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Physiological indices for the estimation of momentary changes in cognitive workload and mental state

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ABSTRACT

With increasing complexity of working environments, the need for active user assistance has emerged. This need is amplified by the ever-increasing diversity of the potential user groups for specific computer applications and complex work-environments. Therefore future human computer interfaces should adapt dynamically to the actual needs of the user. Adaptive automation adds a new dimension to the standard approach of flexibility provisions, which are inter alia the setting of user preferences (e.g. novice and expert levels, toolbar alterations), online advisory systems (e.g. Microsoft Office Assistant), and full automation (no user actively involved). Adaptive automation allows the user to remain in charge but will assist the user to perform the required tasks in the most effective way taking into consideration the context, environment, user preferences and user experience. As such adaptive automation keeps the user in the control loop, whilst adapting the working environment to the actual user needs. Research in this area has started around 1970 in the military domain (Rouse, 1988). So far practical results have been limited to specific implementations. Continuous improvements in computing power, reduction of power consumption, increase of computer memory, and affordability as described by Moore's Laws[1], have brought cheap and fast computing power for everyone almost everywhere. This and the advent of small, high quality, low-cost sensors have led to the option to increase the complexity of the underlying computing programs to the level required to actively support the user in his tasks and to allow embedded guiding and "learning on-the-job" assistance.

This paper addresses an adaptive automation approach that facilitates more dynamic user assistance in a generic way, solving part of the context and interaction problems. The proposed approach has been called the Operator Status Model (OSM). Some physiological candidate measurements for the real-time classification of the user functional state are assessed in a laboratory experiment, with emphasis on the requirements for the creation of the underlying real-time data interpretation algorithms.

[1] Gordon Moore of Intel identified in the early 1970s: 1. The processing power of a microchip doubles every 18 months. 2. The price of a given level of computing halves every 18 months.

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Summary

With increasing complexity of working environments, the need for active user assistance has emerged. This need is amplified by the ever-increasing diversity of the potential user groups for specific computer applications and complex work-environments. Therefore future human computer interfaces should adapt dynamically to the actual needs of the user. Adaptive automation adds a new dimension to the standard approach of flexibility provisions, which are inter alia the setting of user preferences (e.g. novice and expert levels, toolbar alterations), online advisory systems (e.g. Microsoft Office Assistant), and full automation (no user actively involved). Adaptive automation allows the user to remain in charge but will assist the user to perform the required tasks in the most effective way taking into consideration the context, environment, user preferences and user experience. As such adaptive automation keeps the user in the control loop, whilst adapting the working environment to the actual user needs. Research in this area has started around 1970 in the military domain (Rouse, 1988). So far practical results have been limited to specific implementations. Continuous improvements in computing power, reduction of power consumption, increase of computer memory, and affordability as described by Moore's Laws[1], have brought cheap and fast computing power for everyone almost everywhere. This and the advent of small, high quality, low-cost sensors have led to the option to increase the complexity of the underlying computing programs to the level required to actively support the user in his tasks and to allow embedded guiding and "learning on-the-job" assistance.

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1 Need for adaptivity

The continuous economic pressure to increase productivity at acceptable safety levels and with low environmental impact leads to a situation where working environments are becoming more complex. The advent of computers in the working environment in the early seventies has multiplied the rate of complexity increase. Right now a stage has been reached where most users do no longer fully understand all details of the process relations which need to be controlled, left alone the mechanisation used to control those processes. This observation of an increasing distance between operator and processes was already made by Woods and Cook (1991) with the statement “Overall, technology centred automation appears to produce increments in workload and subtle decrements in practitioners’ understanding of their environment.”
The rapidly changing working environments lead to the need of user retraining at a pace, which is difficult to maintain. Due to people’s background and abilities, not all are able to keep up with this continuous change in working environment if we stick to the traditional way of work environment development. At the same time especially the technical advanced communities (e.g. United States, Europe, Japan) are ageing, leading to the observation that the diversity of workers’ abilities and computer skills will broaden. Young and elderly people have to do the same complex jobs but will have totally different backgrounds and affiliations with modern, fast changing technology. Options to select only the best operators from the available pool of workers are limited due to the lower instream of candidates on the ‘labour-market’. Both trends lead to the observation that work environments need to become more supportive with respect to the user.

At home, the proliferation of the information society demands more complex computer interactions, which need to be understood by a large part of the community in order to be successful. This again increases the burden on the software designers to come up with flexible solutions to serve people with completely different backgrounds and abilities. In the past, several ways have been invented to accommodate this need. The simplest one is the allowance for user preference settings like selection of a novice or expert level, or the option to modify the task bars. Transition settings also exist, which allow users to use their knowledge of previous programs within new programs. Examples of the later are the transition from WordPerfect to Microsoft Word® and the global standardisation in the user interfaces interactions Microsoft Windows® has brought us. Assistants can provide context sensitive information and allow users to link to other sources of information (e.g. on-line help facilities). Based on pattern recognition and task analysis (e.g. through time-lag sequential analysis), users can be advised to execute likely following steps like for word-processing, the finalisation of a given phrase and automatic setting of the document format. The final alternative is not to bother the user any longer with specific tasks by fully automating it.

Based on considerations like the maintenance of a sufficient level of situation awareness, the most attractive solution seems to be to have the working environment being adaptive to the momentary needs of the user. The key enabler for this kind of adaptivity is the state of technology. Currently, computer intelligence can be embedded in several devices at relatively low cost, with high computing power, sufficient memory and storage capacity, and low power requirements. Even embedding microcomputers in combination with wireless communication devices in clothes has already become viable (Aarts, 2002). The range of small size, low power, low cost and intelligent sensors is also increasing due to their usage in various environments and purposes. As such, a wide range of new sensors and devices can be used to automatically adjust the user's environment to suit his/her dynamic needs. However, the key-question on how to implement this option in order to achieve world-wide acceptance still remains.

2 Adaptive Automation

Several attempts in the field of Adaptive Automation (AA) have already been undertaken. Most of them stem from the military aviation domain due to the dynamic needs of a fighter pilot in complex battle. AA started in this domain by the 'simple' requirement to provide the right information in the right format at the right time. In this context, Hutchins et al. (1986) describe the most effective interfaces as those that achieve "transparency". That is, the interface effectively disappears, enabling the user to interact directly with the objects of interest in the domain and to achieve effective interaction with a minimum of cognitive effort. At almost the same time, Greenberg and Witten (1985) summarised the concerns of AA: "Although obvious advantages accrue… there are also obvious disadvantages to presenting users with a changing, adapting and perhaps apparently inconsistent interface". This statement was repeated by Bennet et al. (2001) by adding that it seems doubtful that "Dynamic Adaptive Interfaces (DAI) can provide effective decision support in complex, dynamic domains". They conclude that "the critical issues in the design of the DAI include decisions about the choice of *(software)* dynamic behaviors, the information and knowledge that should be used to trigger those adaptive behaviors, and the orchestration of these behaviors and information sources to facilitate performance".

In a special issue of the International Journal of Aviation Psychology on adaptive automation, Haas and Hettinger (2001) defined "an adaptive interface to differ from a non-adaptive interface in that it is more knowledgeable of the individual characteristics of the user, of the implications of interactivity between the user and the interface, and of the environmental and interface effects on the user. This increased knowledge of the user provides the ability to respond directly to changes in the dynamic state or characteristics of the operator as provided by direct measurement, in-line models of the human, or both." They conclude that "adaptive interfaces

represent a paradigm shift in interface design in that the adaptive interfaces explicitly measure or implicitly estimate knowledge of the human operator's state during their operation. This knowledge estimate can be derived from (a) direct measurement of physiological or behavioural indices; (b) a perceptual-cognitive model that runs in parallel to the human operator and estimates the human operator's state from the model's knowledge of the environment; (c) the output of a model contained within an algorithm adaptively controlling information portrayal, control affordance or function allocation".
Parasuraman et al. (2000) approach the automation problem from a different perspective by emphasising the relation between automation and human behaviour. Each one influences the other and can not solely be seen in isolation.

3 The information control loop

Haas and Hettinger (2001) stated that "AA is enabled by (a) integration of highly flexible display devices, (b) computational models of situation awareness, workload and operator performance, and (c) direct physiological and behavioural measurement of the operator." The latter statement gets the essence of a possible working system by highlighting an essential element of adaptive automation: the determination of the user's momentary functional state (Hockey, 2003, Wilson, 2003). This functional state can be used to determine the optimal user interface at this time and to initiate the adaptations. However, adaptations of the user interface will subsequently influence the momentary functional state. In other words: there is an additional information control loop. This latter information control loop is depicted in figure 1 by the links to the so-called Operator Status Model (OSM).

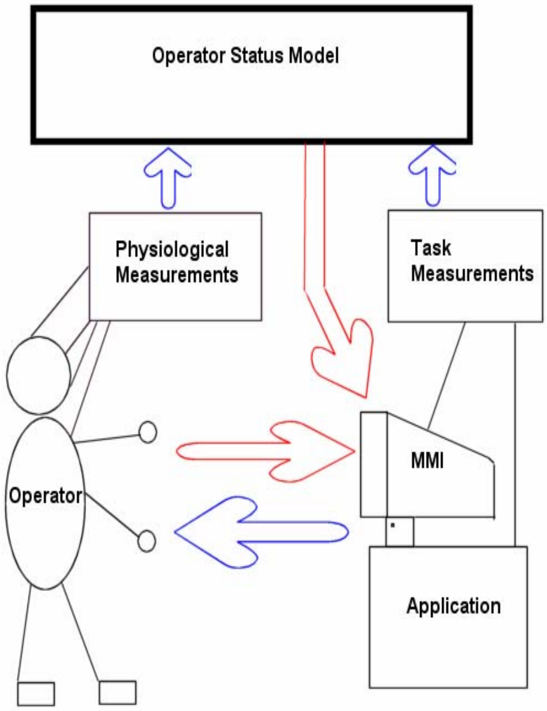

Figure 1: The Operator Status Module (OSM) concept

Figure 1 shows the operator working with an “application” using its Human Machine Interface (HMI). An application in this respect should be seen as a set of combined tasks, like a word processor or a pilot-associate, but –in the extreme– can also include interactions with other team members. Multiple applications (e.g. word processor, mail program, spreadsheets) can be active at the same time.

The envisaged Operator Status Model (OSM) combines the operator’s physiological information with task performance (taken from the active applications) and application states to derive the user functional state, using generic dimensions like workload, visual task load and being occupied with a given task/application. The OSM information can subsequently be used by the applications to change their HMI to optimise the direct information exchange. Potential changes are inter alia the change of information shape and modality (e.g. visual, sound or haptic), the delay of low-priority information messages, the presentation of salient information at prominent locations (e.g. directly at the spot where the user is looking). Basic assumptions behind the OSM are 1. that it is sufficient to know the operator’s functional state expressed in generic dimensions and 2. that each application remains responsible for it’s own adaptations.

Switching between applications (arbitration) is supported by the OSM through the provision of priority lists; the change of the application state (e.g. active in foreground, background, suspended) remains the responsibility of each application. Detailed task related information is therefore not stored in the OSM, but remains within each application.

The analogy with a control loop leads to the following observations. The first one is that the overall loop-gain should not be too high to avoid oscillations. In the OSM context this leads to the requirement that autonomous HMI modifications should not be too drastic and that the update frequency for the changes should not be too fast. Small modifications like attracting the attention to important areas can be considered to be equivalent of a lower loop gain since the basic information remains the same. On the other hand, time and safety critical situations may demand a drastic change of the user’s environment to attract timely attention to the adverse condition. The moment to intervene should ideally take into account the momentary state of the active applications, allowing the user to complete the current task if time allows.
The second observation concerns the allowable delay times in the control loop. If the delay becomes too large, instabilities in user-machine co-operation may result. The OSM implications are that long delay times in HMI changes should be avoided. Long delay times would result in “surprise behaviour” of the interface. In other words the user is no longer expecting the interface to change due to changed physiological and performance conditions. Information delays can not be avoided since time is required to interpret the physiological data. For example, the interpretation of the mid-frequency band (0.1 Hz) of the heart rate requires a delay of about 40 s. The interpretation of average blink rate and duration require data of approximately similar periods. Faster changing information sources may be the Eye Point Of Gaze (EPOG, requires periods of some seconds) and pupil diameter (seconds level), or EEG (seconds level) time series.
A third observation concerns the fact that some hysteresis should be present in the system: not all operator functional state changes should result in a modified HMI. Adaptation is only required if an adverse situation lasts for a given amount of time (actual duration is context dependent). Dead-bands in the action to be taken are therefore a necessity if users are to appreciate the system. However this last observation does not hold for all possible conditions. Safety and time-criticality are examples where dead-bands might be less appropriate.

A distinction needs to be made between continuous operations and event type of operations. The first type is the continuous process to perform a certain task like typing a letter or report. Event-type of operations are concerned with sudden events (e.g. warnings) but may also occur at the start of a task (e.g. typing a letter in a non-standard format). Continuous operations are best served by only gradual changes in the user interface, whilst event operations may need the drastic approach like presenting salient warning and error messages.

4 User functional state determination: VALDAT experiment

One of the key issues to realise above information loop is the real-time determination of the operator functional state. From literature it is known that several physiological candidates can be used for this purpose (Hockey, Gaillard & Burov, 2003). For instance, the assessment of Situation Awareness and the relations between possible measurements to assess the SA construct is given in Hoogeboom (1999). However most reported experiments compare steady state conditions instead to the continuously changing conditions encountered in daily life. Therefore an experiment, called VALDAT, has been conducted to build a database suitable for the verification of iterative data analysis algorithms.

5 VALDAT method

In the experiment information from several physiological signals was recorded whilst the participants were performing different tasks, presented in a random order.

The tasks the participants had to perform were:

- A tracking task in which a target-symbol was to be followed with a one-axis joystick. The driving function for the target used two different velocities, switched at random times. The movement of the symbol could be towards the left or right. At the location of a ‘turn-points’, the symbol followed a circular path to the opposite direction. Due to the target symbol size (very short line), almost no movement prediction was presented, minimising the ‘look-ahead’ time for the participants. An example screen layout is presented in figure 2. The task duration was 7 minutes.
- Continuous Memory Task (CMT): an auditory task in which the user has to recognise a target letter, react to it by pressing a button and count the occurrences. Up to four simultaneous targets, taken from a balanced set of 20 letters, have been used for the tests. The balancing was performed for the Dutch language and focussed on the ‘E’ sound. The CMT task could be run stand-alone, in which the user was presented with a small green filled circle in the middle of the screen, or could be combined with the tracking task. The targets used for the stand-alone task were the letter sets: F, MD, LDG, FKBC. The combined task used the letter sets: B, SX, RCD, RSCD. The task duration was 5 minutes in which approximately 100 stimuli were presented. When combined with the tracking task, the CMT task started 1 minute after the start of the tracking task and stopped 1 minute before the end of the tracking task.

A balanced design with respect to the order of the CMT sequences and the stand-alone/combined execution of the CMT and tracking tasks was used for the experiment.

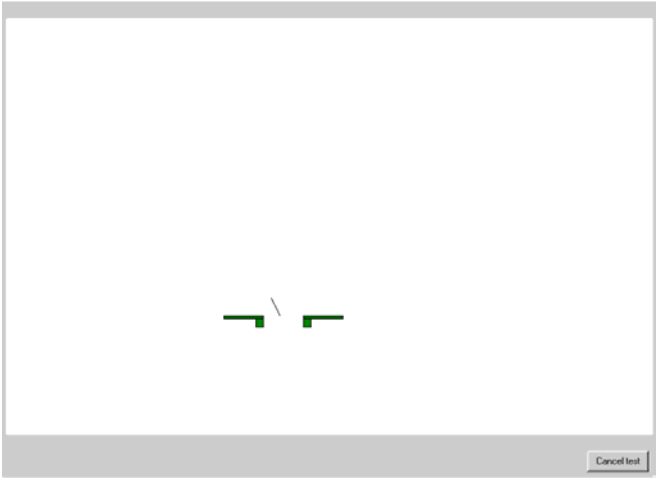

Figure 2: Example screen layout as used for the tracking task. The participant could control a tracking symbol ('bucket') by using a one-dimensional joystick. The task was to keep the small line segment centred above the bucket. Due to the size of the small line segment, almost no preview was present in this tracking task.

In the VALDAT study, 27 healthy test subjects (23 male and 4 female, aged 17-32 years) without glasses or contact lenses served as paid voluntary subjects. All subjects signed an informed consent. In addition, all subjects were requested to abstain from caffeine starting 12 hour before the experiment. Each session lasted for about 1.5 hour. Since the emphasis of this paper is on the derivation of physiological changes within one given subject, in contradiction to comparison of effects of experimental manipulations between several subjects (as reported by Koskelo, 2000), data from only the last 7 subjects is reported in this paper.

6 VALDAT results

The comparison of the pupil diameter for the tested CMT conditions, as shown in figure 3, leads to the observation that the pupil diameter increases with increasing CMT level. This pupil-diameter increase with increasing task load is in-line with observations from other experiments (Sirevaag & Stern, 2000).

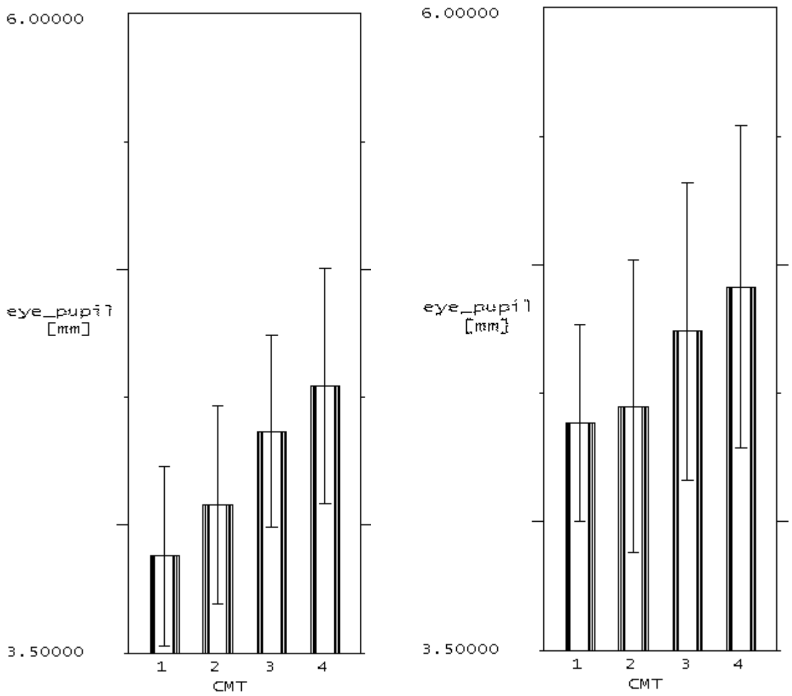

Figure 3: Pupil diameter versus CMT level (1, 2, 3 or 4 target letters). The left figure shows the results of 7 participants without the tracking task, the right figure shows the results when the CMT was combined with the tracking task. The thin line on the bars gives the standard deviation of the measurements.

The addition of the visual tracking task to the CMT increases the pupil diameter further, even though the 'tracking screen' was brighter than the stand-alone CMT screen with a relatively large green dot in the middle of the screen. The found effects seem to be relatively robust: a large portion of the standard deviation can be explained by the individual average pupil size. Within subject normalisation may therefore be required for the data interpretation.

The effects of pupil diameter changes relative to the experimental conditions can also be observed from the individual time-series (figure 4). In the time trace the rest periods are clearly visible: during the time between the tests other lightning conditions existed since the subjects were instructed to fill in rating forms. This already leads to the conclusion that the pupil diameter may be sensitive to the workload conditions, while being very sensitive to the ambient light conditions. Therefore in order to use this index for the real-time automation feedback, the overall light conditions have to be controlled or have to be compensated for.

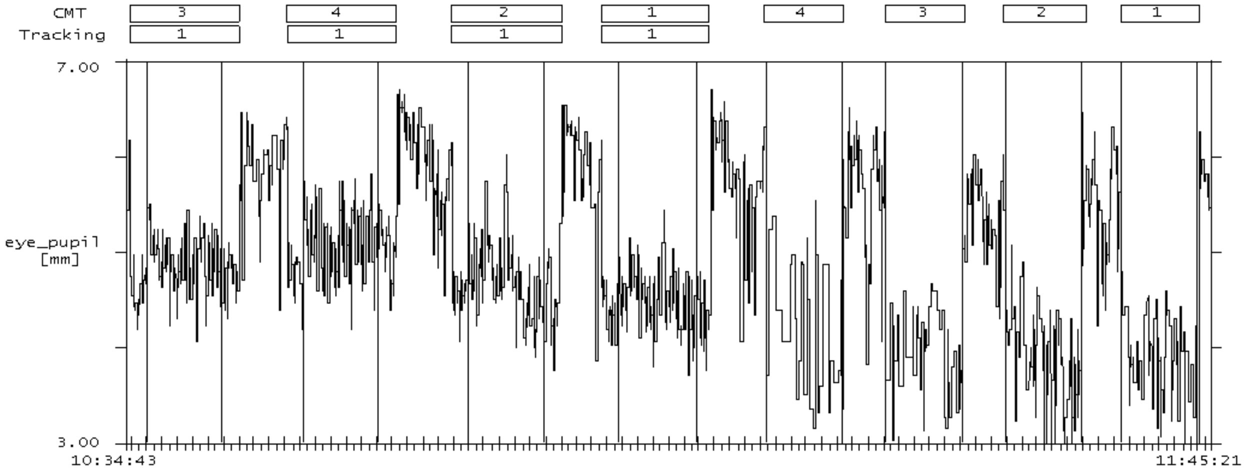

Figure 4: Pupil diameter versus time. The top bar gives the experimental status: the first row with the CMT values indicates the amount of target letters used in the task. The second row shows a '1' when the tracking task was active. Between the task sessions as indicated by the CMT levels, a rest period was present in which other (ambient) lighting conditions existed.

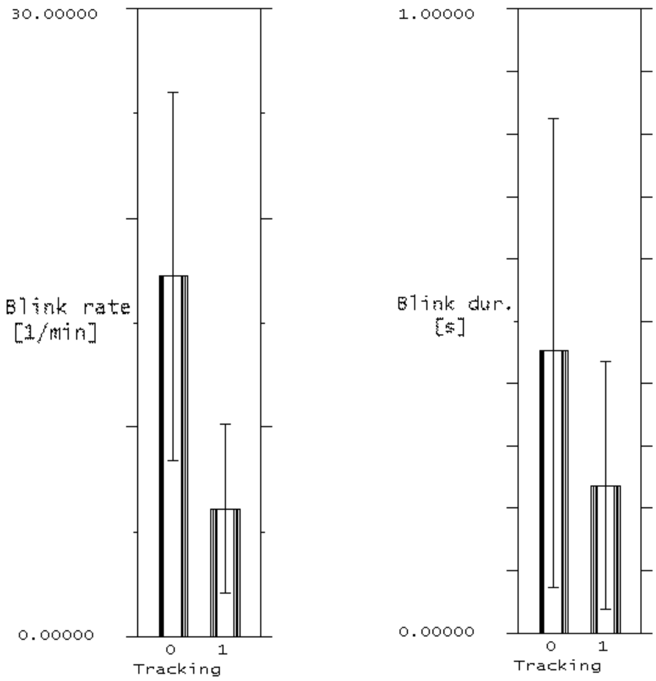

Figure 5: Blink rate (left figure) and blink duration (right figure) versus tracking condition averaged over the 7 subjects. The thin line presents the standard deviation, the 'bars' present the average value. The impact of the visual tracking task (0=off, 1=tracking) on both signals is very clear.

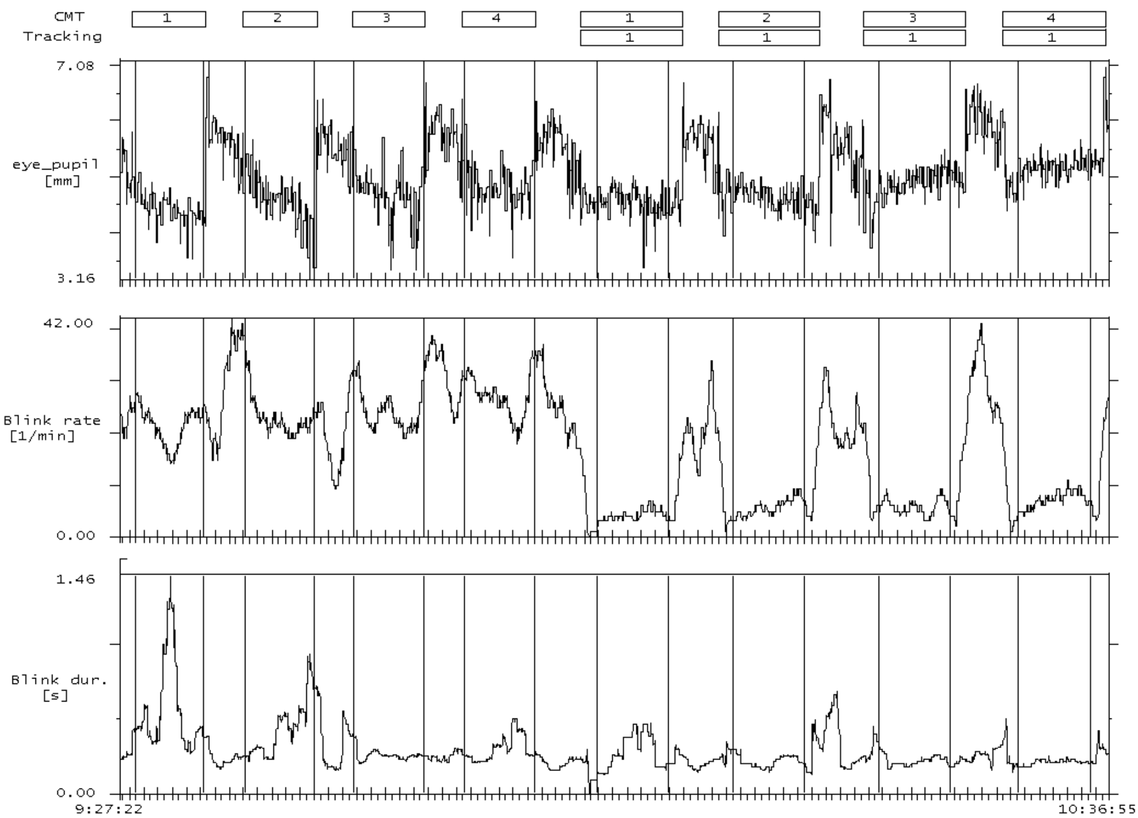

Figure 6: Time-series of eye pupil diameter, blink rate and blink duration. The later two are calculated for a moving window of 1 min, with a step-size of 1 s. As with the previous time-history, the task status is indicated in the top lines.

The blink rate and blink duration are other potential eye-measures. Both are dependent on the type of task: if a task requires visual attention, the blink rate and duration are normally lower than during non-visual tasks. This effect is illustrated in figure 5 and 6, where the blink rate and duration are both reduced whenever the tracking task needs to be performed.
In contrast to other publications, the expected negative correlation of the blink rate and blink duration to the applied CMT level is less clear. However the relation is present in e.g. the second period (CMT=2, no tracking), where the pupil diameter and blink duration behave as expected in opposite directions. Given those time-series, the estimation of mental workload from only the blink rate and duration seems at best doubtful. In addition, due to the required measurement period of approx. 1 minute, the signal will lag with at least half the measurement window size, hampering the real-time interpretation and adjustment of the user interface even further. Significant reduction of the length of this window is not possible due to the increase of calculation noise.

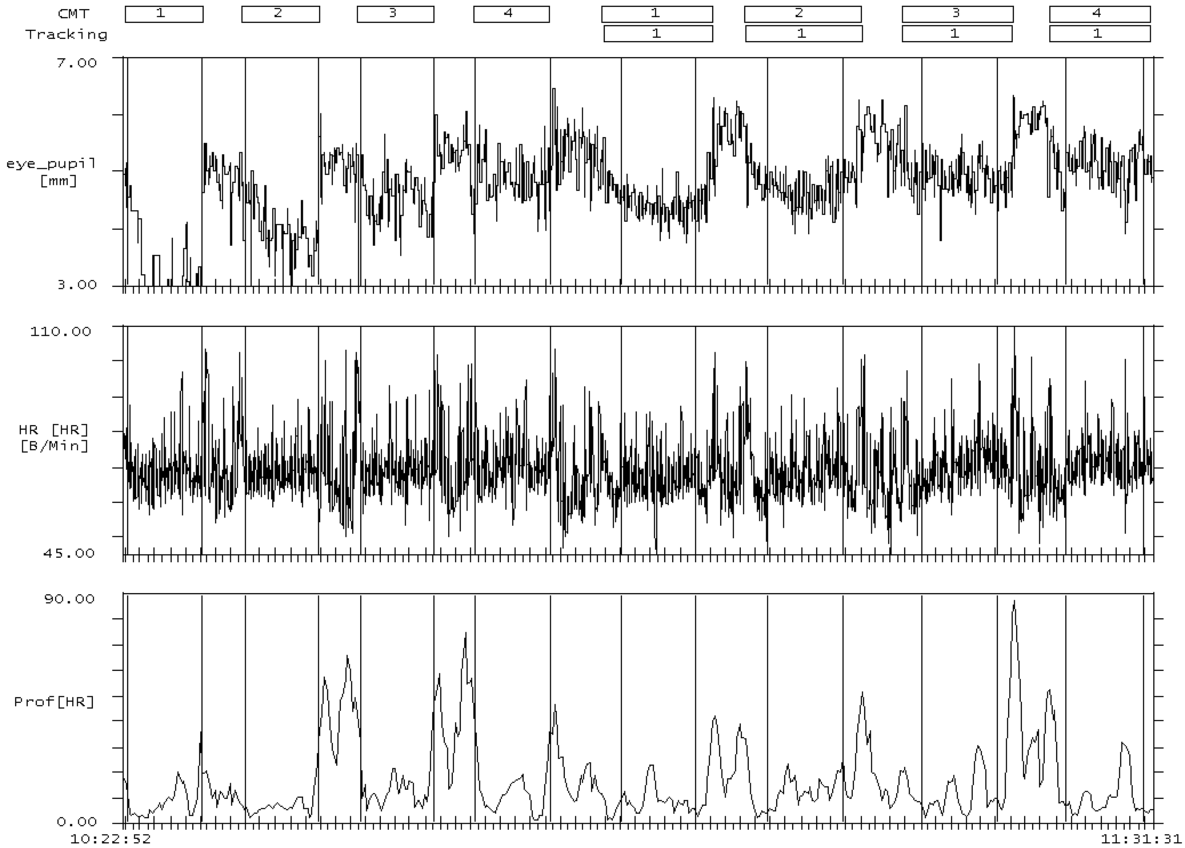

Figure 7: Time history of the pupil diameter, the heart rate (HR) and mid-band energy of the heart rate (Prof [HR]) relative to the task conditions as depicted in the top lines. The profile of the 0.1 Hz HRV is calculated by a moving window of 1 minute, with a step size of 10 s.

An example of a time history of the heart rate HR and mid-band energy of the heart rate (HRV profile, or Prof [HR]) is presented in figure 7. The relation between the pupil diameter and the task condition is again present. HR reacts to the task load conditions, but quickly returns to the nominal value of about 70 bpm. Judging the increasing slope of the signal during the task conditions, some time-on-task effects seem to be present. However, the estimation of the user functional state from HR data seems to be a challenge using this example time-series. In contrast, the HRV profile clearly shows the difference between rest and task conditions. The difference in task load between the several CMT tasks is in this example less clear.

7 VALDAT conclusion

From the presented data it can be concluded that the presented physiological parameters are sensitive to taskload conditions. Inversely, the use of the signals to derive taskload is less straightforward due to the sensitivity of the signals to confounding factors like ambient light

conditions for the pupil diameter. Since each physiological signal reflects only part of the human functional state, it seems advisable to use a combination of the possible measures. So far a unique and clear indicator for the functional state has not been found. This statement is in-line with the conclusion of Orden et al. (2001), who recommend a combination of blink frequency, fixation frequency, and pupil diameter. Mulder et al. (this issue) come to the same conclusion using several cardiovascular time series.
However, both blink rate and blink duration can be used to distinguish visual task loading. Changes in heart rate variability (especially the 0.1 Hz component) provide a strong indication of changes in workload conditions, and are less affected by the visual load of a task. Changes in pupil diameter reflect changes in workload levels, provided ambient light levels remain the same. Also this parameter is relatively insensitive to the visual load of a task. As such the pupil diameter and HRV seem to complement each other: the pupil diameter changes relatively fast with respect to task load, whilst the HRV reacts relatively slow due to the used low frequency components. A combination of the two signals is expected to lead to a stable and relatively fast indication of momentary mental workload.

8 Conclusions

In this paper it is stated that future HMI developments will require adaptive automation to transform the computers to real companions or team players. To be able to create this companionship, an approach nicknamed Operator Status Model (OSM) has been depicted. This OSM can be seen as part of an additional information control loop, adapting the behaviour of computer applications to the actual needs of its users. Based on the analogy with a control loop, some requirements for the adaptation process have been worked out. Basic requirements include the delay times and overall loop-gain.
To verify whether some of the well-known physiological parameters can fulfil the role of a simple sensor for the real-time estimation of the operator’s functional state, an experiment called VALDAT was conducted. Data from this experiment shows that it is advisable to use a mixture of measurements to estimate the momentary functional state since each signal taps into different parts of the mental processes. It was found that the combination of pupil diameter, heart rate variability and blink rate seems to be useful for the real-time estimation of momentary workload and visual task load levels. Having reliable indices for those two user’s state dimensions already provides a way forward for the implementation of more adaptive human machine interfaces by closing the information control loops.

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