Combining Skin Conductance and Heart Rate Variability for Adaptive Automation During Simulated IFR Flight

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Abstract. Adaptive automation increases the operator's workload if there are signs of hypovigilance, and takes over more responsibility in case of workload becoming too high. We refined a closed-loop adaptive system for varying the strength of turbulence in a professional simulator. In the experimental condition, twenty-four subjects flew three blocks with ten 2-min flight sections under varying turbulences. Each of the three blocks applied different combinations of autonomic measures for adaptive automation. Physiological responses were calculated every 2 min for adjusting the turbulence strength for the next 2 min, dependent on an individual setpoint. Another twenty-four yoked control subjects flew the same sequence of turbulences as the corresponding experimental subjects without adaptive automation. By combining nonspecific skin conductance responses and heart rate variability, experimental subjects' skin conductance responses oscillated very close to the individual setpoint, indicating a constant vigilance level as a result of adaptive control compared to yoked control subjects.

Keywords: Vigilance, workload, adaptive automation, human-computer interaction, psychophysiology, aviation psychology.

1 Introduction

A certain degree of the operator's attention is a prerequisite for successfully operating complex man-machine systems. Increasing the degree of automation in a system may restrict the operator's role to one of a mere observer, thus considerably reducing his/her vigilance. Furthermore, complex systems may allow for multiple modes of automation. In case of an unexpected change in situational demands or a system failure requiring immediate operator actions, he/she may not be able to perform an appropriate response since he/she may have lost situational or mode awareness. Thus, there is a need for precautionary measures to prevent an operator from vigilance decrement in case of operating automated man-machine systems.

A very powerful tool for keeping the operator's vigilance in an optimal range is adaptive automation, which refers to the capability of a system to adjust its mode or increasing/reducing the degree of automation dynamically as a consequence of changes in the operator's vigilance [1,2]. In case of hypovigilance, the system may alert the operator, thus increasing his/her attention. In turn, if the operator's workload

D. Harris (Ed.): Engin. Psychol. and Cog. Ergonomics, HCII 2007, LNAI 4562, pp. 639–647, 2007.

becomes too high, the system may automatically take over more responsibility for the task in question.

Vigilance decrement as well as high workload may result in performance decrement and thus should be detectable by performance changes. However, in case of a fully automated system, no measure of the operator's performance will be available from the original task [3]. An introduction of secondary tasks would not only unnecessarily increase the operator's workload but also induce motivational problems. Since vigilance decrement is typically accompanied by a decline in psychophysiological arousal, it can be monitored by measures of central and autonomic nervous system (ANS) activity. Therefore, these measures may be used to continuously monitor the operator's attentional state. Increased workload is accompanied by an increase in arousal that is reflected in psychophysiological measures as well. Setting up an adaptive automated man-machine system will allow for both upward and downward adjustments in automation to keep the operator in an optimal state for operating the system.

Arousal shifts are reflected in various psychophysiological measures such as spontaneous electroencephalography (EEG) or cardiovascular (ECG) and electrodermal activity (EDA). Physiological recordings to be used in adaptive automation are required to be continuously monitored and on-line evaluated. They are not supposed to interfere with the task or impair the operator's well-being. First attempts to establish man-machine systems for adaptive automation in laboratory environments have used EEG derived indices [1,4,5], heart rate variability (HRV) [2,5], EDA [6,7,8], and blood pressure [9]. One important application for adaptive automation systems is conducting long-haul transport operations in an airplane. Today's commercial aircraft are flown by computer systems that allow for operating modes during which the pilots remain almost passive for long periods of flight. Such a situation is inherent to vigilance decrement, the *"out of the loop performance problem"* in system operators [10], and to *"operator hazardous states of awareness"* in aviation [4]. Because it is impractical to record EEG from commercial pilots, attempts have been made to use autonomic nervous system measures to detect vigilance decrement in pilots [11]. The goal of our current research is to provide an adaptive system, based on electrodermal and cardiovascular measures.

In a previous pilot study [12], we recorded EDA and heart rate (HR) from student subjects during four flight missions in a professional instrumental flight rule (IFR) simulator, varying the strength of turbulence in order to check the usability of ANS measures for adaptive automation. Increasing strength of turbulence resulted in an increment of nonspecific skin conductance responses (NS.SCRs) which can be interpreted as an indicator of increased workload [13]. On the other hand, progression of flight missions was associated with habituation shown by a decreased frequency of NS.SCRs and reduced sum of amplitudes. The aim of the follow-up study [14] was to construct a closed-loop adaptive system, implementing NS.SCRs as adequate arousal indicator and control variable for adjusting the strength of turbulence onset during a flight task with thirty 60-s sections. In the experimental condition, turbulences were varied according to the physiological responses of the subject, dependent on an individually predefined setpoint. Yoked control subjects received the same sequence of turbulences as their experimental counterparts, however without considering their setpoint deviations. Paired comparisons revealed smaller deviations for the experimental subjects compared to yoked control subjects.

Our previous results look promising for the usability of autonomic measures in adaptive automation. It is, however, rather unlikely that a single physiological system will have both sensitivity and diagnosticity to cover all aspects of vigilance decrement and arousal in man-machine systems. Instead, multiple recordings from different physiological systems may be needed in order to gain a full picture of the different arousal and attentional systems [13]. In the present study, three major modifications were made to the experimental setting: Firstly, we compared different combinations of autonomic measures with respect to quality of regulation. Secondly, in order to obtain a more accurate calculation of the subjects' individual setpoint, we took four instead of two baseline recordings. The reason was that in the previous study several subjects produced more NS.SCRs during the baseline recordings under resting conditions compared to workload conditions. Using a wider range of baseline recordings was expected to take care of this problem. Thirdly, we extended recording periods from 1 to 2 min per flight section. In psychophysiological recording, very short epochs may not reliably detect changes in physiological measures.

2 Method

2.1 Subjects

Forty-eight student subjects (24 female, 24 male) aged 20-39 years (M=26.42 years, SD = 5.34 years) from different disciplines took part in the study.

2.2 Task and Design

The subjects had to accomplish the following IFR flight missions: (1) Taking off from Frankfurt/Main airport and climbing out to 2,000 feet. (2) Flying straight and level to a direction of 070, controlling altitude, speed and course. (3) After a change of altitude to 10,000 ft triggered by the instructor outside the laboratory, subjects had to turn to a direction of 060 for the final destination (Erfurt airport). (4) Keeping that course, controlling altitude and speed while facing turbulences (turbulence steps 0, 1, 3 and 5). The choice of turbulence steps was based on subjective ratings from a previous test session with 36 subjects who subjectively evaluated all six turbulence stages in counterbalanced order.

Before starting their task, subjects were familiarized with the flight simulator instruments, using no turbulences and turbulence step 3 for demonstration. Afterwards, subjects performed three blocks based on different combinations of autonomic measures in counterbalanced order: (1) NS.SCRs only, (2) NS.SCRs and HR and (3) NS.SCRs and HRV. Under (1), turbulences were modified according to deviations from an individual predefined setpoint based on NS.SCRs. Under (2), turbulence changes were triggered by deviations of NS.SCRs and HR from predefined setpoints of NS.SCRs and HR in the same direction. Under (3), deviations of NS.SCRs and HRV from their respective setpoints in opposite directions triggered the change in turbulence settings. The latter algorithm aimed at the control of artifacts that are a nagging problem in online parameterization of physiological data. In general, NS.SCRs increase and HRV decreases under elevated arousal. Thus, a change of NS.SCRs and HRV in the same direction (e.g. a simultaneous increase or decrease in both NS.SCRs and HRV) would not trigger changes in turbulence intensity.

Prior to each block, subjects had a 2-min rest for stabilizing their physiology. Afterwards, four baseline recordings were performed (2 x 2 min without turbulences as resting period and 2 x 2 min with maximum turbulence step 5 as workload period). Next, the control computer calculated the subjects' individual setpoint for the physiological measures according to the combination of autonomic measures applied, based on the arithmetic mean of the four baseline recordings.

The subjects were divided into two groups: (1) In the experimental condition, 24 subjects flew ten 2-min flight sections per block, keeping altitude and course while facing different turbulences. Psychophysiological parameters were calculated every 2 min. They were used for triggering the strength of turbulences for the next 2 min, dependent on the setpoint of the individual subject. (2) Another 24 subjects belonged to the yoked control condition, i. e. each control subject received the same block order and sequence of turbulences as the corresponding experimental subject, regardless of his/her own setpoint and hence without adaptive automation.

The yoked pairs were always formed by either two male or two female subjects for control of gender effects. Table 1 shows the design of the study.

Table 1. Repeated measures design for different combinations of psychophysiological parameters

<table>
<tr><th rowspan="2">gender</th><th rowspan="2">condition</th><th colspan="3">blocks (counterbalanced)</th></tr>
<tr><th>NS.SCRs</th><th>NS.SCRs+HR</th><th>NS.SCRs+HRV</th></tr>
<tr><td rowspan="2">male</td><td>experimental (adaptive)</td><td rowspan="4">10 flight sections, 2 min each</td><td rowspan="4">10 flight sections, 2 min each</td><td rowspan="4">10 flight sections, 2 min each</td></tr>
<tr><td>yoked control (non-adaptive)</td></tr>
<tr><td rowspan="2">female</td><td>experimental (adaptive)</td></tr>
<tr><td>yoked control (non-adaptive)</td></tr>
</table>

2.3 Apparatus

We ran a professional IFR flight simulator software on a personal computer (LAS 5.0, made by Fahsig, Germany). The software was extended by the feature of varying the strength of turbulence by means of external control via serial port. Cockpit instruments were displayed on a 17" monitor 0.5 m in front of the subject. Controls for ailerons, elevator and throttle were provided, together with an electrical trim.

A second computer was needed for the control of adaptive automation: (1) Triggering the automatic onset and offset of turbulences on the LAS computer according to the subjects' individual setpoint (comparator function). (2) Starting physiological data recording on a third computer. (3) Receiving the on-line calculated NS.SCRs, HR and HRV from the recording computer for adaptive regulation of the subjects' arousal according to the combination of autonomic measures applied. Fig. 1 gives an overview of the information flow between the subject and the various instruments.

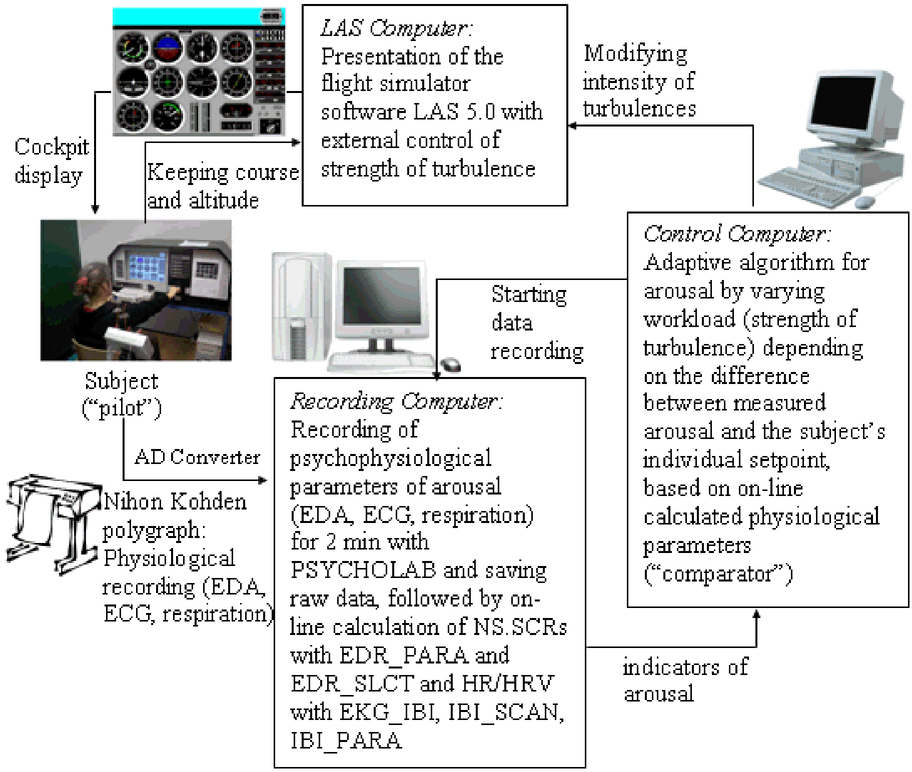


Fig. 1. Closed-loop adaptive system based on autonomic measures

2.4 Recording and Data Analysis

Recording of physiological data (EDA, ECG, respiration) was performed by means of a Nihon Kohden Neurofax EEG-8310 G polygraph, using a personal computer with a customized software package (*PSYCHOLAB,* © Jörn Grabke, 1997). EDA was recorded thenar and hypothenar according to Boucsein [15] from the left hand with two Ag/AgCl electrodes (0.8 cm diameter), using isotonic electrode cream (Med Associates, Inc.), with a sampling rate of 20 Hz, a sensitivity of 0.001 µS, and a 0.3 Hz low pass filter. Frequency and sum of amplitudes of NS.SCRs were used as tonic EDA measures, calculated on-line by customized software (*EDR_PARA* and *EDR_SLCT,* © Florian Schaefer, 2003), using an amplitude criterion of 0.01 µS. ECG was recorded by the Einthoven II-lead (above the right wrist vs. above the left ankle) with two Ag/AgCl electrodes, filled with Hellige electrode cream, at a sampling rate of 200 Hz. A ground electrode was placed on the left forearm. The ECG signal was analyzed by customized software (*EKG_IBI, IBI_SCAN, IBI_PARA,* © Florian Schaefer, 2003) calculating mean HR and HRV as root mean square of successive differences (RMSSD).

A respiration belt containing a piezo element was fastened to the subject's thorax (sampling rate of 10 Hz). Respiration was not used for adaptive automation.

2.5 Statistical Analysis

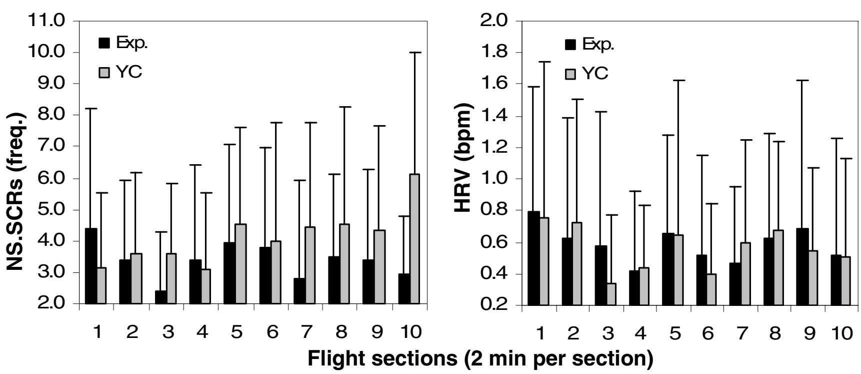
In a first step, the absolute setpoint deviation values were calculated for the psychophysiological parameters involved in the different algorithms. Afterwards, repeated measures ANOVAs were conducted separately for each block, with experimental condition (adaptive vs. yoked control), gender (male vs. female) and sequence of blocks (three combinations of physiological data) as between subject factors and the ten flight sections as within subject factor, using Greenhouse-Geisser corrected degrees of freedom.

In a second analysis, the three blocks were directly compared by repeated measures ANOVAs for each physiological measure, using only flight segments 6 to 10. That additional procedure was chosen because of marked differences between conditions within those flight sections (a posteriori) and helped to evaluate the quality of adaptive automation for the three combinations of autonomic measures applied.

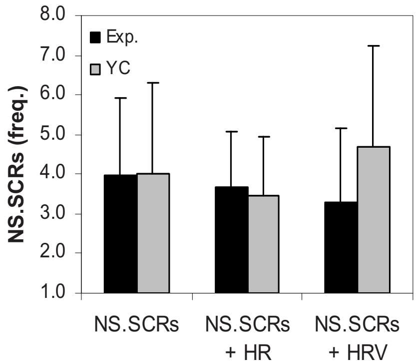
In a third analysis, the frequency of turbulence switches was calculated and submitted to another repeated measures ANOVA, with the same between subject factors mentioned above and number of switches as within subject factor. That procedure was applied to the 24 experimental subjects only as their physiological responses actually triggered the variation of turbulences in contrast to the yoked control group. The probability of error was set to α=.05.

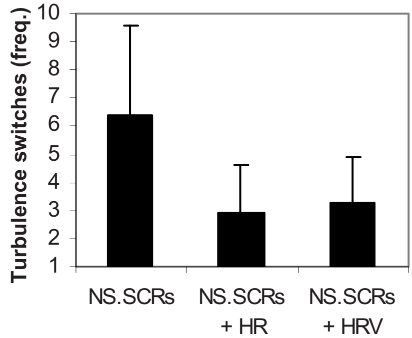
3 Results

Repeated measures ANOVAs and post hoc comparisons revealed that during the combination of NS.SCRs and HRV, setpoint deviations of NS.SCRs were significantly smaller for the experimental group compared to the yoked control group, especially during the second half of the block (flight segments 6 to 10), as supported by a significant interaction of experimental condition and flight segment ($F(6.47, 232.72) = 2.65$, $p=.014$; $t(32.82) = 3.67$, $p=.001$; see Fig. 2). HRV data did not yield significant differences between the two groups (see Fig. 3).



Figs. 2 and 3. Absolute setpoint deviation values (group means) for adaptive (Exp.) and yoked control (YC) condition by coupling of NS.SCRs (left) and HRV (right)





Figs. 4 and 5. Comparison of the three algorithm constellations for NS.SCRs setpoint deviations (left) and frequency of turbulence switches within the experimental group (N=24) for the different couplings of psychophysiological parameters (right)

In a second analysis, a direct comparison of the three blocks using only flight segments 6 to 10 revealed a significant interaction of block and experimental condition, again with smaller setpoint deviations of NS.SCRs in experimental subjects during block "NS.SCRs+HRV" (F(1.85, 66.75)=3.41, p=.042; t(42.15)=2.20, p=.033; see Fig. 4).

An additional analysis within the adaptive automation group (N=24) revealed that the frequency of turbulence switches was significantly higher in block "NS.SCRs" compared to blocks "NS.SCRs+HR" and "NS.SCRs+HRV" with combined physiological parameters (F(1.60, 28.71) = 17.67, p<.001; see Fig. 5).

4 Discussion

The present study examined the adjustment of physiological arousal in a closed-loop system by means of different combinations of physiological measures during a simulated flight mission task in a yoked control group design. In the experimental group, adaptive adjustment was performed by means of either NS.SCRs alone, or NS.SCRs and HR, or NS.SCRs and HRV according to the subjects' individual setpoints taken from four baseline recordings. In the yoked control group, subjects flew the sequence of flight missions of their experimental counterparts without an adaptive control, i.e. regardless of their individual setpoint. Results indicated that the experimental subjects remained closer to their individual setpoint of arousal compared to yoked control subjects as a consequence of adaptive control.

The results supported the usability of autonomic measures in adaptive automation as already found in our previous study [14]. Moreover, we were able to show that coupling of two psychophysiological parameters, namely NS.SCRs and HRV, turned out to show a marked differentiation between the two experimental conditions compared to the other two constellations of algorithms with regard to setpoint deviations of NS.SCRs (see Fig. 4). Obviously, HRV had a modulating effect on switching frequency of turbulences compared to adaptive regulation based on NS.SCRs only. In the latter case, the frequency of turbulence switches was significantly higher than under combined parameters (see Fig. 5). According to Scallen et al. [16], short cycles of automation in adaptive function allocation elevated performance, but at the same time increased subjective workload. Moreover, Hadley et al. [17] observed subjects having more difficulties in switching back from automation to manual operation in case of short cycles of switches. Hence, the high frequency of switches under NS.SCRs alone might have contributed to instabilities within the closed loop, resulting in higher deviations from setpoint values.

In addition, coupling of NS.SCRs and HRV within a single algorithm for adaptive automation can be considered as a powerful tool for counteracting artifacts during on-line assessment. Influences that are regarded as artifacts during psychophysiological recording such as body movements or deep breathing [15] will presumably cause NS.SCRs and HRV to change in the same direction. In this case, the algorithm will not initiate workload modulation. If, however, NS.SCRs and HRV change in opposite directions as a consequence of task demands, the algorithm will vary task demands according to the individual predefined setpoints. For further enhancement of closed-loop stability, the introduction of hysteresis for setpoint values should be considered.

In conclusion, our results can be considered as an important step towards the transfer of adaptive automation from the laboratory to the cockpit. We consider the advantage over the hitherto performed research, e.g. [1,4], twofold. First, we successfully used easy-to-measure autonomic variables instead of EEG measures that would be much harder to record during real flight. Second, probing adaptive automation in a professional IFR flight simulator with an authentic cockpit comes much closer to reality than using the Multi-Attribute Task Battery (MATB), an artificial system that does not provide real flight instruments, and even its tracking task does not come close to the standard-T (indicators of airspeed, attitude, altitude and direction) displays in a glass cockpit. In our opinion, more realistic setups are a prerequisite for the implementation of adaptive automation in such a complex work environment as a cockpit.

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