term approach in this thesis has shown to be helpful in understanding these complex relations and has given suggestions for useful applications and relevant improvements.