Quantitative Analysis of Mental Effort Investment using Photoplethysmogram

Yongqiang Lyu[1,2], Tianshu Yang[1], Xiaomin Luo[3], Chun Yu[1], Lei Wang[3] and Yuanchun Shi[1]
[1]*RTsinghua National Laboratory for Information Science and Technology, Beijing, China*
[2]*Research Institute of Information Technology, Tsinghua University, Beijing, China*
[3]*BGI (Wuhan) Translational Research Center, Wuhan, china*

Keywords: Photoplethysmography, Mental Effort, Psychophysiology Approach, Sensors-based Applications.

Abstract: Recent studies have shown a close relationship between the mental effort and the photoplethysmograms (PPG), but lack an index which can analyze the invested mental effort quantitatively during the cognitive tasks, which is notable for evaluating user experience in ubiquitous scenarios. In this study, we propose the stress-induced vascular response index (sVRI) to quantify the mental effort invested in cognitive tasks, and verify it via the experiments on aritehmatic tasks with different difficulty levels. The results show an outstanding correlation between the sVRI and the task difficulties, which suggests a dose-response of the sVRI when users perform different cognitive tasks with different difficulties. This is useful for evaluating the user experience in performing cognitive tasks to guide the task or the interaction designs.

1 INTRODUCTION

Peripheral vasoconstriction has a methodological advantage over other general arousal measures: it reflects uniquely the activity of the sympathetic nervous system (Iani et al., 2004). Changes in pulse amplitude reflect predominantly sympathetic influences: a decrease in pulse amplitude is caused almost exclusively by the activation of this system (Iani et al., 2004; Harris, 2001; Collins et al., 2005).

It has also been accepted that sympathetic tone is the dominant influence of systolic amplitude. The waveform amplitude of Photoplethysmography (PPG) signals changes in association with sympathetic tone (Award, 2001) (Shelley and Shelley, 2001). However, the absolute amplitude of the PPG signal is not comparable because there are no calibrating procedures currently available to standardize the PPG amplitudes for comparing the waveform of one subject to another. The main difficulty to realize that lies in the uncertainty due to the hardware and subject factors; even the variations in sensor placement may also influence the analysis much (Nilsson et al., 2010). The relative measure without a unit designation is necessary, particularly serving repeated measurements in ubiquitous scenarios.

Photoplethysmogram (PPG) is an optical measurement technique that can be used to detect blood volume changes in the microvascular bed of tissue (Allen, 2007; Alneab et al., 2007). The pulse wave analysis (PWA) of photoplethysmogram provides lots of circulatory information including but not limited to the pulse amplitude (Schmitz et al., 2006). Goor et al. (Goor et al., 2004) has demonstrated that the mental-stress induced peripheral arterial vasoconstriction predicts mental-stress-induced myocardial ischemia. Luo et al (Luo et al., 2011) also assessed the changes of photoplethysmogram appearance and investigated the morphological components of normalized PPG waveform associated with sympathetic activities in past years (Xiao et al., 2011; Luo et al., 2012).

In the quantitative studies of stress-related changes in pulse shape characteristics extracted from the PPG waveform reported previously, a modular system named Detecting Blood Flow Parameters Based on Pulse Wave Measurement and Analysis was employed in the post processing and data mining of PPG signals to search indices representatively fit the stress induced vascular responses (Xiao et al., 2011; Luo et al., 2012). However, it was proven in association with the magnitude of stress tested by the traidtional standard psychological materials, rather than cognitive tasks.

Lyu Y., Yang T., Luo X., Yu C., Wang L. and Shi Y..
Quantitative Analysis of Mental Effort Investment using Photoplethysmogram.
DOI: 10.5220/0004732001660171
In *Proceedings of the International Conference on Health Informatics* (HEALTHINF-2014), pages 166-171
ISBN: 978-989-758-010-9

This study proposes the stress-induced vascular response index (sVRI) with an online statistical noise-filting technique embeded in the PPG sensor. The index is also tested over the arithematic calculation based cognitive tasks to verifiy its dose-response between different difficulties of tasks. In the experimental design, we hypothesized that the association between photoplethysmogram appearance and mental effort investment could be quantitatively measured. We aim to explore the impact of increasing mental effort on its value and quantify its effects on trend of varying mental effort invested throughout experiment. As an extended study of stress-induced vascular response represented by PPG derived features, this study firstly proposes the index of it and verify its dose-response during cognitive tasks.

2 MATERIALS AND METHODS

2.1 Subjects

Twenty-three undergraduate students (12 females, 11 males) were paid to participate in this experiment. Two participants were excluded from the analysis because of failing to comply with the instructions, therefore, the final sample consisted of 21 participants (age range of 21–26 years; M=23.43, SD=2.56 years). All participants were healthy and did not use any medications. None of them was familiar with the experimental task.

2.2 Methods

2.2.1 Setting

The experiments were done in a quiet, temperature-controlled room at 24±2°C. Participants one by one sat in a comfortable chair throughout the experiment. All participants were asked to rest for no less than 20 minutes before each task performance.

2.2.2 The Tasks

The arithmetic calculation is a validated and widely used test able to induce a considerable degree of perceived stress (Dedovic et al., 2005; Rimmele et al., 2007). In the study, a 3-minute mental arithmetic task was performed continuously during which the participants were asked to calculate the arithmetic operations of two 2-digit numbers as quickly and accurately as possible. Their final scores were recorded and correlated to their pays. The tests with bad scores may be reevaluated to be withdrawn from the testing results to be analyzed. The *easy* level of the task difficulty is defined as that there are only additions and subtractions; while the *hard* level is defined as that there appears multiplications frequently. None of the operands were greater than 20. Answers spending more than 15 seconds were automatically judged wrong. Only a tablet PC is used in calculation and its position lies always in the horizontal plane throughout the experiment. Participants were all right-handed and asked to place the tips of their index finger and thumb of their right hand only on touch screen during performance of tasks, which we believed helpful to lower down some uncontrolled noise. The software interface as shown in the following Figure 1 was employed for the participants to complete the arithematic calculation tasks.

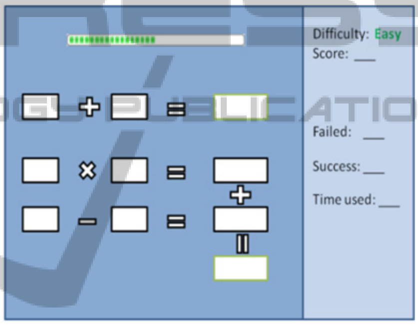
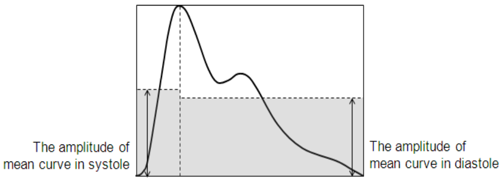


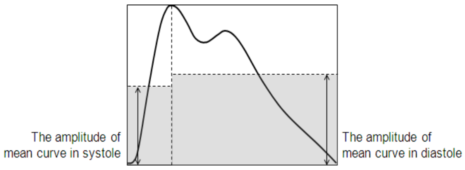
Figure 1: The arithmetic calculating software. There is a timing-count prompt as the progress bar, the calculation inputs and the results panels on the graphic user interface of the software.

2.2.3 Measuring sVRI, Blood Pressure and Heart Rate during the Taks

Blood pressure and heart rate were ever believed correlated to user experience in processing tasks in the acedemic field. So they were also measured together with the sVRI right before, during and after the tasks performed. The blood pressure and the heart rate were all measured with the digital sphygmomanometer, OMRON HEM-7112 (OMRON China Co., Ltd.). The sVRIs were recorded at one fingerflip of the left hand of the participant in sitting position with the left hand placed natually on the table surface. The sVRI was noninvasively measured by a prototype finger-clip sensor developed by us at a sampling rate of 500Hz. Figure 2 illustrates the differences in pulse pattern and quantitative features against different task difficulties.



(a) Pulse pattern associated with task of lower difficulty.



(b) Pulse pattern associated with task of higher difficulty.

Figure 2: The waveform morphology comparison.

This study proposes a time window-based evaluation algorithm to evaluate the sVRI based on the PPG patterns. For example, the time window from *t0* to *t1* in Figure 3, there may be couple of patterns found in the window, and each pattern can be quantified to a normalized number. However, some of the patterns are without sanity or subject to noise. So, a statistical data filtering is needed to normalize the index in order to resolve the effects of the noise and outlying data. As Figure 3 shows, the sVRI model in this study realizes the window based extraction and indexing together with the statistical filtering to give the stable and good-quality sVRI.

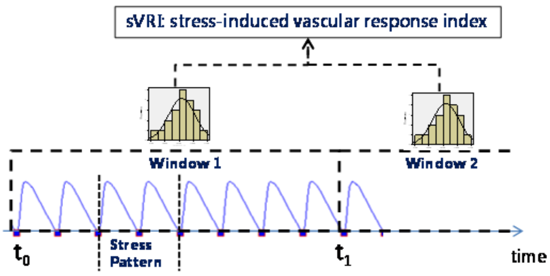


Figure 3: The sVRI calculation model: the original PPG waveforms are extracted as stress patterns, based on which a time window-based index evaluation algorithm is employed to give the sVRI in the target window.

In previous works, the stress-induced vascular response was evaluated from the normalized PPG signals and had been repeatedly proven to be stress-dependent (Luo et al., 2013; Luo et al., 2012). In this study, it is further studied with the statistical filtering technique that helps it become more stable. Furthermore, it becomes a quantitative index which is verfied to capture the dose-response of the user when performing cognitive tasks.

2.3 Experimental Design

In the experiment, all participants were asked to perform the arithmetic test of leveled difficulties to induce a perceived mental effort. Two difficulties were tested in different days with randomized sequence of the participants. The sVRI, blood pressure and heart rate were collected right before, during and after the tasks. At the same time, all participants were asked to finish a survey to verify the task difficulties literally in order to check the experiment design had guaranteed the consistency of the mental efforts and the task diffculties. The results of the sVRI, blood pressure and heart rate measurements of all the participants were analyzed against the task difficulties to examine the dose-response.

2.4 Statistical Analysis

The statistical analysis was performed with the SPSS 16.0. The measured values presented as mean ± standard deviation. The General Lineal Model Repeated Measures and the general paired-samples *t* tests were used to compare subjects' states before, during and after the tasks. The statistical significance was defined as $P<0.05$.

3 RESULTS

Table 1 lists all the testing results of the sVRI, blood pressure (systolic: SBP and diastolic: DBP) and heart rate (HR). The data were organized according to different task levels (the upper part is the *easy* and the lower part is the *hard*). The corresponding measured values were recorded as *mean* ± *standard deviation* in the testing periods of pre-task (before the task), in-task (in performing the task) and post-task (after the task) respectively. The DBP and SBP stand for the diastolic blood pressure and systolic blood pressure respectively.

The first analysis was to test the effect of the difficulty manipulation. According to our survey after the experiments, all subjects thought the *hard* tasks were really harder no matter which level of the task the subjects did first. This is also consistent with the fact that all the participants finished fewer calculations in the *hard* task than in the *easy* task.

The second analysis was to check the baselines of the signal levels of each vital sign (sVRI, SBP, DBP and HR) in order to guarantee there were no accidental outstanding noises introduced before and in the tasks. Table 2 listed the analysis results. The

Table 1: The values of stress-induced vascular response index (sVRI), heart rate (HR), blood pressure (BP) measured in the two levels of tasks.

Task Difficulty		Time Period		
		Pre-task	In-task	Post-task
Easy	sVRI	0.827±0.0551	0.906±0.0479	0.825±0.0539
	HR	79.5±10.8	81.3±8.87	
	DBP	64.3±8.33	63.9±7.84	
	SBP	109.2±15.6	109.5±16.7	
Hard	sVRI	0.832±0.0440	0.931±0.0528	0.844±0.0464
	HR	79.3±11.5	79.6±11.3	
	DBP	64.5±10.6	65.7±8.10	
	SBP	109.6±16.3	110.4±14.6	

Table 2: The paired-sample *t* tests on the vital signs in the same task stage with different difficulty levels.

	Easy	Hard	T	P
Pre-task				
sVRI	0.827±0.0551	0.832±0.0440	0.116	0.735
HR	79.5±10.8	79.3±11.5	0.002	0.967
DBP	64.3±8.33	64.5±10.6	0.007	0.936
SBP	109.2±15.6	109.6±16.3	0.006	0.939
In-task				
sVRI	0.906±0.0479	0.931±0.0528	**5.468**	**0.000**
HR	81.3±8.87	79.6±11.3	0.301	0.587
DBP	63.9±7.84	65.7±8.10	0.513	0.478
SBP	109.5±16.7	110.4±14.6	0.031	0.860

Table 3: ANOVA tests of sVRI, HR, BP over the different stages of the tasks (before and in task).

		Pre-task	In-task	F	P
Easy	sVRI	0.827±0.0551	0.906±0.0479	**9.427**	**0.001**
	HR	79.5±10.8	81.3±8.87	0.353	0.556
	DBP	64.3±8.33	63.9±7.84	0.023	0.879
	SBP	109.2±15.6	109.5±16.7	0.003	0.955
Hard	sVRI	0.832±0.0440	0.931±0.0528	**16.518**	**0.000**
	HR	79.3±11.5	79.6±11.3	0.005	0.946
	DBP	64.5±10.6	65.7±8.10	0.154	0.697
	SBP	109.6±16.3	110.4±14.6	0.025	0.874

Table 4: The results of Repeated Measurements ANOVA.

	Pre-task	In-task	Post-task	F	P
Easy	0.827±0.0551	0.906±0.0479	0.825±0.0539	**8153**	**0.000**
Hard	0.832±0.0440	0.931±0.0528	0.844±0.0464	**14934.13**	**0.000**

pre-task values of those three vital signs were firstly tested via the paired-sample *t* tests in order to verify the normal signal bases of the participants before the tasks. We can see that there are no significant differences found on the three vital signs between the *easy* and *hard* tasks (P > 0.05, also with little *F* values). That is, the base signal levels of the three vital signs were all kept normal and the participants were all in good status to enter the tasks. Secondly, the similar t-tests were done for the data of in-task to check the signal bases of the participants when performing the tasks. It can be seen that there were no significant difference found on the blood pressure and heart rate between the two levels of tasks. It should be noticed that there was a significant difference found on sVRI between the easy task and hard task (P=0 and T=5.468). Figure 4 also gives the bar charts of the sVRI values of the three stages (pre-task, in-task and post-task) in the easy and hard tasks.

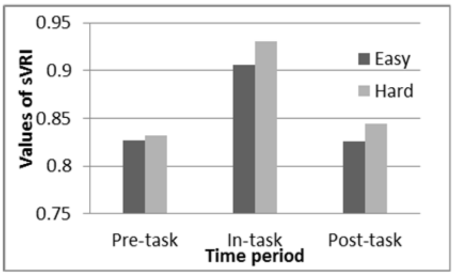


Figure 4: The sVRI values of the three stages.

So, we can differentiate the task levels (hard v.s. easy) just via the sVRI values; it captures the dose-response of the mental effort invested in the cognitive tasks with tiny different difficulties as set in this study.

The third analysis was done to observe the sVRI's changes with the different stages of the tasks: before and during the task. We employed ANOVA tests as Table 3 listed. For the easy and hard task respectively, the ANOVA results tested over the two testing stages: before (pre-task) and during (in-task) the task. From Table 3, we can see that the upper part shows the results of those of the easy task: only the sVRI had outstanding F and P values in this test, which means that the sVRI got significantly different when the participants performed from the pre-task stage to the in-task stage; others (BP and HR) failed to pass the test. We can also see the lower part of the table shows the similar results of the in-task: only the sVRI passed the test with F=16.518 and P=0. Therefore, it can be concluded that there was a clear dose-response on the participants when the cognitive loads of them were increased by an arithematic calculation task. The dose-response is even much clearer in the hard task than in the easy task (higher F and lower P).

The sVRI values were also recorded after the tasks, so the repeated measurements of ANOVA was also used to test the continuous dose-response down through the entire tasks, i.e. from before the task to after the task. Table 4 gives the testing results, from which we can see that there were clear significance found in the sVRI values of three stages in both easy and hard tasks. It means that the sVRI can distinguish the situation how the mental effort invested in processing the cognitive tasks with the small task difficulties set in the experiment; it shows the continuous dose-response in processing the cognitive tasks.

We also tested the correlation between the task difficulties and the sVRIs; we classified three difficulties: no task, easy task and hard task. We got the correlation coefficient r=0.566 with P=0 by Sperman testing, which means there is a moderate correlation between sVRI and task difficulties.

4 DISCUSSION

This study examined the relationship between the mental effort invested in the cognitive tasks and the changes of sVRI. The testing results on the different difficulties of cognitive tasks showed that the PPG-based sVRI can be easily obtained from the real time PPG signals and can be used to distinguish the different extents to which the mental effort is invested during a cognitive task. This can help it adopted in more diverse ubiquitous applications of sVRI, particularly in ubiquitous healthcare service (Farooq et al., 2010; Shin, et al., 2010).

As illustrated in the results, the significant differences of sVRI between different task difficulties indicated that the dose-response against easy task could be represented by a relatively lower increase of sVRI value above the baseline. Conversely, the dose-response against hard task could be represented by a relatively higher increase of sVRI value above the baseline, indicating more mental effort invested. This finding provides strong evidence for the sVRI to be potentially used as a linear classifier of mental effort investment.

In comparison with sVRI, other vital signs such as the heart rate and blood pressure did not reach any convincing significance in task difficulties in this experiment. The similar conclusion has also been reported previously that the effect of mental stress on central pressures is more prominent compared with the effect on peripheral pressures (Vlachopoulos et al., 2006; Madelon et al., 1998), and can partly explain the results.

The major limitation of this study is the relatively small sample size and the age range of participants involved in the experiment. A database of large sample size can be proposed in the future work to setup the baseline of rest state and impact of task difficulty on sVRI, which can evaluate quantitatively an individual against the age-matched normative data as a reference.

5 CONCLUSIONS

As an optical technique for the noninvasive measurement of blood volume changes, PPG is low cost and easy to use, especially suitable for rapid and repeated measurements particularly in ubiquitous environments. In this experiment, PPG-based sVRI is found to be able to reflect the dose-response of the mental effort invested in cognitive tasks: the mental effort invested changes with the task difficulties can be shown efficiently via the sVRIs. This could be used to evaluate the user experience in an interactive task or to evaluate the usability of a cognitive design.

ACKNOWLEDGEMENTS

This work is funded by NSFC 61201357 and FIT foundation of Tsinghua University.

REFERENCES

Allen, J., 2007. Photoplethysmography and its application in clinical physiological measurement. *Physiological measurement*, 28(3), p. R1.

Alneab, M. E., Alobaid, N. & Seifalian, A. M., 2007. Optical techniques in the assessment of peripheral arterial disease. *Current Vascular Pharmacology*, 5(1), pp. 53-59.

Award, A., 2001. "How Does the Plethysmogram Derived from the Pulse Oximeter Relate to Arterial Blood Pressure in Coronary Artery Bypass Graft Patients?". *Anesth Anal*, Volume 93, pp. 1466-1471.

Collins, S. M., Karasek, R. A. & Costas, K., 2005. Job strain and autonomic indices of cardiovascular disease risk. *American journal of industrial medicine*, 48(3), pp. 182-193.

Dedovic, K., Renwick, R. & Mahani, N. K., 2005. The Montreal Imaging Stress Task: using functional imaging to investigate the effects of perceiving and processing psychosocial stress in the human brain. *Journal of Psychiatry and Neuroscience*, 30(5), p. 319.

Farooq, U., Jang, D. G. & Park, J. H., 2010. PPG delineator for real-time ubiquitous applications. In: *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE.* s.l.:IEEE, pp. 4582-4585.

Goor, D. et al., 2004. Sheps DS. Peripheral arterial tonometry: a diagnostic method for detection of myocardial ischemia induced during mental stress tests: a pilot study. *Clin Cardiol*, Volume 27, pp. 137-41.

Harris, C. R., 2001. Cardiovascular responses of embarrassment and effects of emotional suppression in a social setting. *Journal of personality and social psychology*, 81(5), p. 886.

Iani, C., Gopher, D. & Lvie, P., 2004. Effects of task difficulty and invested mental effort on peripheral vasoconstriction. *Psychophysiology*, 41(5), pp. 789-798.

Luo, L. et al., 2013. On psychological measurement and application of photoplethysmography. *China Medical Equipment*, 10(105), pp. 44-47.

Luo, L., Xiao, L., Miao, D. & Luo, X., 2012. The relationship between mental stress induced changes in cortisol levels and vascular responses quantified by waveform analysis: investigating stress-dependent indices of vascular changes.. *Proceedings of the 2012 International Conference on Biomedical Engineering and Biotechnology*, Volume 2, pp. 929-933.

Luo, X., Zhang, B., Hao, X. & Wang, X., 2011. Identification of Photoplethysmogram Appearance for Clinical Interpretation. *proceedings of The World Congress on Engineering and Technology*, Volume 7, pp. 442-445.

Madelon, L. P. et al., 1998. Cardiovascular and endocrine responses to experimental stress: Effects of mental effort and controllability. *Psychoneuroendocrinology*, January, 23(1), pp. 1-17.

Nilsson, L., Goscinski, T. & Lindenberger, M., 2010. Respiratory variations in the photoplethysmographic waveform: acute hypovolaemia during spontaneous breathing is not detected. *Physiological mearurement*, 31(7), p. 953.

Rimmele, U., Zellweger, B. C. & Marti, B., 2007. Trained men show lower cortisol, heart rate and psychological responses to psychosocial stress compared with untrained men. *Psychoneuroendocrinology*, 32(6), pp. 627-635.

Schmitz, C. H., Graber, H. L. & Barbour, R. L., 2006. Peripheral vascular noninvasive measurements [J]. Encyclopedia of Medical Devices and Instrumentation.

Shelley, K. H. & Shelley, S., 2001. "Pulse Oximeter Waveform: Photoelectric Plethysmography.". In: *Clinical Monitoring: Practical applications for anesthesia and critical care.*. s.l.:s.n., pp. 420-428.

Shin, W., Cha, Y. D. & Yoon, G., 2010. ECG/PPG integer signal processing for a ubiquitous health monitoring system. *Journal of Medical systems*, 34(5), pp. 891-898.

Vlachopoulos, C., Kosmopoulou, F. & Alexopoulos, N., 2006. Acute mental stress has a prolonged unfavorable effect on arterial stiffness and wave reflection. *Psychosomatic medicine*, 68(2), pp. 231-237.

Xiao, L. et al., 2011. Assessment of Stress Reactions of Recruits Based on Quantitative analysis of the characteristics of fingertip Photoplethysmographic. *Med J Chin*, 1 Sep, 36(9), pp. 991-994.