Summary
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 overall approach used in the proposed systems is based on the idea that the whole system (human and machine) functions best if workload is kept at an optimal level (Parasuraman et al., 1992; Rouse, 1988). One approach to assess mental workload is to use cardiovascular indices. Some authors have raised questions about the usefulness of such measures in (semi-)realistic work. This criticism has been raised because contradictory results and inconsistencies have been found in the relationship between mental effort and psychophysiological measures (Veltman and Gaillard, 1996; Sirevaag et al., 1993; Mulder, 1992; Wilson, 1992; Jorna, 1992; Porges and Byrne, 1992). The first objective of this thesis was to clarify the relationship between task-related mental effort and cardiovascular responses. The second objective was to propose a new method that can be used to study workload and give better or additional insight. For clarification a distinction was made between state related (or compensatory) effects and short-term effects that are probably more directly linked to changes in task demands. The state related effects were a result of prolonged investment of effort from which the system tries to recover. It was expected that (short-term) effects were more directly linked to the changes in task demands and the reaction to these demands by the operator.

The methods used for data acquisition, processing and analysis were described in chapter two. In chapter three the relation between workload and (compensatory) effects was examined by comparing the results of two long-lasting tasks (two to three hours) performed in an ambulance dispatcher’s simulator. In chapter four, the insights gained in chapter three were used to describe an alternative (short-term) method for analysis of cardiovascular measures, which was less sensitive to compensatory effects of workload and more sensitive to direct changes in task demands. The method was studied in the ambulance dispatcher’s environment. In chapter five the short-term method was applied in a driving simulator to analyse the generalizability and robustness of the method.

Chapter 3: Cardiovascular state changes in simulated working environments

The usefulness of cardiovascular measures as indicators of cognitive workload has been addressed in several studies. In this chapter the question was explored whether cardiovascular patterns in heart rate, blood pressure, baroreflex sensitivity and HRV are consistent within and between two simulated working environments. Two studies were described, both used 21 participants: one in an ambulance dispatch simulation and one in a driving simulator. When performing the ambulance dispatcher’s task an initial strong increase in blood pressure was followed by a moderate on-going increase in blood pressure during the following hour of task performance. This pattern was accompanied by a strong
increase in baroreflex sensitivity while heart rate decreases. In the driving simulator study, blood pressure initially increased but decreased almost to baseline level in the following hour. This pattern was accompanied by a decrease in baroreflex sensitivity, while heart rate decreased as well. Results of both studies were interpreted in terms of autonomic control (related to both sympathetic and parasympathetic effects), using a simplified simulation of a baroreflex regulation model. These results lead to the conclusion that the cardiovascular response patterns, when performing both tasks were a combination of an initial defensive reaction with compensatory blood pressure control. The level of compensatory blood pressure control, however, was quite different for the two tasks. This helped to understand the differences in response patterns between the two studies in this paper and might be helpful for understanding differences in cardiovascular response patterns in general. A substantial part of the effects observed during task performance were regulatory effects and were not always directly related to workload manipulations. Making this distinction may therefore also contribute to the understanding of differences in cardiovascular response patterns during cognitive workload.

**Chapter 4: Short term cardiovascular responses to changing task demands**

In this chapter the question was addressed how we could develop useful measures of mental workload that were mainly sensitive to changes in mental effort and less to other influences. In chapter three, an explanation of differences in effects between studies was given in terms of the compensatory control effect of the baroreflex, which brought about physiological changes that could potentially overshadow changes due to mental effort and therefore reduce the usefulness of cardiovascular measures. However, this might be different for short-term cardiovascular measures. Despite the effects caused by the baroreflex, differences in heart rate, heart rate variability and other cardiovascular measures associated with task related effort might still be present in short-term response patterns. The short-segment analysis approach described in this chapter is based on a time-frequency method in which the spectral power of the cardiovascular measures in specified spectral bands is computed from brief time segments of 30 seconds. To demonstrate the effectiveness of this technique two studies using a simulation of the ambulance dispatcher's task were described both with easy and difficult task conditions. A short-lasting increase in task demand was found to be reflected in short-lasting increases in heart rate and blood pressure in combination with corresponding decreases in heart rate variability and blood pressure variability. These effects were larger in easy task conditions than in hard conditions, likely due to a higher overall effort-level during the hard task conditions. Nevertheless, the developed measures were still very sensitive to mental effort and if this short segmentation approach is used, cardiovascular measures are good candidates for reflecting mental effort during task performance.
Chapter 5: Short term cardiovascular measures for driver support

The short-term approach described in chapter four was tested in a different environment as well. In this chapter the method was applied in a driving simulator to analyse the usefulness in another applied field. With ongoing increases in traffic density and the availability of more and more in-vehicle technology, driver overload is a growing concern. To reduce the burden on the driver, support systems have been proposed to control workload demands. In this chapter the short-term cardiovascular approach was used to assess driver mental workload in a driving simulator. In the driving environment, these measures also prove to be very sensitive to workload changes and they seem less affected by the compensatory influences of the blood pressure control system. Two traffic density levels (7.5 minute segments) were compared in which short-segments (40 seconds) of fog were used to increase workload demands. Higher traffic density was reflected in increased systolic blood pressure and decreased blood pressure variability. Heart rate variability and blood pressure variability measures decreased during driving in fog in the low traffic condition. Cardiovascular measures appeared unaffected by the compensatory effects of the blood pressure regulation system when using the proposed short-term analyses approach. The results showed that the described short-term cardiovascular reactivity also mirrored workload in a driving task.

Discussion and conclusions

In chapter three we found two characteristic, different cardiovascular patterns as a function of time-on-task for the two working environments. As with previous studies reported in literature, the effects could be well explained given the context and the main characteristics of the task. However, the differences between the two studies could also be largely explained by looking at the effects on short-term blood pressure control (the baroreflex). What could be concluded from the comparison made in chapter three is that by understanding the mechanisms of the baroreflex, the results are more usable. We concluded that these compensating blood pressure control effects during long lasting effortful task performance complicate the interpretation of effects of workload on cardiovascular measures, in particular for heart rate and heart rate variability. 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 were able to explain some of these effects and create better measures for workload that can be used in the field of adaptive automation. We concluded that studying cardiovascular measures on a smaller time scale creates the opportunity for a better distinction between (short term) mental workload
effects and compensatory effects of the blood pressure control system, because the compensatory mechanisms work mainly on a larger time scale.