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A methodology to compensate for individual differences in psychophysiological assessment☆

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ABSTRACT

The main methodological drawback to use physiological measures as indicators of arousal is, the large interindividual variability of autonomic responses hindering the direct comparability, between individuals. The present methodology has been tested in two cohorts ($n1 = 910$, $n2 = 845$) of, pilot applicants during a selection procedure. Physiological data were obtained during two mentally, demanding tasks and during a Flight Simulator Test. Five typical Autonomic Response Patterns (ARP), were identified by cluster analyses. Autonomic spaces were constructed separately for each group of, subjects having the same typical ARP, on the basis of their normalized eigenvectors. The length of the, vector sum of scores on autonomic space dimensions provided an integral index for arousal, labeled, Psychophysiological Arousal Value (PAV). The PAV still reflected the changes in mental load during the, tests, but equalized physiological differences among ARP-groups. The results obtained in the first, cohort were verified in the second cohort.

1. Introduction

Psychophysiological measures have been used in a wide area as an index for arousal, or indirectly as a measure of mental load and stress (see Gaillard, 2008). Although promising results have been obtained, the reliability of these measures has been criticized. Several approaches have been developed to make measures more robust. One way pursued is to combine the data obtained from different variables into an overall arousal scale (Baevsky, 1997, 2002; Moran, Montain, & Pandolf, 1998; Steptoe & Vögele, 1991). This approach, however, has been criticized by several authors (e.g., Fahrenberg & Foerster, 1982). Two disadvantages have been raised. Firstly, the common correlation matrices of the different physiological measures show too much inconsistency (Haynes & Wilson, 1979; Wenger & Cullen, 1972), due to large individual differences. Secondly, the intensity of a particular reaction depends on the initial state (Wilder, 1950) of a subject or more correct on the initial localization of the subject in the autonomic space (Berntson, Cacioppo, & Quigley, 1991, 1993). To solve these problems, several researchers tried to identify patterns of psychophysiological responses by means of multivariate methods, such as pattern classification analysis (Christie & Friedman, 2004; Kreibig, Wilhelm, Roth, & Gross, 2007) or by cluster analysis (Allen, Boquet, & Shelley, 1991; Speisman, Osborn, & Lazarus, 1961; Stephens, Christie, & Friedman, 2010).

Another approach is to investigate the mechanisms underlying the changes in heart rate. Cacioppo and coworkers (Berntson, Cacioppo, Quigley, & Fabro, 1994; Cacioppo, 1994; Cacioppo, Uchino, & Berntson, 1994) focused on source analyses "beyond" heart rate, which resulted in a three dimensional autonomic-response model for the autonomic control of heart rate (see also Backs, 1998, 2001). The present approach (see also Johannes & Salnitski, 2004; Johannes, Salnitski, Soll, Rauch, & Hoermann, 2008) is an extension of the method developed by Cacioppo and coworkers. The main difference with our scaling approach is that the number of coordinates and the number of included end organs are extended. Our method is based on the assumption that an orthogonal vector model is able to assess the sum of the autonomic mechanisms affecting physiological variables. This results in an "autonomic space" in which the eigenvectors[1] are the

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[1] In a factor analysis the eigenvector represents the power (or strength) of a particular factor, based on the interconnectedness and the common variance of the contributing variables which load on that factor. To limit the number of factors, in

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dimensions of the space model and the eigenvector scores represent the loads of all measures to be integrated. The aim of the present work is to develop a methodology, which is in addition able to account for individual differences. This methodology identifies individual autonomic response patterns (ARPs) in psychophysiological variables and uses pattern-specific integration.

In earlier studies (Johannes, Eichhorn, & Fischer, 1994; Johannes, Salnitski, Thieme, & Kirsch, 2003) we demonstrated that ARPs obtained during a mentally demanding test, are affected differently, as a function of environmental demands, coping styles and individual states. We also showed that the number of typical ARPs is limited. In the present study we will show that there are five typical ARPs in healthy subjects. These ARPs can be used for pattern-specific scaling, when it can be demonstrated that the eigenvectors of different ARP-groups are similar, even when the overall correlations between subjects are low (Haynes & Wilson, 1979). If reliable ARPs can be identified, one can normalize the scores of the eigenvectors separately for each group of subjects showing the same typical ARP. In this way, pattern-specific vector units are obtained which can serve as reference to make comparisons among subjects, even when their ARPs are different. The vector length in this vector space is assumed to represent the sum of autonomic reactivity in a particular subject. In this way the intensity of the response can be compared between subjects.

2. Methods

The selection procedure of pilots and other air personnel at the German Aerospace Center (DLR) (Goeters, 1998a, 1998b; Hoermann, 1998a, 1998b) is a well-organized and documented procedure. A quality management system, certified according to ISO 9000, guarantees the continuous control of quality. A Flight Simulator Test (FST) is a standard part of the selection procedure. Only the applicants, who successfully passed all tests on the first day, were admitted to perform the FST on the second day. The physiological assessment was used for research purposes only, not for the selection. The psychophysiological assessment was ethically approved by the local committees for several studies (space experiments, bed rest studies, isolation studies). The subjects signed an informed consent form prior to the selection procedure. This included explicitly the voluntary participation in the additional scientific program.

2.1. Subjects

All subjects were ab-initio candidates for airline pilot training. The pilot applicants underwent a two-day selection process. There were two cohorts. Whereas the results of earlier studies (Johannes et al., 2008) were based on all available complete data sets, the present data were cleansed to exclude outliers which could have disturbed the grouping results. In Cohort 1910 subjects *(838 male, 72 female)* remained and 845 *(771 male, 74 female)* in Cohort 2 (exclusion procedure is described in detail in section 4.1). The cohorts did not significantly differ with respect to age (21.15 years, SD 2.43). The subjects were slim (BMI 23), nonsmokers and sportive active. *The herein newly presented cohort 2 consisted of inhabitants of the FRG (809, 95.7%), Austria (20, 2.4%), Switzerland (5, 0.6), and 8 other European countries (11, 1.1%).*

2.2. Procedures

The assessment of the physiological measures took place in two separate sessions. On the first day subjects had to perform two mentally demanding cognitive tasks in the TTS and on the second day they performed the FST.

2.2.1. Two task session (TTS)

The subjects were examined in groups of five in an air-conditioned room maintained at 21 °C. Computer monitors were located in front of them on small tables. The headsets were used to record each subject's voice commands and to give audio instructions. The preparation phase took 15–20 min, including the task instructions. The two tasks were applied in a fixed order (MANOMETER task, MATRICES-task). To maximize the loading effect the MANOMETER-task was always presented first, because this task was found to be more challenging in earlier research (Johannes et al., 1994) focusing on task types and task intensities as recommended by Allen et al. (1991) or Steptoe and Vögele (1991). Several researchers have recommended an "active" rest (Piferi, Kline, Younger, & Lawler, 2000). Therefore after each task a 3-minute video-clip (with accompanying tranquil music) was presented to induce relaxation. Each test phase lasted 5–6 min, depending on the subject's working speed.

The mental load was manipulated differently in the two tasks. In the MANOMETER-task time pressure was enhanced by increasing the number of gauges to be pursued. All pointers had to show in one half of the screen direction (right, left, upper, lower half) as given in the upper part of the display. In this case subjects had to check if the system is "Okay!". If at least one of the pointers differed more than 90 degrees from the given direction subjects had to state "Error!". The pace of the presentation varied in such a way that the error rate remained on the same level (between 20 and 25%), the number of gauges increased from five to nine.

The MATRICES-task consisted of cognitive solving problems similar to those of the Raven test (Raven, 1971a, 1971b). The series started with easy tasks. Ten cognitive problems had to be solved by the subjects. An adaptive testing procedure was used: if the correct solution was found, the next task had the next higher level of difficulty. If a task was not solved correctly, the task was on the same level. If the subject failed again to find the solution of this task, one task of the next lower level of difficulty was given.

2.2.2. Flight Simulator Test (FST)

The FST took place in an air-conditioned room. Two subjects were tested simultaneously by two instructors. The test consisted of three training tasks, followed by three test tasks. During the training tasks, the instructor answered all questions and provided information and help as comprehensively as possible. The FST comprised challenging flight exercises under instrument flight rules (IFR) and was described in detail in Johannes et al. (2008).

2.3. Variables

2.3.1. Psychological variables

In a first phase of the pilot selection procedure several biographic and psychological data were obtained. Among them, the Temperament Structure Scales (TSS, Hoermann & Maschke, 1996; Maschke, 1987) was applied for personality assessment. After the FST was completed, subjective statements from the participants were recorded on paper protocols. In the cohort 2 the subjects answered additionally the NASA Task Load questionnaire (TLX, Hart & Staveland, 1988) *and the instructors evaluated the perceived excitation of the subjects by means of a nine-step Likert scale. The task performance during the FST was evaluated by visually analyzing a chart plot of the track, the altitude profile and the speed profile. Using standardized criteria the visually detected deviations were transformed into Stanine values for five dimensions and combined into one integrated task result. A final overall score was given as an expert rating* (Sus, 1993). *The instructors evaluated the subjects for "resilience" using a nine-step Likert scale.*

2.3.2. Psychophysiological variables

Only the main points of the measurement system and the data-analysis are described here; see Johannes et al. (2008) for more details. A compact light weight version of the HealthLab system (Koralewski Industrie Elektronik oHG (KIE), Hambühren, Germany, www.koralewski.de) was used for the measurements.

The selection of the physiological measures was based on a series of previous studies (Johannes et al., 1994) in which several measures were examined on usability and validity, in particular for applications in the field. More systemic set of measurements were used in other application studies (e.g. Ledderhos et al., 2010) with enhanced laboratory possibilities for the baseline assessment. But herein blood pressure was successfully applicable only during the TTS. The variables of blood pressure proofed to be highly relevant for the pattern (ARP) differentiation. In particular, ARP 5 showed a hypertensive pattern, characterized by high blood pressure (and low PTT values). Due to technical and safety limitations impedance cardiography and blood pressure cuff (arm or finger) are not appropriate in field applications like flying a plane, docking a space craft, or the FST. Therefore, during the FST we used PTT which is assumed a reliable correlate of blood pressure (Obrist, Light, McCubbin, Hutcheson, & Hoffer, 1980; Payne, Symeonides, Webb, & Maxwell, 2006; Steptoe, Smulyan, & Gribbin, 1976; Weiss, Del Bo, Reichek, & Engelman, 1980).

During the TTS and the FST electrocardiogram (ECG), skin resistance, finger skin temperature (FT) and pulse wave were registered continuously. In addition, during the TTS oscillographic blood pressure (BP) was monitored and respiration registered by means of a resistance belt, fitted to the subject's chest. The pulse transit time (PTT) served as an indicator of blood pressure changes during the FST. The PTT was calculated as the interval between the R-peak of the ECG and the time point of the highest slope of the first front of the pulse wave. The tonic parameter skin conductance level (SCL) was calculated from the skin resistance between the finger sensor (dry Ag/AgCl electrode) and the ground electrode of the ECG. Finger temperature was registered by a thermo sensor (type FS-03/M) integrated together with the SCL electrode and the plethysmography sensor into a compact finger sensor. The oscillographic BP cuff (MobiloGraph) was fitted to the subject's right arm. The calculation of the physiological measures (means and standard deviations (SDs)) was performed by means of the NEURON-32 software package of the HealthLab system. *Artifacts were automated detected, counted and excluded by the firmware of the HealthLab system. The artifact recognition system was verified in former applications and of*

most applications factors having an eigenvector lower than one are omitted from further analyses, not yet herein. Therefore we will use the original term eigenvector.