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ESTIMATION OF OPERATORS' FATIGUE USING OPTICAL METHODS FOR DETERMINATION OF PUPIL ACTIVITY

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Abstract
Objectives: The purpose of this study was to develop and initially validate an objective, yet quick, method for assessment of human fatigue. This aim can be achieved by the use of an optical, non-contact method of analysis of pupil activity. The study involved 2 phenomena typical for the behavior of the human pupil: pupillary reflex and pupillary movements. The 1st phenomenon is related to the pupillary light reflex (PLR), which presents the results of physiological adaptation mechanisms of the human eye. The pupillary unrest index (PUI) is an additional parameter referring to the tendency for instability of the pupil. **Material and Methods:** Indicators of these 2 mechanisms were assessed under the same experimental laboratory conditions. Assessment was conducted on a group of volunteers (N = 10) during 4 controlled series of measurements performed at night. Pupillary reflex parameters associated with PLR and pupillary unrest index (PUI) were recorded using F^2D Fit-For-Duty, a commercially available system made by AMTech Pupilknowlogy GmbH. Baseline pupil diameter, oscillations, reflex latency, maximum reaction time, pupil constriction time, pupil dilation time, and constriction amplitude were recorded. **Results:** As a result of the study, we were able to demonstrate correlation and confirm the usefulness of PLR and PST methods in the assessment of sleep deprivation. Parameters of PLR that may indicate human fatigue were identified. The effect of light impulse sequences on the dynamics of pupillary reflex and the relationship between PUI (pupillary unrest index) measurement duration and sleepiness assessment validity, were assessed. **Conclusions:** The results of the pilot studies were sufficient to develop minimum requirements for a PLR sensor that would be capable of estimating the level of fatigue with accuracy of a PUI method, but at a 5 times faster rate.

Key words:
Fatigue, Activity of the pupil, Pupillography, Pupillary Light Reflex, Pupillary Unrest Index

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INTRODUCTION

The authors' experience in the design of microsensory measurement solutions and psychophysiological signals forms the basis of this research [1–6]. Their research focuses on the development of non-contact sensors allowing for a continuous analysis of fatigue under changing conditions (drivers, engine drivers, crane operators) or even extreme environment (typical of emergency rescue services, soldiers, commercial and military pilots).

Research work utilized a commercial measuring system with sensors that are an interesting combination of hardware and software solutions. This specific class of optical sensors, based on visual image analysis, is used in pupillometry and enables identification of eye movements, parameters associated with eye shadowing, and dynamics of the pupillary response. The evaluation of pupil motion provides functional information about the autonomous nervous system [7]. The pupillary light reflex (PLR) is a response of the iris to changes in the intensity of light falling on the retina. This reflex is modulated by the state of eye accommodation, as well as sensory and emotional factors. Iris constrictor and relaxant muscles are the effectors that maintain a constant level of illumination of the retina. Time characteristics of the pupillary reflex depend on the state of the autonomic nervous system (ANS), the sympathetic nervous system (SNS), and the parasympathetic nervous system (PNS) (Figure 1).

Circular and radial muscles control the size of the pupil. The former are innervated by parasympathetic fibers, and the latter by sympathetic fibers. Thus, radius of the pupil is controlled by the sympathetic and parasympathetic autonomic nervous systems, in response to environmental light – a mechanism called the pupil light reflex. Therefore, the pupillary radius response to an external light stimulus may provide an indirect means to assess the integrity of neuronal pathways controlling pupil size.

Sympathetic stimulation of α-1 adrenergic receptors causes contraction of the radial muscle and subsequent dilatation of the pupil (mydriasis). Conversely, parasympathetic stimulation causes contraction of the circular muscle and constriction of the pupil (miosis). The pupillary reflex is mediated by acetylcholine and noradrenaline, causing miosis and mydriasis, respectively. Thus, changes in the pupil size in response to a light stimulus are based on a functional equilibrium between sympathetic and parasympathetic activity.

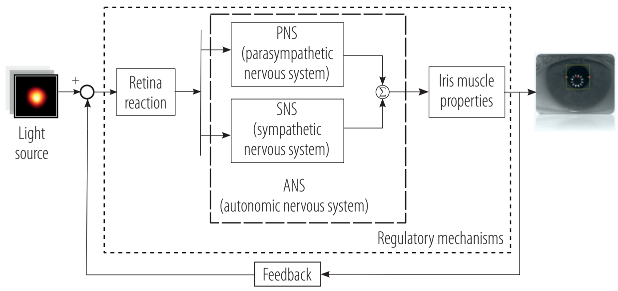


Fig. 1. Components of the mechanisms controlling pupil behavior

It is reasonable to expect that the overall condition of the autonomic nervous system will affect the pupillary response to a stimulus of light. Parasympathetic dysfunction may cause relative mydriasis of the pupil in light conditions and diminished constrictor reflexes with or without pupillotonia, which is thought to result from aberrant reinnervations. Sympathetic dysfunction may cause relative miosis of the pupil in the dark, increased re-dilatation lag and attenuation of the startle reflex [8].

Pupillometry was initially used in ophthalmology [9]. The size of the pupil is crucial for interpretation of perimetry of the visual field, electroretinography and the preoperative assessment for refractive surgery [10]. It is also utilized in neuro-ophthalmology for the assessment of lesions of the afferent or efferent nervous pathways [11]. The PLR has already been studied to detect a PNS defect in different conditions: alcoholism, diabetes, AIDS, depression, anxiety, drug addiction and schizophrenia. Pupillography is also being utilized in research on the Alzheimer's and Parkinson's diseases [12]. Since pupillary dilation is regulated autonomically, an effort was made to use this method as a valid measure of pain [13]. Research using pupillometry is being carried out to assess alertness in hypersomnolent patients. Observation of pupil behavior is also used in clinically sleepy patients [14], as well as in the assessment of cardiac autonomic function in athletes [15].

As shown, this method has a variety of clinical applications. Furthermore, the identification of pupil dynamics is also the subject of research concerning monitoring of various areas of human behavior [16–18]. This is mainly due to the possibility of assessment of the human psychophysiological status influenced by the level of sleepiness or alertness through the so-called fatigue wave, which is the basis of pupillographic sleepiness test (PST) [19]. The size of the pupil is predominantly controlled by sympathetic inhibition of the parasympathetic Edinger-Westphal nuclei. Spontaneous changes in pupil size are mainly the effect of reduced central sympathetic activity. Fatigue waves are slow rhythmic oscillations of the pupil size observed in the darkness in a state of reduced alertness. The PST test should be conducted in complete darkness (infrared goggles) and silence for 11 min. During the test, the patient should be placed in a comfortable sitting position. The result of the frequency analysis by Fast Fourier Transformation is given in a power value for the frequency range of < 0.8 Hz as a mean of the entire measurement.

In their study, the authors made use of another parameter referring to the tendency of the pupil for instability, i.e., the pupillary unrest index (PUI) (rPUI® is determined by AmTech, it will be used interchangeably with PUI for the remainder of this article). It is defined by cumulative changes in the pupil size based on the mean values of consecutive data sequences [20,21].

In summary, the increasing oscillations of pupillary movement are a result of reduced activity of the sympathetic nervous system. Decreasing SNS activity leads to changes in the dynamics of PLR parameters, such as prolonged pupil dilation, increased amplitude of contraction and prolonged overall duration of the reflex.

Current literature lacks publications comparing the parameters of PST, such as PUI, with pupillary reflex parameters or the interpretation of these ratios with respect to sensory or mental fatigue. There are several predefined parameters describing the PLR. Parameters that were used in this analysis are those provided by F^2D Fit-For-Duty device by AMTech, which was used in this research. These parameters are presented in Figure 2. Latency (L) describes the delay between the light impulse and pupil reaction, duration of reaction (DR) is the time to reach the minimum diameter, time of minimum diameter (TMD) refers to the length of time during which the diameter is less than 50% of the initial value, 2/3 contraction interval (2/3 CI) refers to the time at which the amplitude reaches 1/3 of the value in the contraction phase, 1/3 redilatation interval (1/3 RI) represents the time at which the amplitude reaches 1/3 of the value in the redilatation phase, and amplitude (A) defines the difference between the maximum and the minimum value of the diameter [22,23].

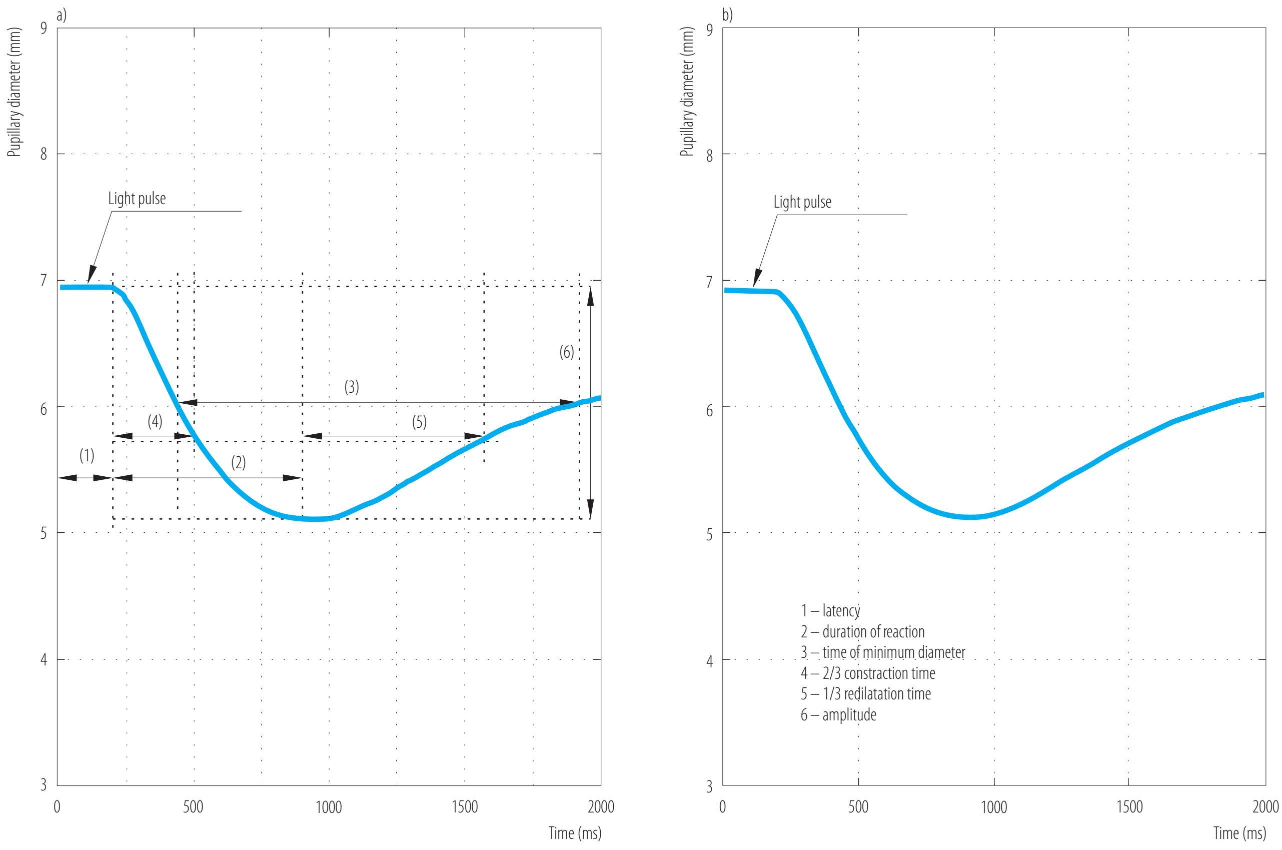
The authors conducted a study analyzing parameters defined in Figure 2 in an attempt to assess the strength of the relationship between PLR and PST parameters.

MATERIAL AND METHODS

Experimental design

The object of the study was to identify and verify changing PLR behavior in relation to the PUI factor (calculated on the basis of the PST test) described in the literature. The 1st phase of the study was preceded by a series of experiments using the commercially available F^2D Fit-For-Duty device by AMTech.

The F^2D recording of spontaneous and involuntary pupil movements in the darkness is the simplest method to objectively measure and evaluate the level of sleepiness. The system includes infrared goggles, which are



PLR – the pupillary light reflex.

Fig. 2. Changes in pupil diameter in response to a light pulse with the description of selected parameters to characterize these changes – average of all PLR measurements: a) left eye, b) right eye

used to conduct PUI measurements. Sampling frequency equals 25 Hz, with spatial resolution of 0.05 mm.

The experimental model assumed verification of PLR parameter usability in correlation with the results of pupillography sleepiness test. For each subject, the tests were conducted 4 times during the night hours at 2.5-h intervals. Experiments were conducted using truck simulator SYMSAM-2. The simulator made by ETC-PZL Aerospace Industries is a fully functional driving simulator that includes: driver's panel, virtual environment module, instructor/system operator panel and simulation software. It contains all the steering features, dashboard and a rear-view mirror simulation system. It is equipped with a 3D image-generating computer system and a color virtual reality environment seen by the driver. Images are projected onto a flat 3-panel screen located 250 cm from the driver's seat back panel.

Additionally, FlexComp Infinity monitoring system was used. It offers 10 high-speed channels (2048 samples/s) and communicates with Thought Technology sensors. During the experiment sensors that specialize for: electrocardiography (EKG), skin conductance, skin temperature, respiration waveform, and blood volume pulse waveform were connected.

The sensors pass signals to the host computer via the microprocessor-controlled FlexComp Infiniti encoder unit. The encoder samples the incoming signals, digitizes, encodes and transmits the sampled data to the TT-USB interface unit. A fiber optic cable is used for transmission, providing maximum freedom of movement, signal fidelity, and electrical isolation. Due to the ability to view data in online mode, the subjects were monitored for their ability to participate in the subsequent phases of the experiment. Their psychophysical ability was verified using Piórkowski and cross devices (APK apparatus – visual-motor coordination test device).

Data obtained from the simulator were not directly used in the analysis. The simulator was used to standardize the behavior during the 4 monitored tasks. The observation test recorded events such as spotted pedestrians, trucks and cars, and traffic light changes at an intersection where the car simulator was placed. The study subjects were not aware of the fact that the obtained results were not the main object of the study.

Study subjects

Research was performed at night on a group of 10 volunteers in a laboratory environment. Their mean age was 27±0.4 years. Each study participant was informed about the study design and provided an informed consent [24]. On the day of the experiment, the participants abstained from caffeine intake of any form for at least 4 h before the test and for the entire duration of the test. Additionally, in accordance with methodology requirements, each participant spent 7–8 h resting the night before the study. Each participant performed the test 4 times (Task 0, Task 1, Task 2, Task 3) between 11:00 p.m. and 6:30 a.m.

Experimental procedure

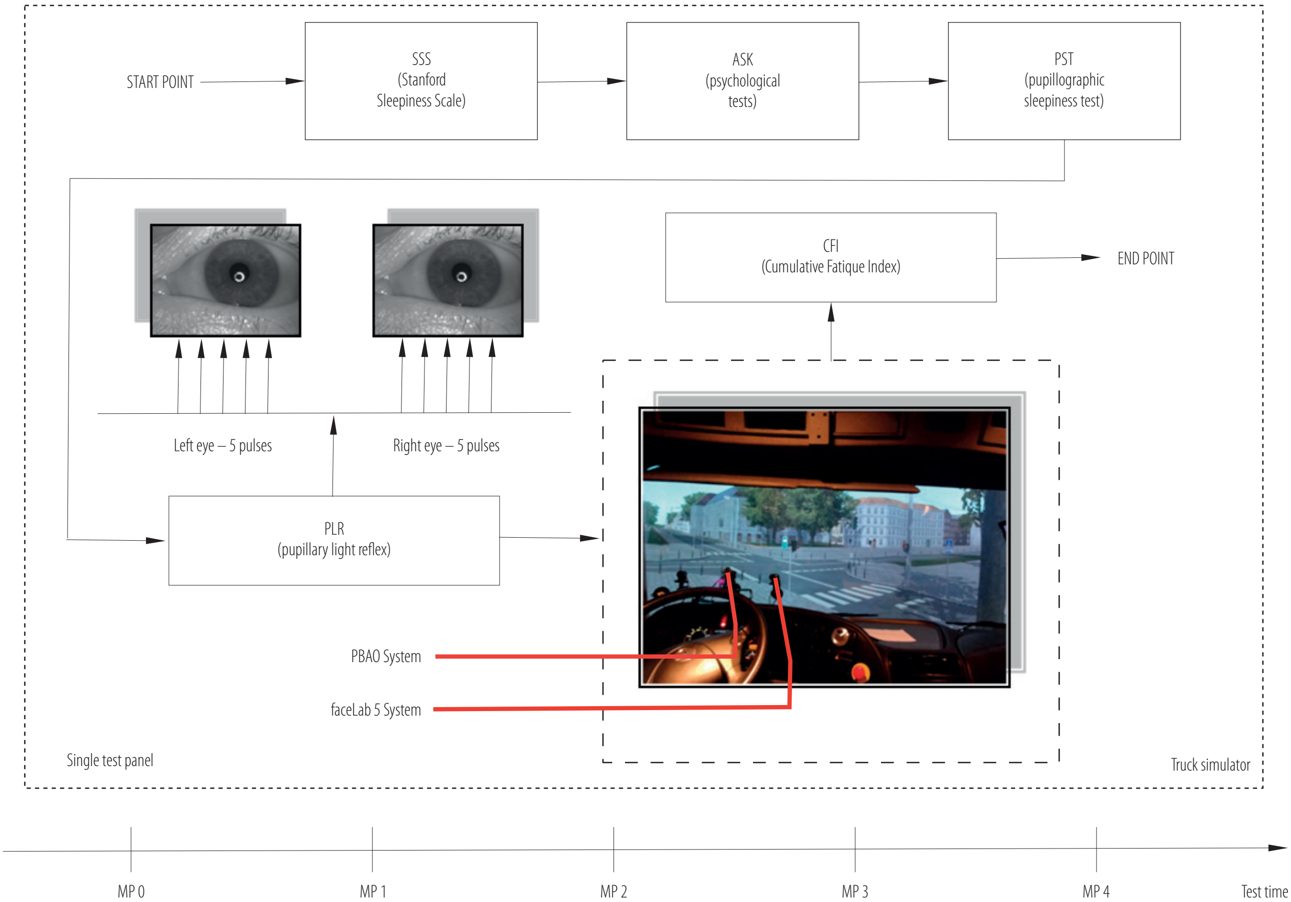
Measurement of the participants' PLR and PST was one of the elements of the experiment. It also included assessment of the subjective level of fatigue using Japanese Questionnaire and the level of alertness measured by SSS (Stanford Sleepiness Scale), which is a quick and easy way to assess a person's level of alertness. The test using the APK apparatus was also performed. The device is intended for psychological tests for e.g., drivers and heavy-machinery operators in terms of the speed of psychomotor reaction at an imposed or random rate, eye-hand coordination skills, perception of speed and accuracy, time-limited decision-making and resistance to fatigue. Simple psychological tests were designed only to control psychomotor ability throughout the study. They did not have an impact on the main objective of the experiment.

Measurements utilizing the goggles began with a PST test lasting 11 min as required by the procedure. Next, after a 2-min interval, PLR test commenced.

The pupillary light reflex measurement was performed on both eyes, which were subjected to a series of 5 flashes at 30-s intervals. A block diagram of the experimental model is presented in Figure 3. Repeated eyeball stimulation with a source of light is the result of work performed by researchers on the measurement of physiological parameters [25]. The right eye was subjected to light stimuli first. The duration of pupillary reflex measurement was 150 s. Then, over a period of 60 s, the system switched to the left eye, which similarly to the right eye, was subjected to a series of 5 impulses of light over a period of 150 s. The entire process was carried out with the subjects wearing goggles to ensure the same measurement conditions, mainly in terms of accommodation.

Each measurement ended with a short 5-minute session in the truck simulator, during which the subjects had to observe the intersection and memorize the number of traffic light changes, the number of pedestrians passing through the intersection, the number of passing motorcyclists, cars and trucks. The vehicle was immobilized, with active control systems, visualization and sound.

Due to the fact that the PST is a well-established method utilized in sleep research/medicine and consists of an 11-min recording of pupil diameter by infrared video pupillography, the PUI factor was used as a reference for verification of the analyzed pupillary reflex parameters



MP 0 – measuring point 0: daily; MP 1 – measuring point 1: ~ 11:00 p.m.; MP 2 – measuring point 2: ~ 1:30 a.m.; MP 3 – measuring point 3: ~ 4:00 a.m.; MP 4 – measuring point 4: ~ 6:30 a.m.
PBAO – oculomotor activity examination subsystem.

Fig. 3. Block diagram of the experimental model – the pilot study phase

in the assessment of the level of sleepiness and reduced concentration.

STATISTICS

The fundamental purpose of the statistical analysis was to estimate the change in the values obtained using the PLR and the PST in subsequent measurements (4 sets of measurements over the duration of the experiment – Task variable). A number of fundamental (Tables 1–3) and supporting (Tables 4 and 5) analyses was performed, along with a presentation of the behavior of the analyzed variables (Figures 4–7, 8a, 9 and 10).

Statistical analysis was performed using classic statistical methods based on the variance analysis. A single-index multivariate testing in the initial analysis of a given PLR data was performed. Based on these results, the variables that changed significantly in subsequent observations were identified. A single-index univariate analysis was performed for this subgroup of variables. A *post hoc* analysis (test: least significant differences – LSD, Scheffe, Tukey HSD and Bonferroni) was performed to collect detailed information about the nature of changes in the individual variables analyzed. The factors used in the analysis were those defined by the variables Task, Eye, Profile

Table 1. Relative amplitude of pupillary contraction at subsequent measurement points (Task 0–3)

Task	PLR measurements (n)	Relative amplitude	
		M	SD
0	100	24.21	5.11
1	100	25.53	5.28
2	100	26.22	5.36
3	100	27.28	5.47

PLR – pupillary light reflex; M – mean; SD – standard deviation.

Table 2. Contraction velocity at subsequent measurement points (Task 0–3)

Task	PLR measurements (n)	Contraction velocity	
		M	SD
0	100	3.98	0.82
1	100	4.21	0.89
2	100	4.29	0.83
3	100	4.49	0.87

Abbreviations as in Table 1.

Table 3. Results of the *post hoc* analysis (least significant differences test – LSD test) for rPUI_relative

Task	LSD test – rPUI_relative			
	0	1	2	3
0	–	0	0	0
1	0	–	0	0
2	0	0	–	0.002
3	0	0	0.002	–

rPUI – pupillary unrest index.

(sequence of light excitation). Table 3 shows the LSD test results for the Task factor.

An identical scheme was adopted for the analysis of PUI data. The only difference was that the tests were performed for the variables Task and Window. Anova analysis was performed using data obtained from the SSS and the psychological tests (for the Number variable). Manova analysis utilized the results of the psychological tests (for the Reaction Time variable). Throughout the analysis, the Task variable was the most important factor analyzed. Variance analysis assumed that the dependent variables were expressed in at least the interval scale. Additionally, the dependent variables should follow normal distribution within the groups. The 2nd objective was verification of homogeneity (equality) of variance. Error variance (sum of squares – SS error) was calculated by adding the sum of the squares within the groups. If the variance of the 2 groups was different, it was not appropriate to add them together and the variance within the group

Table 4. Changes in statistically significant relative amplitude (RA) and contraction velocity (CV) parameters in response to the number of light pulses, in terms of the task variable

RA		CV	
light pulses (n)	p_{RA}	light pulses (n)	p_{CV}
1	0.591	1	0.188
2	0.093	2	0.077
3	0.013	3	0.027
4	0.003	4	0.003
5	0.001	5	0.001

p_{RA} – relative amplitude p value; p_{CV} – contraction velocity p value.

Table 5. Pupillary unrest index (rPUI®) estimation error (Err_{rPUI}) with time-limited measurement

Window	Err_{rPUI} (%)				
	total	Task 0	Task 1	Task 2	Task 3
1	100.00	100.00	100.00	100.00	100.00
2	75.68	81.75	81.50	78.50	67.02
3	57.46	55.21	64.81	48.29	63.11
4	43.59	32.63	51.98	36.28	51.28
5	27.47	23.01	39.96	19.26	30.61
6	18.19	16.24	31.93	12.70	16.94
7	5.81	7.29	14.45	3.29	2.85
8	0	0	0	0	0

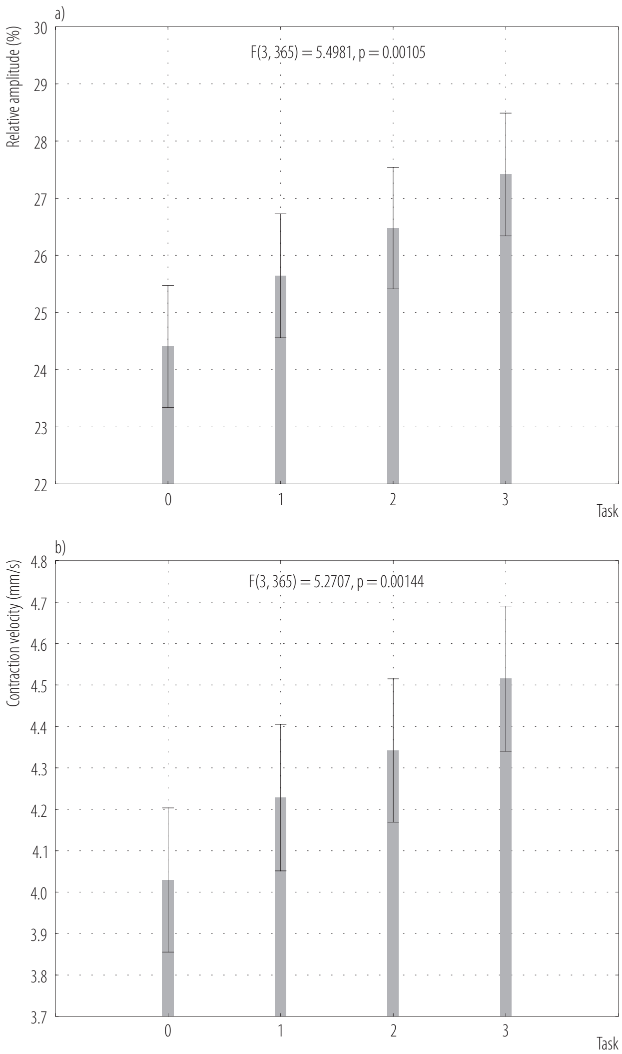


Fig. 4. Graph changes: a) amplitude of contraction, b) rate of pupillary constriction in subsequent stages of measurement

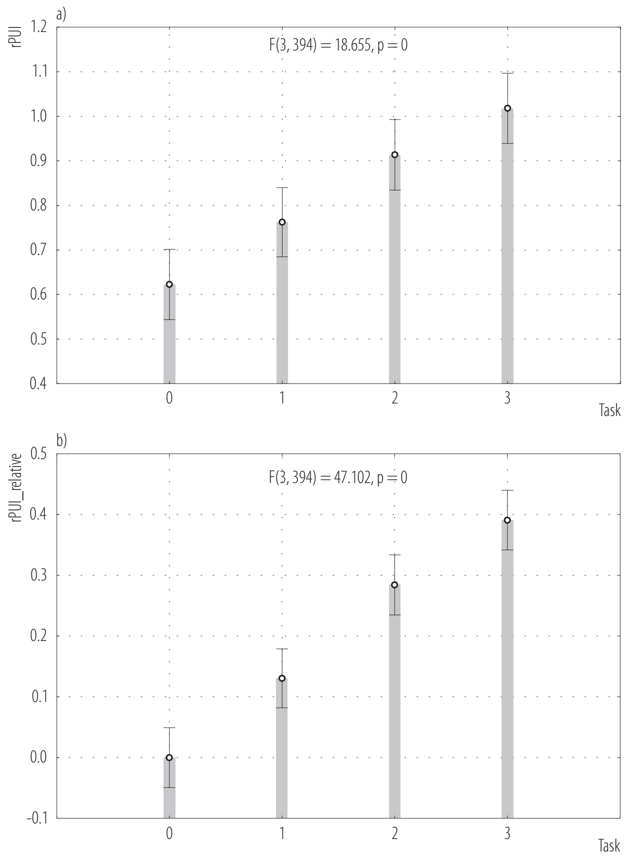


Fig. 5. a) Pupillary Unrest Index (rPUI®) value, b) relative change of rPUI®, at subsequent measurement points

could not be estimated (because there was no common variance).

The study tested the assumptions of Anova/Manova analysis, i.e., deviation from normal distribution of the individual dependent variables within the groups (defined as Task, Profile, Window, Eye variables) by means of the Kolmogorov-Smirnov and Shapiro-Wilk test. Levene's test was used to assess homogeneity of variance. The analysis of variables from PLR, SSS and psychological tests presented in this work indicates that the values of these statistical tests did not produce statistically significant results that would allow for the rejection of the hypothesis of normal distribution and homogeneity of variance. Skewness values for the individual variables were in the range of –0.430–0.011. A slight deviation from the norm was observed in the rPUI® variable, for which the maximum value of skewness was 0.741. All the analyses were performed using Statistica 10 PL software.

Figures below show PLR source signals (Figure 11) with labeled vector changes and PUI for measurement sequences (Figure 12). Individual pupil behavior is shown, including significantly different baseline pupil diameter. This formed the basis for the analysis, the results of which are discussed later in this article.

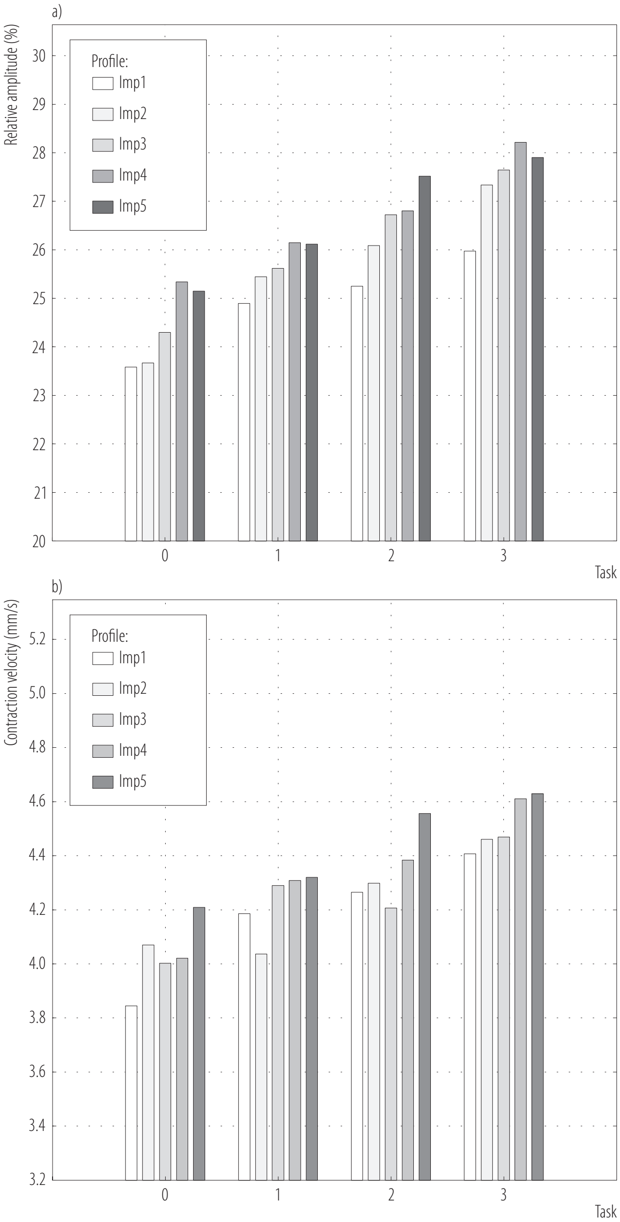


Fig. 6. Parameters: a) relative amplitude and b) contraction velocity generated for 5 subsequent pupillary light reflex (PLR) impulses (Imp)

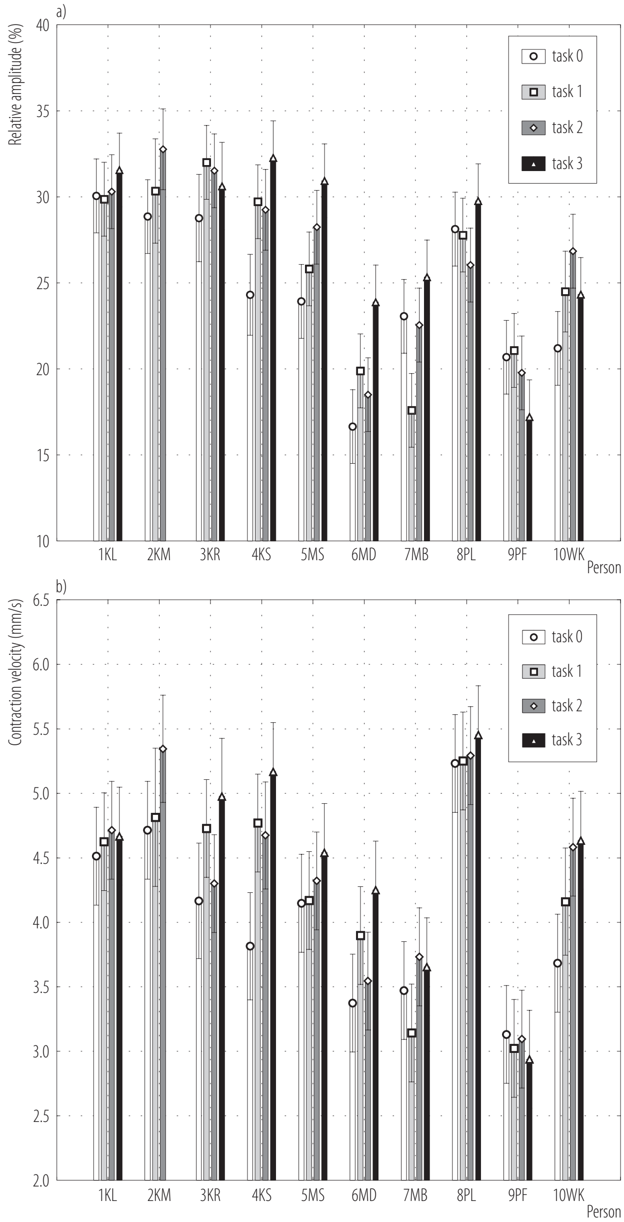


Fig. 7. Relative change: a) pupillary contraction amplitude, b) rate of pupillary constriction, for a single participant in subsequent stages of measurement

RESULTS

The results of the pupillary reflex analysis are located at the beginning, because they constitute the most important element of the analyses. Statistical analysis of a series of detected pupillary reflex parameters was performed. These parameters are presented in Table 6.

A univariate, multi-dimensional analysis of variance was performed. The purpose of the analysis was to demonstrate changes associated with the subject's fatigue by using the PLR method during the experiment.

Figure 4 presents the results for 2 parameters relative amplitude (RA) and contraction velocity (CV), which

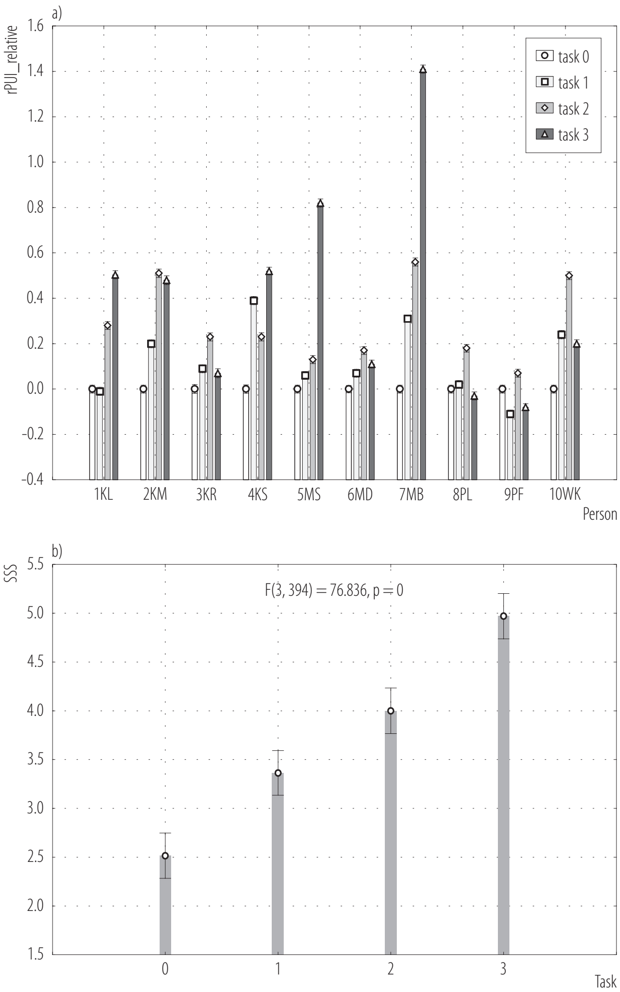


Fig. 8. a) Relative value of Pupillary Unrest Index (rPUI®) parameter for a single person at subsequent measurement points, b) declared Stanford Sleepiness Scale (SSS) values at subsequent measurement points

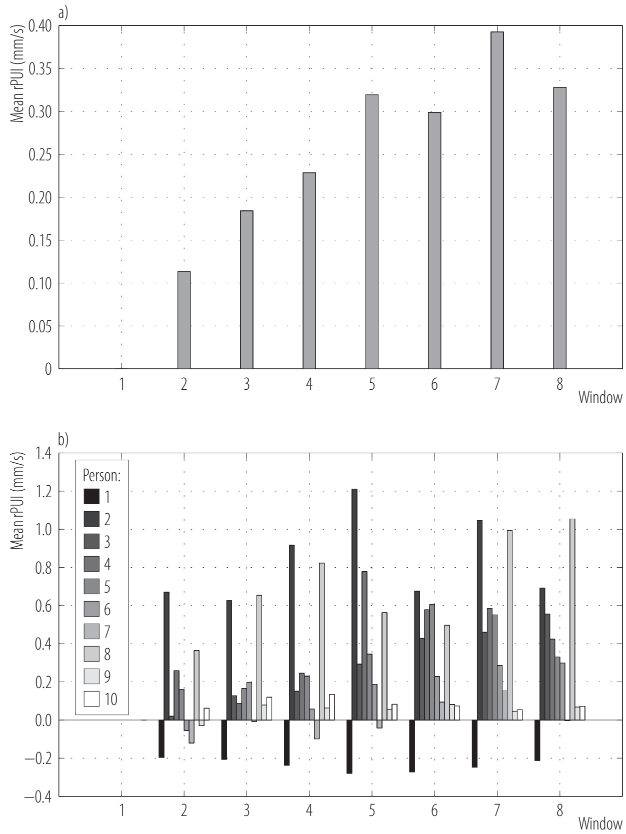


Fig. 9. Pupillary Unrest Index (rPUI®) value: a) for the entire group (total), and b) individually for all persons studied, shown according to subsequent measurement windows

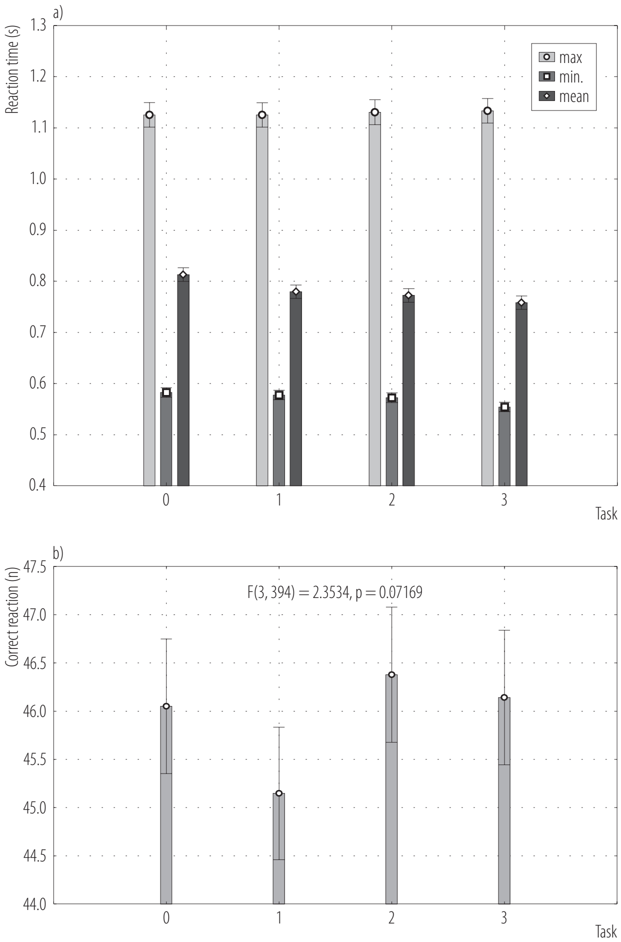
were proven to be significantly statistically different ($p < 0.05$).

The test probability is shown in each figure (Figure 4). The differences in other parameters as determined by the 4 sets of PLR measurements (Table 6) were not statistically significant.

Figure 4 shows a change in the average values for the RA and the CV parameters for both eyes and 5 light stimuli. Statistically significant difference of $p = 0.00105$ for RA and $p = 0.00144$ for CV, is evident.

Table 6. Statistically analyzed pupillary light reflex (PLR) parameters

Parameter	Unit
Latency	s
Duration of reaction	s
Amplitude	mm
Relative amplitude	%
Contraction velocity	mm/s
Dilatation velocity	mm/s
2/3-constriction interval	mm
2/3-constriction time	s
1/3-redilation interval	mm
1/3-redilation time	s
Time of minimum diameter	s



max – maximal value; min. – minimal value.
APK apparatus – Piórkowski and cross devices (visual-motor coordination test device).

Fig. 10. a) Response times measured with the APK apparatus, b) number of correct answers at subsequent measurement points

Tables 1 and 2 show the average values of RA and CV along with the standard deviation recorded at subsequent periods of measurement.

As regards the RA and the CV parameter, *post hoc* analyses were performed, the results of which are presented in Tables 7 and 8.

The tests clearly show that it is possible to identify changes in the pupillary reflex on the basis of RA and CV in the 3rd and 4th measurement. The statistically significant results are also present between the 2nd and the 4th measurement.

Table 7. Results of the *post hoc* analysis (LSD test) for relative amplitude (RA)

Task	LSD test (RA)			
	0	1	2	3
0	–	0.161	0.009	0
1	0.161	–	0.235	0.028
2	0.009	0.235	–	0.310
3	0	0.028	0.310	–

LSD – as in Table 3.

Table 8. Results of the *post hoc* analysis (LSD test) for contraction velocity (CV)

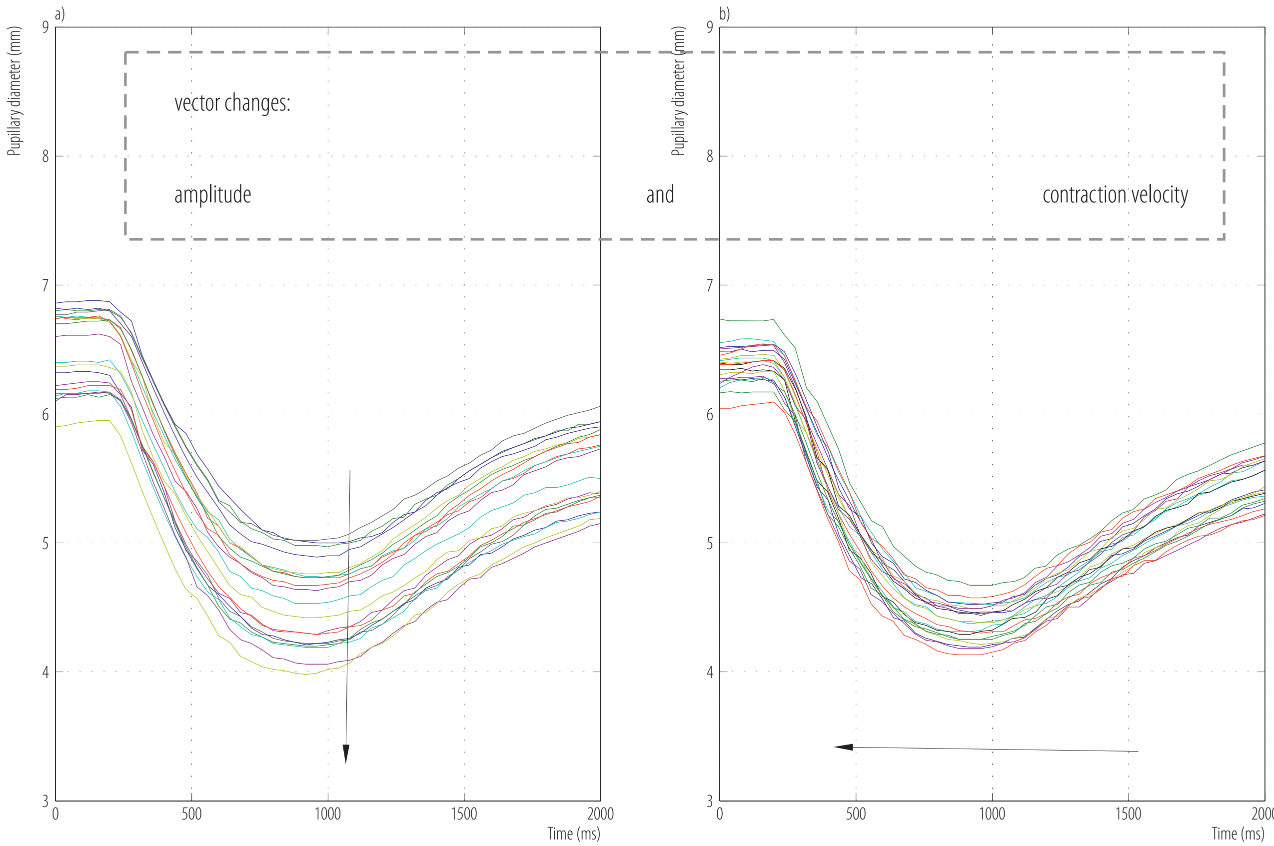
Task	LSD test (CV)			
	0	1	2	3
0	–	0.156	0.004	0
1	0.156	–	0.140	0.017
2	0.004	0.140	–	0.362
3	0	0.017	0.362	–

LSD – as in Table 3.

The PLR results were referred to the results of PST (PUI), as a widely-adopted and recognized method for the assessment of fatigue. A 1-dimensional, 1-way analysis of variance was used in the case of the PLR. The analysis took into account only one rPUI® parameter and the Task factor. In this case, the purpose of the analysis was to show the changes associated with fatigue as measured by the PUI over duration of the experiment.

The results are in line with expectations. Subsequent measurement periods show the growth of the rPUI_relative parameter. A proper trend of changes is preserved along with the differences in the average values of rPUI_relative, which are large enough to yield values of $p < 0.005$ in the subsequent measurements.

The rPUI_relative parameter was assigned for the analysis. It represents the relative change of rPUI® and eliminates the individual characteristics affecting the rPUI® value, which is different in each individual.



PLR: pulse = 250 ms, λ = 660 nm.

Fig. 11. Source data recorded in the pupillary light reflex (PLR) study – person no. 3, 4 tasks, 5 pulses each: a) left eye, b) right eye

Mean rPUI® values were calculated from the obtained measurement data and a relative growth of this indicator was independently analyzed for each person. It was observed that the rPUI® parameter is highly personalized. For this reason, rPUI_relative parameter was set up to estimate the relative change in the amplitude of involuntary, oscillating movements of the pupil relative to the 1st measurement (Task 0). Changes in behavior are similar, regardless of absolute rPUI® value or relative individual value being analyzed.

Comparison of the results presented in Figures 4 and 5 shows an agreement between the parameters obtained by the PLR and the PST methods.

Tables 9 and 10 show the average values of the rPUI® and the rPUI_relative parameters at subsequent measurements.

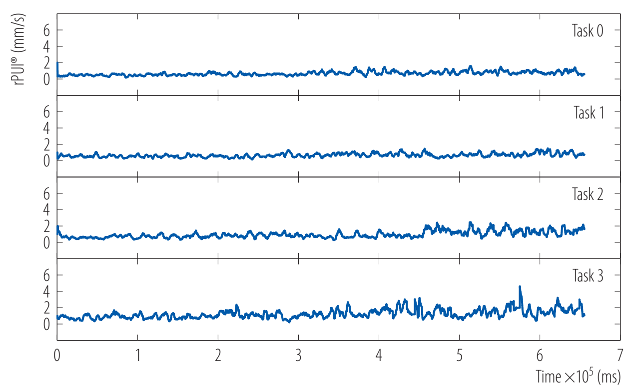


Fig. 12. Source data for Pupillary Unrest Index (rPUI®) – sequence of 4 measurements (tasks), person no. 3

As in the case of parameters obtained in the PLR test, the *post hoc* analysis was also performed for the rPUI_relative parameter. The obtained results show that changes in

Table 9. Pupillary unrest index (rPUI®) results at subsequent measurement points (Task 0–3)

Task	PUI measurements (n)	rPUI®		
		M	min.	max
Total	40	0.83	0.23	2.28
0	10	0.62	0.23	1.13
1	10	0.76	0,29	1.37
2	10	0.91	0.36	1.63
3	10	1.02	0.38	2.28

rPUI® – the pupillary unrest index (PUI) determined by AmTech, used interchangeably with PUI for the remainder of this article.
Other abbreviations as in Table 1 and Figure 10.

Table 10. Relative results rPUI® at subsequent measurement points (Task 0–3)

Task	PUI measurements (n)	rPUI_relative		
		M	min.	max
Total	40	0.28	–0.08	1.41
0	10	0	0	0
1	10	0.13	0.01	0.39
2	10	0.28	0.07	0.56
3	10	0.39	–0.08	1.41

Abbreviations as in Table 1 and 9 and Figure 10.

this parameter are so substantial in subsequent measurements that their differences are statistically significant in any combination of measurements (Table 3).

As a result of a strong similarity in the behavior of parameters obtained by the PLR and the PST, the authors were able to perform an analysis to try to determine the optimal method of measurement using the PLR only. In the experiment, the PLR was measured through a series of 5 light pulses. Thus, the authors wanted to find out what effects the number of light pulses had on the values of RA and CV, and whether there was any association with the level of fatigue (measuring period). Due to the size of the population tested, Figure 6 shows the average values of RA and CV taking into consideration the number of stimulations applied (Profile 1–5), without providing the results of statistical tests. It can be concluded that in both parameters – RA and CV, the 5th stimulation produced larger and more visible changes as compared to the 1st stimulation.

Since the authors had the results of 5 light stimulations, an independent analysis of variance for the Profile factor (light pulse number) was conducted. It took into account the individual light pulses independently and observed their variation at subsequent periods of measurement.

Analysis of data presented in Table 4 indicates that the method of pupil stimulation has significant influence on the values of RA and CV parameters. With only a single stimulation and p value of < 0.05, it would be impossible to distinguish between the different phases of the test.

In the univariate analysis of variance for the Task factor, both RA and CV showed relatively small inter-group variability in comparison to intra-group variability, with the following values: $p_{RA\_1} = 0.591$ and $p_{CV\_1} = 0.188$. Having only a single pupillary reflex measurement, it would be impossible to assess the level of increased sleepiness in subsequent measurement sessions likewise in the case of 2 and 3 light stimuli where the p values were higher than 0.05. Utilization of a series of 4 stimuli on a single eye provided a statistically significant difference between RA and CV values in subsequent sessions (Task), $p_{RA\_4} = 0.003$, $p_{CV\_4} = 0.003$. This difference increased when the results of the 5th stimulation were added to the analysis.

The answer as to why this was occurring was presented in Figure 5, which displays values for RA and CV parameters for the 5 consecutive pulses in a given measurement session. Each subsequent Task displayed a growing tendency for greater contraction in a shorter time.

This phenomenon was also reflected in Figure 13, which displays the differences in pupillary reflex for the right and left eye (the right eye was stimulated first).

The authors present a graphical representation of the key parameters obtained by the PLR (RA and CV) method

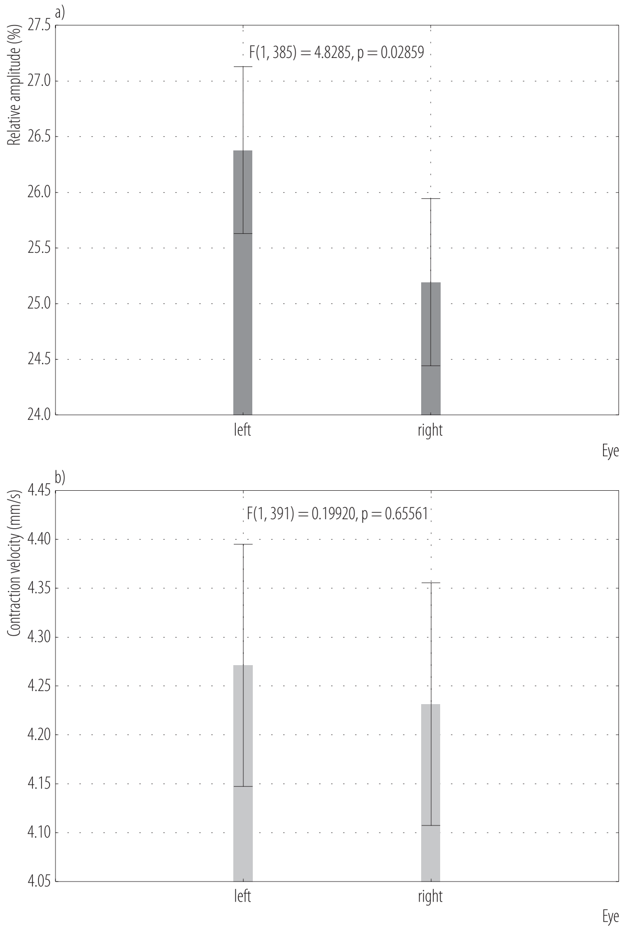


Fig. 13. Parameters a) relative amplitude and b) contraction velocity generated independently for the left and the right eye

(Figure 7) and the PST (rPUI®) method (Figure 8a) to demonstrate the individual behavior of these variables.

The results shown in Figure 10, i.e., the constant values of Reaction time and Number parameters, suggest sleep deprivation. The results of analysis of variance confirm the permanence of the average values of these variables in the subsequent points of measurement. In both cases, no statistical significance for the Task factor was observed.

A comparative analysis of Figure 4, 5, and 8b clearly shows a strong similarity in the behavior of the PLR, rPUI®, and SSS parameters.

The authors aimed at determination of the minimum requirements for a highly sensitive method of assessment of fatigue, faster than the PST, which takes 11 min to complete. Nonetheless, the authors are convinced that future studies performed on a larger group of subjects will demonstrate a stronger correlation of these behaviors.

The entire experiment with the analysis was conducted in an attempt to find a quick method of assessment of fatigue using PST, and consequently the PLR. Since the system used in the study allowed for rPUI® calculation in 8 measurement windows for a total of an 11-min measurement period, analysis of its behavior during the experiment was performed. The parameter was calculated every 82.5 s. The results are shown in Figure 14.

Figure 9b shows individual differences between the parameter values. Relationship between rPUI® and the task number is preserved regardless of the test duration (Figure 14). Task 3 in Figure 14 was performed in a state of greatest fatigue, as manifested by the largest amplitude of change in pupil size, per unit of time.

$$\mathrm{Err}_{\mathrm{rPUI}_i} = 1 - \left| \left(\frac{\frac{1}{K}\sum_{j=1}^{K} \mathrm{rPUI}_j}{\frac{1}{N}\sum_{i=1}^{K} \mathrm{rPUI}_i} \right) \right| \times 100\% \quad (1)$$

where:

N – maximal number of windows (N = 8),

I – window number, for which error is calculated,

K – window number, at which hypothetical test conclusion occurs.

Analysis of estimation error $\mathrm{Err}_{\mathrm{rPUI}}$ in Figure 15, Table 5 indicates that amplitude variations of rapid, involuntary and oscillatory changes of pupil diameter displayed fairly linear characteristics. In the 5th window, at 412.5 s of the study, rPUI® reached value, which despite minor variations, was maintained for the remainder of the study. If we were to take values from individual measurement windows to estimate the resultant rPUI®, then one could say that we managed to shorten the measurement period by nearly 40%. However, rPUI® calculation method

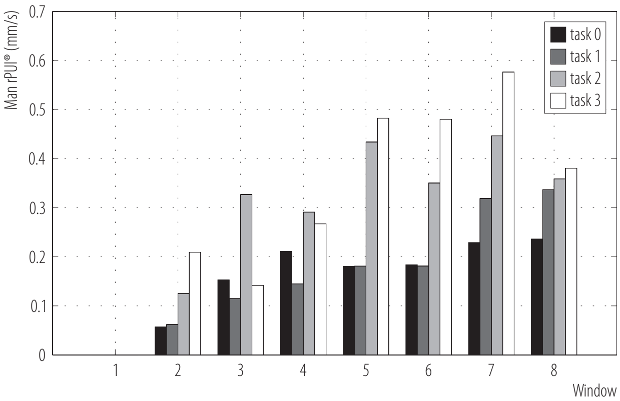


Fig. 14. Pupillary Unrest Index (rPUI®) value for all persons (N = 10) studied at consecutive measurement windows, separated into tasks

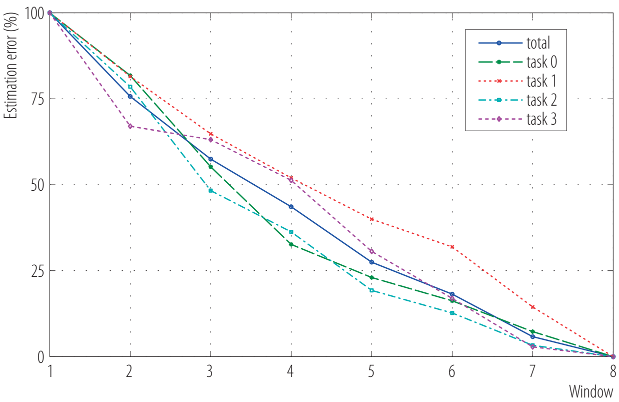


Fig. 15. Pupillary Unrest Index (rPUI®) estimation error in terms of the duration of study

implemented by the F²D Fit-For-Duty system uses the average value of all 8 measurement windows. Upon acceptance of measurement error $Err_{rPUI} < 10\%$, the resulting reduction in measurement time is only 12.5%.

DISCUSSION

An increase in the relative amplitude and contraction velocity parameters is due to reduced SNS activity and increased PNS activity. Comparison of the results with PUI measurements allows for an indirect assumption that PLR may be used to assess the level of sleepiness and alertness, given that an accurate measurement system is used.

When analyzing the results presented in Figure 5 and Figure 8b, it is evident that both: the objective fatigue expressed by the rPUI®, and the subjective fatigue (SSS test), increased with each subsequent measurement.

During the PLR experiment, the authors measured the RA and the CV parameters with stimulation of the left and right eye. Interesting results were observed. The obtained values should be identical regardless of the stimulated eye. The results in Figure 13 showed a variation. This observation is important in the context of the development of an optimal method of measurement. The difference in the obtained values is most likely due to accommodation time of the eye measured as the 2nd one, and the influence of stimulation of the opposite eye. The eye examined as the 2nd one (the left eye) was blacked out for 2.5 min longer than the right eye and was subjected to an extended stimulation with light, 5 passive flashes and 5 direct flashes.

A graphical representation of the key parameters obtained by the PLR method (Figure 7) and the PST method (Figure 8a) demonstrates the individual behavior of the variables. Although the average values for the entire population demonstrate an increase with consecutive periods of measurement (Task), this behavior was not uniformly observed. This finding raises 2 very interesting conclusions. Individual changes in parameters are strongly associated with the human circadian cycle. In most cases (6 persons), the critical time of functioning in the morning occurred at 4:00 a.m. In 4 individuals it shifted to 6:30 a.m. (the 4th period of measurement during the experiment). Two phases of fatigue arouse from the 4 periods of measurement. The 1st phase lasting until 2:30 a.m. consisted of the first 2 measurements and the 2nd phase consisted of the subsequent 2 measurements ending at 6:30 a.m. Figures 7 and 11a show that in the 2nd phase, 90% of the cases displayed an increase in the parameters obtained from the PLR and the PST. An exception is a test subject marked

Table 11. Reaction times (RT) measured with the APK apparatus at subsequent measurement points (Task 0–3)

Task	Correct reactions (n)	RT_{max}		$RT_{min.}$		RT_{mean}	
		M	SD	M	SD	M	SD
Total	398	1.129	0.122	0.572	0.049	0.781	0.070
0	99	1.126	0.081	0.582	0.051	0.813	0.081
1	102	1.125	0.085	0.578	0.058	0.780	0.063
2	98	1.131	0.044	0.572	0.044	0.772	0.050
3	99	1.133	0.210	0.554	0.034	0.758	0.070

Abbreviations as in Table 1 and Figure 10.

Table 12. Correct reactions measured with the APK apparatus at subsequent measurement points (Task 0–3)

Task	Correct reactions		
	n	M	SD
Total	398	45.9	3.5
0	99	46.1	3.6
1	102	45.1	3.8
2	98	46.4	2.9
3	99	46.1	3.8

Abbreviations as in Figures 1 and 10.

as Person 9PF. This finding may have been caused by a temporary stimulation of the subject, perhaps due to a change in the music that was played to all the test subjects. Although these sounds were of similar tone, they could have had an excitatory effect on the test subject. It also demonstrates the importance of the environment in which the research is conducted.

From the point of view of the authors, it is important that the changes occurring in the 2 phases of the experiment were consistent in most cases (PLR vs. PST). The differences that occurred were likely the result of a temporary stimulation that may occur during minor sleep deprivation. The PLR and the PST measurements were performed consecutively and lasted a minimum of 16 min. The PST measurement lasted 11 min, while the dual PLR measurement lasted 2.5 min for each eye. Activation of the SNS and the PNS may occur during this time. It indicates a very sensitive method of measurement capable of identifying states of ANS arousal during sleep deprivation lasting less than 48 h.

The experiment utilized equipment that recorded response times to light stimuli and the number of correct responses (Tables 11 and 12). As indicated, a proper experimental group was chosen – a group that was able to adapt to the study conditions and requirements, resulting in similar findings of a 7-h-long test performed at night time. It is not difficult to breakdown the compensation mechanism for physical, mental and sensory fatigue. However, it was the goal of the study to conduct the measurements at monotony of the night and with no sources of stimulation. Analysis of the ANS behavior as reflected in the PLR phenomenon could have been conducted only under the conditions of time passing, darkness and sight fixated on the moving objects. Changes were observed and correlated fully with the results of the SSS questionnaire and the changes in rPUI®.

The authors depended on the continued psychophysical ability of the test subjects, despite the observed sleep deprivation. This enabled them to monitor the level of fatigue and assess the likelihood of falling asleep during PST testing. Experiment setting, standards associated with research equipment, methods of measurement and disciplined implementation of methodology enabled the determination of key parameters that are critical in terms of the structure of an optical sensor.

CONCLUSIONS

The aim of the study was to find indicators for a quick and accurate method of assessment of fatigue manifested by somnolence among individuals performing tasks under dynamic or even extreme conditions. Analysis of pupil behavior was used for this purpose. Pupil behavior was analyzed during excitation by a pulse of light lasting 250 ms and a wavelength of 660 nm, also known as PLR, and involuntary, oscillating pupil movement recorded in complete darkness (PST). According to the standards, PST testing is performed for 11 min. This length of time is accepted in the laboratory environment and requires that scene images be obscured. This obviously makes performing the duties of an operator impossible as would be the case in monitoring drivers, crane operators, engine drivers, pilots, not to mention soldiers in combat.

The authors conducted a unique study attempting to compare 2 physiological phenomena associated with pupil behavior under various conditions. The pupillographic sleepiness test (PST) was regarded as a reference, described in the literature as an indicator of the level of sleepiness. The designed experiment, which identified the parameters of pupillary reflex reactions to stimulation with light, demonstrated a close relationship between the changes occurring in rPUI® and those taking place in relative amplitude and contraction velocity. The article presents only those parameters (see Table 6), which similarly to rPUI® were shown to be statistically different in subsequent measurements. This is an extremely important observation, which suggests that the selected PLR parameters may indeed indicate reduced concentration or sleepiness in humans.

These parameters reflect changes taking place in the autonomic nervous system caused by even minor sleep deprivation (< 48 h).

This data may be obtained over 4 times faster and without the need of obscuring the operator's field of vision. Shorter duration of the study may be accomplished by abandoning serial pupillary reflex measurements, as was the case in this experiment. This is of great significance in cases where the measurement is done with a mobile device and under dynamic conditions. It should be also noted that the sequence of applied stimuli affects the values of dynamic PLR parameters, especially RA and CV. These parameters are characterized by high inter-subject variability.

However, shortening the duration of PST examination provides little benefit, because in the case of a relatively large rPUI® estimation error, the amount of time saved will be small. The study results suggest that the duration of PST examination may be shortened by about 12% with maintained margin of error of 10%. This confirms the benefit of technology developed on the basis of PLR.

Sleep deprivation measurements were conducted 4 times and the time between them was controlled in terms of activities performed by the respondents. They participated in truck simulator sessions that did not require physical effort and were preceded by psychological control tests. The measured reaction times (RT – Figure 10a) and the number of correct responses (N – Figure 10b) before subsequent measurement phases (labeled on the graphs as: Task 0, Task 1, Task 2, Task 3) did not show any statistically significant differences.

The measured reaction times and N parameters reflect psychomotor ability at a constant level, while PLR/rPUI®/SSS indicators show significant changes associated with reduced alertness or increased sleepiness.

These results support the idea that PLR can be effective in the assessment of sleepiness. Subjective feeling of sleepiness was evident in the study subjects. Test consistent with the SSS clearly shows that a sense of fatigue in the study participants increased by 100% during the experiment. The authors were able to define the relationship between the PUI, PLR and SSS. The results of simple psychological tests focusing on temporary psychomotor ability, along with SSS results suggest that the PLR can be an effective and accurate indicator of fatigue used not only in a laboratory setting.

These observations contribute significantly to the development of a rapid, objective and accurate assessment of fatigue models in terms of reduced concentration and sleepiness. They may be implemented in precision optical sensors, which are part of real-time fatigue assessment systems.

However, a more precise description of the correlation between these 2 methods requires further studies on a larger group of subjects.

The authors are currently conducting research on objective methods for the verification of sensitivity and accuracy of optical fatigue sensors based on PLR, through the use of functional neuroimaging (fMRI) and multichannel mapping of bioelectric activity in the brain. Such combination of methods will allow for an objective, neurometric evaluation of the processes of fatigue, reduced concentration, sleepiness with a decreased response to external factors. The fMRI method enables imaging of blood flow changes in brain structures involved with the activities designed in the experiment. In the case of studies in which both specificity and sensitivity are recorded simultaneously, the reliability may reach values close to 100%.

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