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Physiological Markers of Vigilance Variation in a Supervisory Task

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ABSTRACT

Many recent studies show that physiological markers can support the assessment of cognitive states such as human attention or vigilance variation. In the perspective of new cockpit or future products that are evaluated in a more ecological simulation context, we investigate which and how such physiological metrics could complete the often used classical methods such as subjective ratings or direct observation. Before assessing their robustness in a more ecological environment, we present the results of two experiments aiming to select the set of relevant metrics: A psychomotor vigilance task classically used in the study of vigilance and a second task that combined an alarm detection task and a supervisory task. Global results show that the combination of ECG and eye-tracking indicators is a promising solution for the investigation of pilot vigilance decrement in a cockpit simulator.

Keywords: Vigilance, Physiological markers, Supervisory task, PVT

INTRODUCTION

Vigilance or sustained attention refers to the ability of individuals to monitor the situation in a continuous stream and detect infrequent or occasional critical features over time. The ability to maintain an appropriate level of vigilance over long periods of time underlies success on a range of tasks. Particularly, staying alert allows to detect infrequent signals and to allocate the right level of cognitive resources to respond to expected or unexpected events. In this context, valid assessment of vigilance is operationally important.

Vigilance is typically assessed using subjective, performance-based, and/or physiological measures. Subjective ratings involve sampling the participant response to the amount of vigilance used by using a questionnaire (Ross, Russell, & Helton, 2014). However, self-assessment techniques when performed during the test should not be too frequent in order to limit their impact on the task. Moreover, human beings are often inefficient when assessing their own cognitive states. Performance measurement is based on the evaluation of an individual's ability to perform the task. There is a long history of using decreased performance with time on task as a gauge of vigilance decrement (Warm, Matthews, & Finomore, 2008). Examples of performance metrics susceptible to vigilance include reaction time, response speed to emergency events, and lapses. However, such metrics are not always easy to implement when it comes to supervisory tasks and the level of vigilance can sometimes vary without directly impacting the level of performance in the task. In this context, there is a need for both unobtrusive and more sensitive methods for assessing operator vigilance. Physiological measurement of vigilance has been proposed in this sense (Oken, Salinsky, & Elsas, 2006). Physiological measures of vigilance are devoted primarily to continuous measurement of the physical responses of the body. These changes are measured in cardiac activity, brain activity, respiratory activity, and eye activity. Interestingly, physiological metrics appear to be more sensitive (i.e., physiological measures may be able to detect a drop in alertness before operators can report it) than subjective and performance based metrics. These findings are interesting for human factors in aeronautics as it appears as a way to complement the self-assessment ratings and observations with physiological metrics collected during assessment with pilots in a cockpit simulator.

However, before integrating a set of physiological metrics in a representative cockpit, we propose to test the robustness of a selection of physiological metrics proposed in two lab tasks: A psychomotor vigilance task (PVT) classically used in the study of vigilance and a second task that combined an alarm detection task and a supervisory task. Particularly, we proposed to explore four different markers of vigilance derived from electrocardiographic (heart rate variability), oculometric (blink frequency and eye closure) and electroencephalographic (alpha power) signals. The objective is to assess the robustness of the selected physiological markers selected.

EXPERIMENTAL DESIGN

Participants

Seventeen participants participated in the experiment. Eight participants (4 males; M = 25 y.o. SD = 3.6) completed the first task (PVT) while nine participants (5 males; M = 23.2 y.o.; SD = 4) completed the second task (supervisory task). All participants were voluntary and naive to the study's hypotheses.

Tasks

Psychomotor Vigilance task – Psychomotor vigilance task (PVT) has emerged as one of the most widely used tools to assess vigilant attention in fundamental (Chua et al., 2014) and applied research (Ferguson et al., 2008; Russo et al., 2005). The PVT is a computer-based reaction-time task, pioneered by Dinges and Powell (1985). It allows the collection of a large amount of data in a relatively short period of time. These characteristics increase the sensitivity of the test to detect even small changes in vigilant attention. In our version of the PVT, each trial (Figure 1) started with the presentation of a yellow rectangle on a black background. Participants attended to the LED display for the duration of the test (30 min) and were instructed to press a central button as quickly as possible after the appearance of a visual stimulus

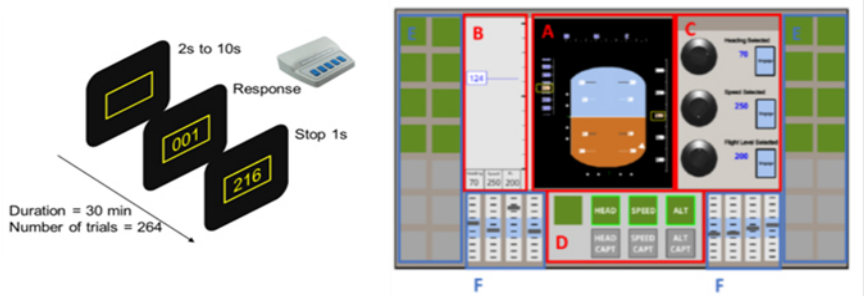

Figure 1: Procedure for a trial of the psychomotor vigilance task (left) and autopilot interface used for SAMT (right).

(a timer) presented at a variable interval of 2–10 sec. The displayed value, corresponding to the participants' RT, remained displayed for 1s. Given the simplicity of the task, the participants performed three trials beforehand to practice.

Simplified Aircraft Monitoring Task (SAMT) – In this study, we propose a set of tasks representative of those performed in aircraft piloting. Derived from the multi-attribute task battery (MATB) classically used in aeronautics, we focus here on the supervisory components of the pilot task. In this sense, we designed a new task called SAMT. In this task, participants interacted with a tactile interface (Figure 1). They had to perform two subtasks in parallel: supervise the actions of the autopilot and detect alarms. The first subtask required to control the heading, speed, and altitude of the aircraft using the autopilot interface. For this task, displays A, B, C and D were used. Display A indicates the altitude, the speed and the course followed but also the orientation of the aircraft compared to the horizon. Display B indicates the instructions to follow. In addition to presenting the values to be followed, above each parameter were scrolled the next values to be adopted and the timing to follow. Participants had to set the values to be tracked via screen C. Finally, screen D allowed the participants to know if the parameters were followed by the autopilot. The second subtask was performed via screens E and F. For the squares appearing on screen E, the participants had to press as quickly as possible on the square whose color had changed. The gauges in the F screens oscillated vertically and had to stay in the blue zone. If a gauge moved out of this boundary, participants had to press that gauge as quickly as possible as well. This detection task took priority over the supervision task. A total of 16 alarms appeared during the task. The appearance of these 16 alarms was divided into 4 separate blocks according to their appearance frequency (i.e. high or low). When the frequency was low, the block lasted 16 minutes, whereas when it was high, the block lasted 8 minutes. The task was composed of two blocks of each frequency. They appeared in alternation (low, high, low high).

Measures

As mentioned above, we were interested in four different markers of vigilance derived from electrocardiographic, oculometric and electroencephalographic signals.

Electrocardiographic markers – ECG data were recorded using Biopac system. The evolution of heart rate variability (HRV), that is how much the heart rate varies, has been computed for the two tasks performed. First empirical evidence indicated that decrease in vigilance is characterized by an increase in HRV (Porges & Raskin, 1969). Nowadays, the heart rate variability (HRV) is used as a robust metrics for vigilance measurement (Larue, Rakotonirainy, & Pettitt, 2011; Henelius, et al., 2014). In our study, we used a time-domain indicator called SDNN. SDNN is calculated as the standard deviation of all of the RR intervals (i.e., the distance between each heartbeat) and was computed for the 2min time windows.

Oculometrics markers – Oculometric data were recorded using the hardware SmartEye Pro 3.0 and the software SmartEye 6.2.4. The system included 2 infrared illuminators and 3 cameras (120 Hz) placed above the screen to avoid any direct contact with the participant. Two different metrics were collected: the PERcentage of eyelid CLOSure (or PERCLOS) and the blink frequency. PERCLOS measures the percentage of time during which the eyes are closed over a window of several minutes (usually 1 to 3 minutes). An eye closure is usually characterized by an 80% (sometimes 70%) closure of the eye compared to its nominal size. The correlation between PERCLOS and performance decrements in vigilance tasks has been demonstrated in a number of experiments (Wierwille, et al., 1994; Dinges, Mallis, Maislin, & Powell, 1998). Blink frequency is a well-validated indicator of visual attention; it is reduced during periods when attention is oriented toward significant external stimuli, and this reduction is proportional to the required attention (Campagne, Pebayle, & Muzet, 2005; Stern, Walrath, & Goldstein, 1984). It corresponds to the number of blinks over a given time window. Note that we used the blinks identified by the Smart Eye algorithm in our study.

Electroencephalographic metrics – EEG data were recorded using actiCHamp system. In our study, we were interested in the evolution of the alpha power. Nowadays, there is a very large literature concerning the relationship of oscillatory activity and vigilance (Foxe, & Snyder, 2011; Frey, Ruhnau, & Weisz, 2015). Overall, there is increased slow frequency activity (alpha and theta bands) with decreasing vigilance. After signal preprocessing (segmentation, 2nd order Butterworth bandpass filter from 1Hz to 80 Hz and a notch for 49 to 51Hz, visual inspection and signal rejection, ICA), we performed a time-frequency analysis of the time series by applying a Morlet transform to each segment. For the PVT data analysis, the trials were separated into 4 blocks and the 1st block was used as the baseline. For the supervision task, the rest period was chosen as the baseline. Normalization was performed by dividing the spectral power by that of the baseline and the measurements were then expressed in decibel via a logarithmic transformation. In both cases, the alpha frequency band was between 8Hz and 14Hz. In the PVT, the analysis was restricted to the electrodes located on the occipital lobe (i.e. O1, O2 and Oz) whereas in the correlation analyses performed with the supervisory task data, all the electrodes were taken into account.

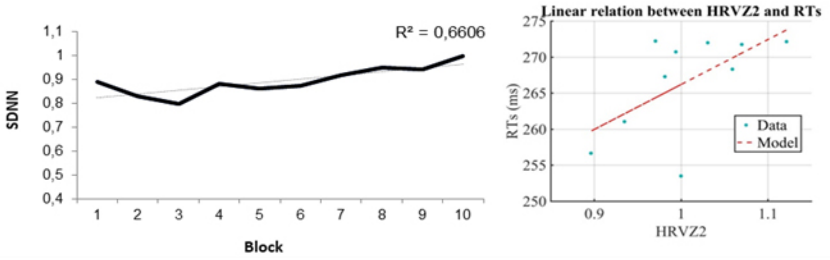

Figure 2: Time course of HRV (left) and RT/HRV relationship (right) during the psychomotor vigilance task.

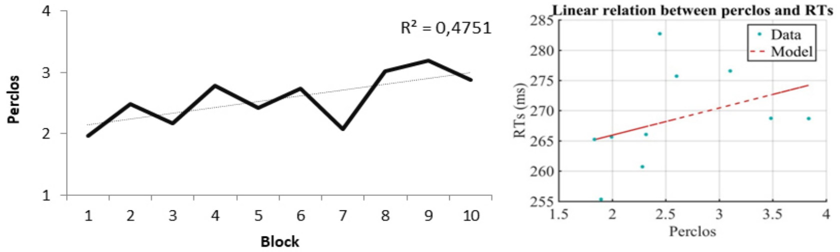

Figure 3: Time course of PERCLOS (left) and RT/PERCLOS relationship (right) during the psychomotor vigilance task.

RESULTS

PVT Results

As a reminder, performance metrics are typically used as vigilance markers during this PVT task, so trials characterized by low vigilance generate higher reaction times. In this context, we were interested in 1/ the evolution of our physiological markers over time, 2/ the relationship between these markers and reaction times.

Before exploring the evolution of our physiological metrics, we explored the evolution of reaction times over time to assess whether a decrease in performance was observed during the task. At the behavioral level, we did not observe a significant decrease in performance over time $F(1,14) = 1.5, p > 0.1$.

ECG - The results (Figure 2) show a linear relationship between the time on task and HRV (R^2=0.6606). Furthermore, when we look at the correlation between this metric and RTs, we find that when we add the HRV factor to our RT explanation model, it predicts Reaction Times (RTs) better than a simple model where we only take the average of RTs ($p = 0.001772$).

Oculometric measure - The results (Figure 3) show a linear relationship between the time on task and PERCLOS (R2=0.4751). As observed for HRV, there also appears to be a relationship between RT and PERCLOS such that a model with PERCLOS predicts the obtained RT better than without (p = 0.005364). Contrary to the results obtained for PERCLOS, no relationship between blink frequency and time is observed. Furthermore, the addition of the "Blink frequency" indicator does not explain predict the RT data better than without.

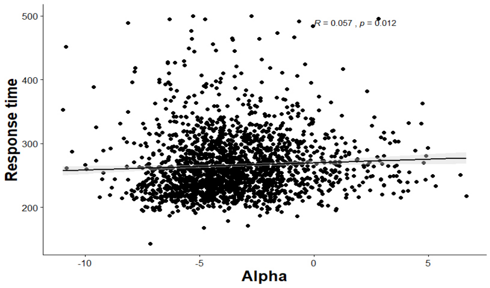

Figure 4: RT/Alpha Power relationship during the PVT.

EEG measure - In contrast to the other metrics, we do not observe a change over time in alpha activity. However, analysis of the correlation between response time and alpha activity associated with each trial demonstrates a positive correlation between alpha and RTs ($r = 0.068$, $p = 0.0016$), so that the higher the reaction time (and therefore the lower the performance), the higher the alpha (Figure 4).

The results obtained during the PVT seem to confirm the relevance of the proposed metrics (HRV, PERCLOS and Alpha Rhythm) as markers of the evolution of vigilance, contrary to the results obtained for blink frequency. In particular, these three metrics are correlated with performance in this psychomotor vigilance task. In a second step, we were interested in the evolution of the three "responsive" metrics (i.e., HRV, PERCLOS & alpha activity) during our supervisory task (i.e., the SAMT).

SAMT Results

In this second experiment, we were interested in the decrease in vigilance over time and compare different periods with low and high alarm frequency. The question was therefore whether the three successful physiological measures in our first experiment were sensitive to the phenomenon of vigilance decrement in a supervisory task.

ECG - The results demonstrate an increase in HRV over time (Figure 5), as previously observed in the PVT task (R^2=0.8833). As a reminder, the difficulty of the detection task evolved during the 4 blocks (low, high, low, high) which explains the evolution observed (increase between block 1 and 2, then decrease between block 2 and 3, then increase "again between block 3 and 4).

Oculometric measure – A same tendency is observed for the PERCLOS (Figure 5), with an increase in PERCLOS over time (R^2=0.6149).

EEG measure – Finally, we observed a marginal increase in alpha over time (−4.8 vs −4.2 Hz), $F(1,8) = 4.4$, $p < 0.1$.

The three metrics that were responsive to changes in vigilance during the PVT task are therefore found to be also responsive to changes in vigilance during our SAMT task. In addition, we also added a subjective scale (Samn-Perelli) before and after completion of the supervisory task to explore changes in fatigue levels. Participants report an increase in fatigue (Samn-Perelli) after the supervision task (4 vs. 4.8), $F(1,8)= 5.8$, $p <.05$.

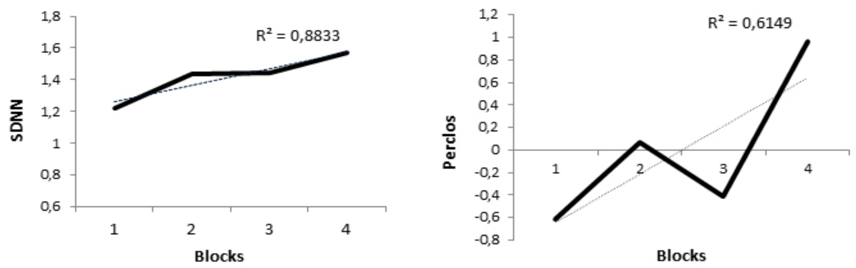

Figure 5: Time course of HRV (left) and PERCLOS (right) during the supervisory task.

CONCLUSION

In this study, we proposed to assess the interest of the four physiological markers: heart rate variability, blink frequency, eye r closure and EEG alpha power. To do so, we used two different tasks: a task classically used in the study of vigilance (i.e., the psychomotor vigilance task or PVT) and a task of monitoring an automatic pilot. The first study allowed us to demonstrate that the PERCLOS, the heart rate variability and the EEG alpha power were sensitive to variations in vigilance. In particular, we observed that these metrics were significantly correlated with changes in reaction times, a metric classically used in the PVT task as a marker of vigilance state. Interestingly, we also observed that these physiological metrics seem to be sensitive to the decrease of vigilance over time classically put forward in these vigilance tasks, where the only behavioral metrics classically used in PVT task (here, RT) would not allow to highlight a significant loss of vigilance. The relevance of these physiological markers to highlight decreases in vigilance over time is confirmed in the SAMT since the three metrics previously highlighted show a sensitivity to time on task consistent with the evolution of the level of fatigue reported by the participants. Thus, it appears that the sensitivity of these metrics to changes in vigilance does not depend on the nature of the task. The use of SAMT also allowed us to explore this decrease in alertness in an underload context, which allows us to get closer to the ecological context. Taken together, these results confirm the relevance of physiological measures to characterize and quantify changes in vigilance levels over time. The next step will be to evaluate the robustness of these metrics in a representative cockpit. One limitation concerns the difficulty of relating performance to decreased vigilance in our SAMT. One prospect would be to identify performance metrics that might be relevant for use in this task.

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