Cognitive Neurodynamics (2020) 14:709–721
https://doi.org/10.1007/s11571-020-09617-2

RESEARCH ARTICLE

Assessing cognitive load in adolescent and adult students using photoplethysmogram morphometrics

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Received: 7 December 2019 / Revised: 11 June 2020 / Accepted: 7 July 2020 / Published online: 14 July 2020

Abstract

Compared to cardiac parameters and skin conductivities, the photoplethysmogram (PPG) recorded at fingertips and other parts near to peripheral nerve ends have been recently revealed to be yet another sensitive measure for cognitive load assessment. However, there is so far no research on measuring adolescents' cognitive load using physiological signals. A comprehensive study on the effects of PPG morphometrics over a cohort covering both adolescent and adult students is also absent. In this study, we analyze the morphological features of PPG on cognitive load assessment and compare them between adolescent and adult students. Experiments on two-level arithmetic tasks show that the PPG morphometrics reached the same level of significance on the effect of task difficulty/period as heart rate, and different morphological behaviors were also shown between adolescent and adult students during the cognitive task effects, which may imply their physiological differences across age. Physiological signals recorded by wearable devices are also found to be effective in measuring cognitive load.

Keywords Cognitive load · Autonomic nervous system · Photoplethysmogram morphometrics · Heart rate · Adolescent cognitive load · Wearable devices

Introduction

Cognitive load is considered the load that performing a particular task imposes on the human cognitive system (Meshkati 1988; Paas and Van Merrienboer 1994; Yeh and Wickens 1988). It is a multidimensional construct and reflects the demand for both psychological and physiological resources in complex cognitive tasks. Human learning and performance are largely constrained by limited working memory. The measurement of cognitive load is thus crucial to human–computer interaction (HCI) design (Oviatt 2006; Paas and Van Merrienboer 1994; Sweller et al. 1998), as well as teaching and learning designs, as the control and manipulation of the task according to cognitive load assessment can optimize the learning experience and HCI.

The assessment of cognitive load can be conducted via three dimensions: the task-centered dimension (i.e., stress or task demand (Young et al. 2015)), the human-centered dimension (i.e., mental effort), and the synthesized dimension (i.e., performance (Jahns 1973)). Mental effort, which refers to the cognitive capacity invested in the task (Paas and Van Merrienboer 1994), is essential to measure cognitive load in practice. Mental effort reflects all three causal factors of cognitive load, i.e., task and human characteristics and the interaction between the two (Paas et al. 2003). Mental effort is linked to both cognitive capacity (cognitive resources available) and intentional

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autonomic arousal. Due to variations in arousal, the same person may perform differently on the same task at different times (Askew 1998). By measuring the cognitive load of teachers and students, teaching or learning effort can be further assessed. Furthermore, combining learners' mental effort and performance output, teaching effectiveness can be objectively and quantitatively evaluated.

Measures for assessing mental effort include rating scale techniques, behavioral methods, and psychophysiological techniques. The rating scale-based methods are subjective and rely on participants' memory of their cognitive process, while the other methods are objective and based on the assumption that variations in cognitive functioning can be reflected by behavioral and physiological signals. In addition, physiological signals, such as electroencephalography (EEG), electrocardiography (ECG), blood pressure (BP) and electrodermal activities (EDA, i.e., skin conductivity-based measures), are believed to have promising potential to provide more precise and accurate measurements. However, there are a variety of limitations in sensitivity, reliability, and availability for these measures. Although researchers usually assess mental effort by a combination of multiple measures to improve the assessment, combining multiple measures is not ubiquitously available across applications. There is much inconvenience or inaccuracy in measuring physiological signals such as ECG and blood pressure on a wearable device.

Compared to cardiac parameters and skin conductivities, the photoplethysmogram (PPG) recorded at the fingertips and other parts near peripheral nerve ends has been recently revealed to be yet another sensitive measure for cognitive load assessment (Lyu et al. 2015). PPG is an optically obtained vital sign that is used to show the blood volume changes in the peripheral blood vessels, which reflects both the cardiac activity and the status of vasculature. The low-frequency components of the PPG waveform are attributed to respiration, sympathetic nervous system activity and thermoregulation (Allen 2007). PPG morphometrics have also been correlated with other cardiac parameters (such as ECG and blood pressure) and physiological state (such as age, blood pressure, and heart rate). When cognitive load occurs, the sympathetic nervous system will become excited and elicit a series of reactions, such as increased heart rate and vasoconstriction, and the morphology of PPG will change accordingly. Furthermore, many previous studies (Berntson et al. 1991; Charkoudian and Rabbitts 2009; Hernando et al. 2019; Joyner et al. 2010; Malpas et al. 2001; Pfeifer et al. 1983; Shabanah et al. 1964; Sherwood et al. 2002) also suggested that the PPG acquired at the fingertips or other body parts near peripheral nervous ends can sensitively reflect sympathetic nervous system (SNS) activity.

To our knowledge, there are currently no studies measuring adolescent cognitive load using physiological signals. Many studies have shown that adolescents are in the midst of many physiological and psychological changes (Artemenko et al. 2018; Mueller et al. 2017; Romeo 2013). Specifically, adolescence is also a significant period of continued neural maturation in hypothalamic–pituitary–adrenal (HPA) axis reactivity, resulting in heightened stress-induced hormonal responses (Romeo 2013). It is presently unclear whether adolescents have different physiological responses than adults when cognitive load occurs. In this study, we were mainly concentrated on the differences in PPG morphometrics, which are easily accessible and less invasive among measurable physiological signals. Moreover, a comprehensive study on PPG morphometrics across a cohort including both adolescents and adults is still absent. We characterized and defined the morphological features of PPG and verified their psychometric properties in assessing cognitive load for both adolescent and adult students.

In this paper, the sensitivity of PPG morphometrics on cognitive load assessment and the differences between adolescents and adults are analyzed. Experiments on two-level arithmetic tasks[1] show that PPG morphometrics can reach the same level of significance on the effect of task difficulty/period as heart rate, and different morphological features are also compared between adolescents and adults during the cognitive task. The physiological signals recorded by wearable devices are also found to be promising in measuring cognitive load. We show that the PPG morphometrics are effective in revealing the status of cognitive load and that it is more appropriate to establish separate indices and criteria for adolescents and adults on cognitive load assessment. Our findings may provide some guidance for teaching and HCI design to be more flexible and efficient.

The main contributions of this study are as follows:

- As an addition to traditional measures, PPG morphometrics were comprehensively studied for assessing cognitive load in adolescent and adult students.
- Both fingertip PPG and wearable PPG reached significance in differentiating effortful conditions associated with tasks of varying difficulties that were used to impose cognitive loads.
- The performance and sensitivity of morphometrics on the assessment of cognitive load during cognitive tasks between adolescent and adult students were compared. The results showed that there was a difference in the

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[1] The arithmetic calculation is used in a large literature in physiology and biophysiology as a task to study stress via mental effort (Ritter et al. 2007).

level of significance between adolescent and adult students across morphometric measures.

The remainder of the paper is organized as follows. First, the background of PPG morphometry and correlated information are systematically presented. Second, the basic methodology and experimental design are introduced. Then, the experimental results and analyses are reported. Finally, the limitations and applicability of this study are presented.

Background

Most of the PPG morphometric measures are visualized in Fig. 1. The upper part of Fig. 1 models a standard PPG waveform by morphometric characterization, and Tables 1 and 2 give the corresponding morphometric measures and meanings for the time domain and frequency domain, respectively, some of which were also similarly formulated in previous research related to PPG feature analysis (Kavsaoglu et al. 2014). The lower part of Fig. 1 shows the corresponding first-order derivative and second-order derivative to the PPG waveform. Tables 3 and 4 give their detailed measures and meanings, respectively.

The original time-domain and frequency-domain measures of a standard PPG waveform have been mentioned in a range of previous studies. To date, there has not been a set of standard symbols and denotations for the subwaves and features found, and we provide some relatively general denotations for them in this study that are slightly different from the previous ones, such as those using x, y, z and *IPA* for subwaves (Elgendi 2012; Kavsaoglu et al. 2014). For some definitions rarely seen in other publications, we also mark their referred sources in the tables accordingly. In related studies, the first-order derivative indices (Alty et al. 2007; Millasseau et al. 2002) were not as well studied as the second-order derivative indices (Baek et al. 2007; Otsuka et al. 2006; Takazawa et al. 1998), which were first proposed as domains of interest in the 1980s in cardiac medicine professions. In this study, we chose to follow a similar ABCDEF symbol and denotation system with those invented in the cardiac research domain to maintain a similar stylish convention with the PQRST system in ECG studies. The waveforms of the first-order derivative are named a_1, b_1, c_1, and d_1. The waveforms of the second-order derivative are named a_2, b_2, c_2, d_2, and e_2.

The blood volume changes in peripheral blood vessels that PPG records reflect both the heart activities and the blood vessel status; therefore, the PPG signals are actually tightly correlated to ECG and blood pressure, which are widely used for studying the heart and circulatory systems. A range of studies have revealed the potential of PPG in indicating heart diseases as well as hypertension. In addition, PPG has also been widely used to indicate blood vessel health status, such as those observed with aging (Baek et al. 2007; Bortolotto et al. 2000; Millasseau et al. 2002), stiffness (Alty et al. 2007; Millasseau et al. 2002; Shimazu et al. 1986), and blockages (Awad et al. 2007; Bortolotto et al. 2000; Otsuka et al. 2006; Takazawa et al. 1998). Moreover, aging has been associated with increased vascular stiffness and peripheral resistance and reduced vasoconstriction in response to sympathetic stimulation (Hogikyan and Supiano 1994), which could be a possible

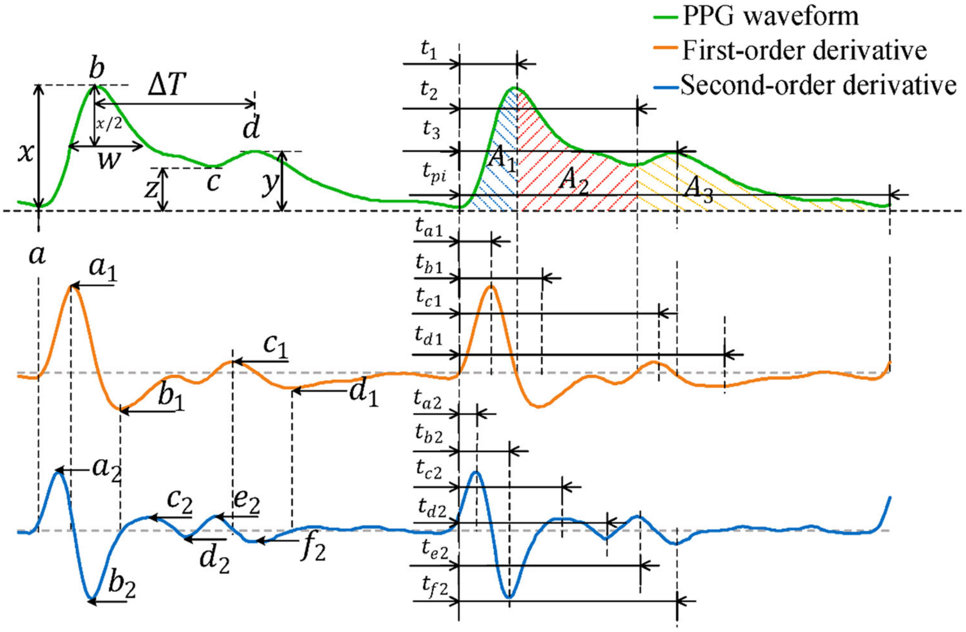

Fig. 1 PPG waveform, its first-order derivative and its second-order derivative

Table 1 Original time-domain measures

No.	Measure	Meaning
1	a	Starting point of the waveform, normally set to zero
2	b	Systolic peak is an indicator of pulsatile changes in blood volume caused by arterial blood flow (Asada et al. 2003; Chua and Heneghan 2006; Murray and Foster 1996)
3	c	Dicrotic notch means the closure of the aortic valve and subsequent retrograde flow (Dawber et al. 1973; Mosby 2016; Murray and Foster 1996)
4	d	Diastolic peak means the reflection strength of the pressure wave by arteries (Brumfield and Andrew 2005; McDuff et al. 2014)
5	t_{pi}	Elapsed time of the entire pulse wave, also equivalent to the instantaneous heart rate. Pulse interval (abbr. pi): the distance between the beginning and the end of the PPG waveform, highly correlated with R–R intervals in ECG signals (Lu et al. 2008)
6	y/x	Augmentation index (AI) (Kelly et al. 1989), also named RI as a reflection index (Padilla et al. 2008). It is related to the stiffness of the aorta and depends on the tone of the peripheral arteries (endothelial function) (Zhang et al. 2018)
7	$(x - y)/x$	Alternative augmentation index, related to the AI
8	z/x	Alternative augmentation index, related to the AI
9	$(y - z)/x$	Alternative augmentation index, related to the AI
10	t_1	Elapsed time to systolic peak, a useful feature for cardiovascular disease classification (Alty et al. 2007)
11	t_2	Elapsed time to dicrotic notch
12	t_3	Elapsed time to diastolic peak
13	ΔT	Elapsed time between systolic peak and diastolic peak is also known as pulse propagation time (PPT) and correlated with age and mean arterial blood pressure (Millasseau et al. 2002)
14	$t_b/2$	Elapsed time from the point that the pulse reaches its half height to the point it recovers to half height. It correlates with the systemic vascular resistance better than the systolic amplitude (Awad et al. 2007; Mueller et al. 2017)
15	t_1/b	Systolic peak upward angle
16	$d/(t_{pi} - t_3)$	Diastolic peak downward angle
17	t_1/t_{pi}	Systolic peak time ratio, normalized elapsed time to systolic peak
18	t_2/t_{pi}	Dicrotic notch time ratio, normalized elapsed time to dicrotic notch
19	t_3/t_{pi}	Diastolic peak time ratio, normalized elapsed time to diastolic peak
20	$\Delta T/t_{pi}$	Between-peak time ratio
21	$A_1 + A_2 + A_3$	Area under curve (AUC) (Alty et al. 2007), an indicator of the volume of blood in the tissue scanned by the transducer
22	$A_3/(A_1 + A_2)$	The inflation point area ratio (IPA) (Wang et al. 2009), a very good indicator of total peripheral resistance when it changes after exercise
23	$(A_2 + A_3)/A_1$	Pulse area ratio, defined as the stress-induced vascular response index ($sV\ RI$) (Lyu et al. 2015)

Table 2 Frequency-domain measures

No.	Measure	Meaning
1	f_{base}	Fundamental frequency, the reciprocal of t_{pi}
2	f_{2nd}	Frequency of the second harmonics (Millasseau et al. 2002)
3	f_{3rd}	Frequency of the third harmonics
4	P_{base}	Power spectral density (PSD) of the fundamental frequency
5	P_{2nd}	Power spectral density of the second harmonics (Millasseau et al. 2002)
6	P_{3rd}	Power spectral density of the third harmonics

reason that PPG morphometrics behave differently when cognitive load occurs.

The time relationship between the PPG and ECG is illustrated in Fig. 2, where the delay between the ECG R wave and the peak of the PPG pulse is defined as T. It has also been defined as the pulse arrival time (PAT) and can be used to estimate blood pressure (BP) combined with heart rate (Cattivelli and Garudadri 2009). Blood pressure can also be inferred from PPG morphometric measures. Therefore, many algorithms (Imholz et al. 1988; Kachuee et al. 2017; Peter et al. 2014) for noninvasive blood pressure continuous measurement using PPG have been proposed. These algorithms use many features mentioned in the previous section and include the augmentation index

Table 3 The first-order derivative time-domain measures

No.	Measure	Meaning
1	a_1	First peak of the volume change velocity
2	b_1	First valley of the volume change velocity
3	c_1	Second peak of the volume change velocity
4	d_1	Second valley of the volume change velocity
5	t_{a1}	Elapsed time to a_1
6	t_{b1}	Elapsed time to b_1
7	t_{c1}	Elapsed time to c_1
8	t_{d1}	Elapsed time to d_1
9	t_{a1}/t_{pi}	a_1 time ratio, normalized elapsed time to a_1
11	t_{b1}/t_{pi}	b_1 time ratio, normalized elapsed time to b_1
12	t_{c1}/t_{pi}	c_1 time ratio, normalized elapsed time to c_1
13	t_{d1}/t_{pi}	d_1 time ratio, normalized elapsed time to d_1

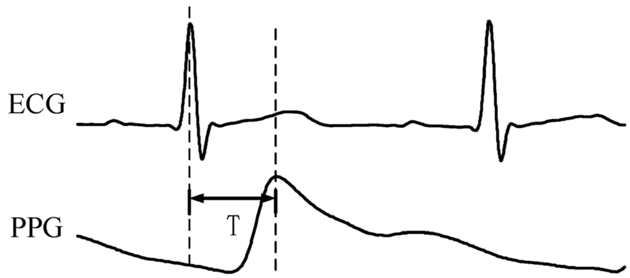

Fig. 2 ECG and delay PPG

and inflection point area ratio (Millasseau et al. 2002; Padilla et al. 2008; Wang et al. 2009). The calculation methods of these features may be slightly different across papers but involve consistent basic concepts. Some researchers have modeled blood flow changes from the heart to peripheral blood vessels (Goldwyn and Watt 1967; van de Vosse and Stergiopulos 2011). These models explained the information contained in PPG changes in some way.

PPG morphology is also correlated with the sympathetic nervous system (SNS) activity, which controls the contraction and relaxation of peripheral blood vessels. The general response to both physical and psychological stress is the activation of the sympathetic nervous system with inhibition of the parasympathetic nervous system (Wolf 1997). When stressed, there will be increases in heart rate, left ventricular ejection fraction, cardiac output and vasodilation. Some of these physiological manifestations

Table 4 The second-order derivative time-domain measures

No.	Measure	Meaning
1	a_2	First peak of the volume change acceleration
2	b_2	First valley of the volume change acceleration
3	c_2	Second peak of the volume change acceleration
4	d_2	Second valley of the volume change acceleration
5	e_2	Third Peak of the volume change acceleration
6	f_2	Third valley of the volume change acceleration
7	t_{a2}	Elapsed time to a_2
8	t_{b2}	Elapsed time to b_2
9	t_{c2}	Elapsed time to c_2
10	t_{d2}	Elapsed time to d_2
11	t_{e2}	Elapsed time to e_2
12	t_{f2}	Elapsed time to f_2
13	b_2/a_2	Ratio of the amplitude of b_2 wave to that of a_2 wave, reflects increased arterial stiffness and increased with age (Imanaga et al. 1998; Takazawa et al. 1998)
14	e_2/a_2	Ratio of the amplitude of e_2 wave to that of a_2 wave, decreased with age (Baek et al. 2007; Takazawa et al. 1998)
15	$(b_2 + e_2)/a_2$	Ratio of the amplitude sum of b_2 and e_2 over a_2
16	t_{a2}/t_{pi}	a_2 time ratio, normalized elapsed time to a_2
17	t_{b2}/t_{pi}	b_2 time ratio, normalized elapsed time to b_2
18	$(t_{a1} - t_{a2})/t_{pi}$	Normalized elapsed time from peak a_2 to peak a_1
19	$(t_{b1} - t_{b2})/t_{pi}$	Normalized elapsed time from peak b_2 to peak b_1

are highly related to the measures of t_{pi}, *AUC*, *IPA*, *sVRI*, etc. It has been proven that PPG can also efficiently reflect the SNS because peripheral vasoconstriction is controlled only by the SNS (Lyu et al. 2015; Zhang et al. 2018). There are also many physiological signals that can reveal stress levels, including heart activity, breathing, and blinking, but they are all controlled by the parasympathetic nervous system (Berntson et al. 1991; Farmer et al. 2014) and are not as sensitive as the signals controlled only by the sympathetic nervous system. Therefore, it may be inappropriate to consider measures such as t_{pi} as sensitive measures. Some morphometrics such as *IPA* and *sVRI* that reflect pure SNS activities may be sensitive enough. Consequently, PPG could be as direct and sensitive to SNS activities as electrodermal activities (EDA) (Boucsein 2012), but this is still to be further researched.

Methodology

The study presents a classic arithmetic calculation task, which requires the subject to have basic mathematical operation ability. Participants were required to perform continuous subtraction within a specified period, where the subtractions remain the same, such as consecutive subtractions of 7, 13, 77, etc. Adults and minors have slightly different topics. The experimental data of the subjects, including task scores, experimental performance and physiological signals, i.e., PPG signals, were collected in real time during the experiment through arithmetic task performance, experimental recordings and portable wearable physiological signal detection equipment. After the experiment, the participants completed the self-report sheet. Finally, the above data were comprehensively analyzed, and the experimental results were obtained.

Hypotheses

According to the relationships between PPG morphometrics and cognitive load described in "Background" section, we suppose that some measures can be used to assess cognitive load and stress. We designed an experiment with two task difficulties and two testing periods to evaluate the following specific hypotheses:

- Hypothesis A—Period effect: Some measures will show significant differences between different periods (i.e., pre-task and in-task).
- Hypothesis B—Difficulty effect: Some measures will show significant differences based on difficulty (i.e., easy and hard).
- Hypothesis C—SNS activities: Some measures related to SNS activities will show significant differences between periods or difficulties.

Participants

A total of 36 participants were recruited in this experiment, including 17 adults (9 men and 8 women; average age: 22.4 years) and 19 adolescents (10 boys and 9 girls; average age: 16.8 years). All of them were university students or high school students.

All subjects were physically and mentally healthy, and their hearing and vision (including corrected vision) were normal. They were all right-handed and had never participated in related cognitive experiments. Before the experiment, they had carefully read and signed the informed consent form approved by the ethics committee of the Department of Psychology of Tsinghua University. Additionally, both minors and their guardians had carefully read and signed the informed consent form and the form for underage (8–17 years old) participants. Each adult participant was paid 50 yuan with an additional bonus of 13 to 30 yuan added according to the experimental performance. Each adolescent participant was awarded a set of hand-painted postcards and a notebook for participation in the experiment.

Apparatus and settings

The experiment used a standard clinical finger-clip PPG sensor (sampling frequency 200 Hz) and a wearable wristwatch (sampling frequency 20 Hz) to collect the PPG and HR signal of the subject. The sensor was uniformly placed on the left index finger of the subject, and the wristwatch was uniformly worn under the left wrist joint of the subject. The two experiments were carried out in a laboratory environment with normal light levels and constant temperature and humidity. The task was presented on a laptop screen. The participants watched relaxing videos and operated a standard keyboard to input their answers to the arithmetic problems. The sound was played through SONY headphones, and the volume was set in advance to a moderate level.

Stimuli and protocol

The experiment consists of two parts: the explanation phase and the formal experiment. Each participant was tested separately. After the formal test began, the physiological signals of the subjects were recorded. During the explanation phase, the participants were required to understand the purpose and steps of the experiment while relaxing. The formal experiment consists of five parts, as shown in Fig. 3.

First, the baseline test was conducted, in which the subjects were asked to sit for 1 min and 30 s with closed eyes and 1 min and 30 s with open eyes for baseline blink data collection as indicated by the experimental test program. The participants then watched a 5-min video. After the video, the subjects were asked to perform the first calculation task (difficult mode). The initial subtraction was 73 from 5000 for both adults and minors. The subject needed to calculate the solution within 10 s of the specified time. If the calculation was correct, then 4927 became the minuend for the next question, from which 73 was subtracted, and so on. The calculation task duration was 5 min, during which each correct answer resulted in 5 points and errors removed 3 points, and the system recorded the final score of the test.

After the first mental arithmetic task, the participants relaxed and rested again while watching a video. The video content was immediately followed by the previous video for 10 min. After this second rest period, the subject performed the second calculation task. This task was the simple mode; the initial number was 4000, and the subtracted number was 13 for adults and 7 for minors. The subject needed to perform continuous subtraction for the total time of 5 min. The limit time for each question was 10 s, and the scoring method was the same as in the first task.

At the end of the experiment, the participants completed the questionnaire for the self-report and scored the difficulty and cognitive load of the two mental tasks on a scale of 1 to 4. Regarding difficulty, a score of 1 indicated that the task was very simple, and a score of 4 indicated that the task was very difficult. Regarding cognitive load, a score of 1 indicated that the subject felt no pressure during the task, and a score of 4 indicated that the subject was full of stress during the task.

Analysis and results

In this study, the data were divided into different segments according to the experimental process. The study calculated the average values of the PPG and HR data under the different segments as dependent variables for subsequent analysis. Repeated measures ANOVA was performed, in which the period was divided into two stages: pre-task and in-task. The difficulty of the task was divided into two levels: easy and hard. The period and difficulty were the main factors in the analysis. The main effect of period or difficulty on the cognitive load was assessed according to whether there was a significant difference in the mean value of the different variables across periods or difficulties.

Before the analysis, it was necessary to perform a spherical test on the correlation between the repeated measurement data. If the test result was $p > 0.05$, there was no correlation between the repeated measurement data. The measurement data conformed to the Huynh–Feldt condition, which can be processed by one-way ANOVA. If the test result was $p < 0.05$, it indicated that there was a correlation between the measured data, so the data cannot be processed by one-way ANOVA. All statistical analyses in this study were performed in SPSS 25.0 with a significance of 0.05 and two-tailed testing.

Performance data

For the scores of performance and self-assessment cognitive load, we used the paired t test to examine significant level of difference under different difficulty. Figure 4 shows the performance and self-report cognitive load in two mental arithmetic tasks, where the significant level is also marked with stars. The scores in the hard mode (134 ± 55) were significantly lower ($p < 0.001, t(16) = -8.91$) than the scores in the easy mode (253 ± 61), and the results of the self-reports showed that the performance scores were negatively correlated with cognitive load across difficulties. The self-assessment scores of cognitive load in the hard task (2.65 ± 0.79) were higher than those in the easy task (1.65 ± 0.49), with a significance level of $p < 0.001, t(16) = 4.12$.

Figure 5 provides the performance results of the adolescent participants. The scores in the hard mode (52 ± 62) were significantly lower ($p < 0.001, t(18) = -18.15$) than those in the easy task (298 ± 67), and the performance scores showed a negative correlation with the cognitive load according to the self-report, where scores in the hard task (3.00 ± 0.82) were higher than those in the easy task (1.58 ± 0.77), with a significant difference ($p < 0.001, t(18) = 5.30$). Both sets of results showed that the task difficulty set in this experiment was reasonable. In

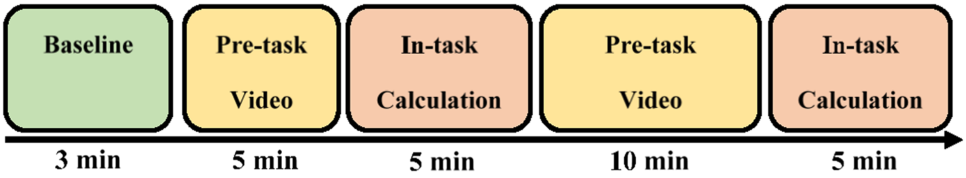

Fig. 3 The experimental protocol

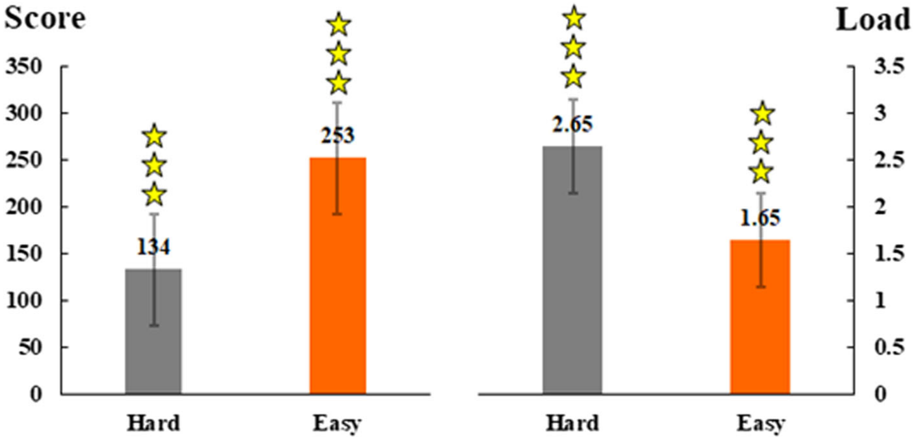

Fig. 4 The performance data (means and SE) across different task difficulties in the adults: **a** total scores; **b** mental load. The three stars above indicate the significance level at 99%

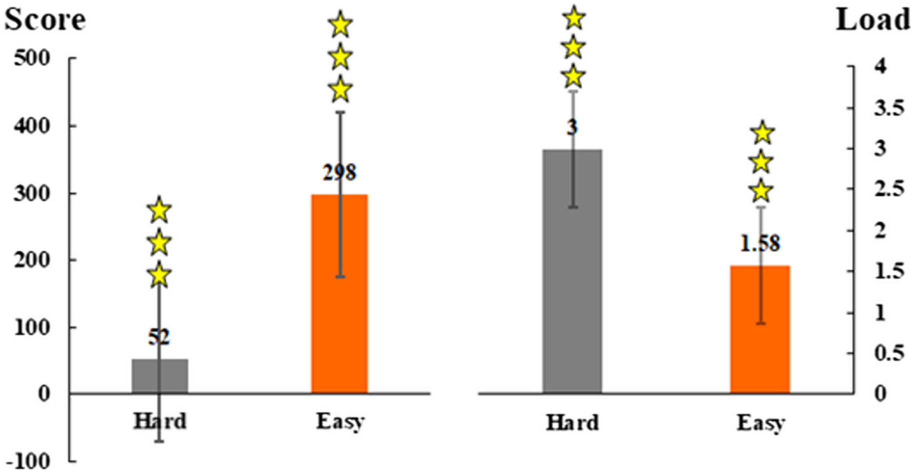

Fig. 5 The performance data (means and SE) across different task difficulties in the adolescents: **a** total scores; **b** mental load. Three stars: significant at 99%

summary, the two figures prove the rationality and effectiveness of the experimental design; that is, the cognitive load caused by the simple task was low, and the cognitive load caused by the difficult task was higher.

Physiological data

By repeated measures ANOVA, we found some measures showing significant differences across periods and difficulties. Table 5 reports the average and corresponding standard deviations of the different physiological measures for the adult subjects during the task. The subscript '(F/W)' indicates the source of data: '(F)' means the finger-clip PPG sensor and '(W)' means the wearable wristwatch. These measures included *sVRI*, *AUC*, t_{pi}, t_1/t_{pi}, t_{a1}/t_{pi}, t_{b1}/t_{pi}, t_{a2}/t_{pi}, and t_{b2}/t_{pi} (note that t_{pi} is equivalent to heart rate). Repeated-measures ANOVA of the 2 periods (pre-task and in-task) × 2 difficulties (easy and hard) was performed for each of those measures and used to first examine the physiological responses during different testing periods. The analysis results are presented in Tables 7 and 8 and include p and F values for the main effects of period and difficulty and η^2 for the effect sizes, which were the partial eta squared values in SPSS.

Table 8 reports the within-subject effects of different measures from the adults across the different periods and difficulties. Combined with the results in Tables 1, 2, 3, and 4, we obtained some measures that showed significant period and difficulty effects on cognitive load: $t_{pi(F)}$, $t_{pi(W)}$ and t_{a2}/t_{pi} significantly decreased ($p < 0.05$), and $t_1/t_{pi(F)}$, t_{a1}/t_{pi}, t_{b1}/t_{pi} and t_{b2}/t_{pi} significantly increased ($p < 0.05$), while the subjects performed the tasks.

Meanwhile, we note that *sVRI* and *AUC*, which are related to SNS activities, were significantly different across periods or difficulties in the adults. However, the *AUC* is also dually controlled by PNS. It is directly correlated with heart rate. Indicators such as *IPA* were not significant for any effect. According to the heart rate measure $t_{pi(W)}$ (F (1, 16) = 23.25) collected by the wearable device, it had significant period effects on cognitive load. In particular, $t_{pi(W)}$ significantly decreased ($p < 0.01$), which was consistent with the results of physiological measures collected from the clinical finger clip.

Table 5 Means and standard deviations of physiological measures in adults

Measures	Easy task		Hard task	
	Pre	In	Pre	In
$sVRI_{(F)}$	4.989 ± 0.791	4.592 ± 0.595	4.675 ± 1.006	4.291 ± 0.605
$AUC_{(F)}$	23.114 ± 11.791	12.528 ± 7.229	25.172 ± 10.234	12.152 ± 7.704
$IPA_{(F)}$	0.688 ± 0.333	0.619 ± 0.267	0.577 ± 0.225	0.533 ± 0.272
$t_{pi(F)}$	0.844 ± 0.088	0.756 ± 0.093	0.824 ± 0.098	0.716 ± 0.104
$t_{pi}(W)$	0.786 ± 0.065	0.733 ± 0.064	0.771 ± 0.075	0.715 ± 0.055
$t_1/t_{pi(F)}$	0.129 ± 0.014	0.146 ± 0.015	0.137 ± 0.020	0.153 ± 0.017
$t_{a1}/t_{pi(F)}$	0.075 ± 0.016	0.081 ± 0.010	0.071 ± 0.010	0.077 ± 0.008
$t_{b1}/t_{pi(F)}$	0.173 ± 0.199	0.194 ± 0.203	0.182 ± 0.245	0.204 ± 0.243
$t_{a2}/t_{pi(F)}$	0.051 ± 0.010	0.047 ± 0.008	0.053 ± 0.014	0.049 ± 0.009
$t_{b2}/t_{pi(F)}$	0.106 ± 0.015	0.118 ± 0.013	0.112 ± 0.022	0.124 ± 0.015

Table 6 Means and standard deviations of physiological measures in adolescents

Measures	Easy task		Hard task	
	Pre	In	Pre	In
$sVRI_{(F)}$	4.443 ± 0.688	4.153 ± 0.765	4.401 ± 0.642	4.022 ± 0.680
$AUC_{(F)}$	16.781 ± 9.022	9.689 ± 6.022	14.985 ± 8.102	7.851 ± 4.663
$IPA_{(F)}$	0.715 ± 0.212	0.652 ± 0.263	0.719 ± 0.372	0.576 ± 0.173
$t_{pi(F)}$	0.812 ± 0.076	0.719 ± 0.080	0.788 ± 0.075	0.703 ± 0.091
$t_1/t_{pi(F)}$	0.140 ± 0.022	0.154 ± 0.298	0.141 ± 0.187	0.157 ± 0.026
$t_2/t_{pi(F)}$	0.372 ± 0.057	0.392 ± 0.070	0.377 ± 0.053	0.419 ± 0.063
$t_3/t_{pi(F)}$	0.478 ± 0.074	0.492 ± 0.100	0.483 ± 0.073	0.524 ± 0.092
$t_{a1}/t_{pi(F)}$	0.073 ± 0.008	0.081 ± 0.008	0.075 ± 0.008	0.082 ± 0.009
$t_{b1}/t_{pi(F)}$	0.195 ± 0.027	0.204 ± 0.022	0.198 ± 0.027	0.213 ± 0.027
$t_{a2}/t_{pi(F)}$	0.038 ± 0.006	0.041 ± 0.005	0.041 ± 0.007	0.041 ± 0.005
$t_{b2}/t_{pi(F)}$	0.110 ± 0.013	0.124 ± 0.014	0.111 ± 0.014	0.126 ± 0.017

Table 6 shows the results of the within-subject effects across periods and difficulties for the adolescents. We found that all measures t_{pi}, t_2/t_{pi}, t_3/t_{pi}, and t_{b1}/t_{pi} showed significant effects of period and difficulty. Specifically, t_{pi} (F (1, 18) = 43.796, $p < 0.01$) showed a significant negative period effect ($p < 0.05$) on cognitive load, while the remaining measures presented positive period effects ($p < 0.05$) on cognitive load. In contrast with the easy task, t_{pi} significantly decreased (F (1, 18) = 19.120, $p < 0.01$) in the hard task, which meant that the participants had a higher heart rate. The remaining measures t_2/t_{pi}, t_3/t_{pi}, and t_{b1}/t_{pi} showed lower mean values in the easy task. These data showed significant positive effects of difficulty. In addition, the results also proved that the task difficulty of this experiment was reasonable and distinguishable; that is, the cognitive load was higher in the hard task, and the cognitive load was lower in the easy task.

According to Table 7, the measures related to pure SNS activities, such as $sVRI$ and AUC, were only significant across periods. Combined with the results in Table 8, we found that only the AUC measure was significant across periods, which meant that the cardiac output was significantly increased during the task.

Discussion

Discussion of the results

This study tested hypotheses of period effects, difficulty effects, and SNS activities. First, the significant differences in self-assessment and performance scores showed that the difficulty setting of the cognitive task was reasonable, and the participants had a relatively higher cognitive load in the hard task than in the easy task. After the separate hypotheses test for adults and adolescents, we found that the measures t_{pi}, t_2/t_{pi}, t_3/t_{pi}, and t_{b1}/t_{pi} for the adolescents and AUC, t_{pi}, t_1/t_{pi}, t_{a1}/t_{pi}, t_{b1}/t_{pi}, t_{a2}/t_{pi}, and t_{b2}/t_{pi} for the adults showed significant effects across both periods and difficulties. However, the measures $sVRI$, AUC, t_1/t_{pi}, t_{a1}/t_{pi} and t_{b2}/t_{pi} for the adolescents and $sVRI$ for the adults showed only a significant effect across periods.

Table 7 Within-subject effects across periods and difficulties by repeated measures ANOVA for adolescents

Measures	Effects of period			Effects of difficulty		
	p	F $df1, df2$	η^2	p	F $df1, df2$	η^2
$sVRI_{(F)}$	0.037*	5.068 1, 18	0.220	0.387	0.787 1, 18	0.042
$AUC_{(F)}$	< 0.01**	43.633 1, 18	0.708	0.128	2.542 1, 18	0.124
$IPA_{(F)}$	0.105	2.921 1, 18	0.140	0.429	0.656 1, 18	0.035
$t_{pi(F)}$	< 0.01**	43.796 1, 18	0.709	< 0.01**	19.120 1, 18	0.515
$t_1/t_{pi(F)}$	< 0.01**	18.109 1, 18	0.502	0.319	1.052 1, 18	0.055
$t_2/t_{pi(F)}$	0.011*	9.828 1, 18	0.496	0.013*	9.217 1, 18	0.480
$t_3/t_{pi(F)}$	0.049*	5.015 1, 18	0.334	0.032*	6.226 1, 18	0.384
$t_{a1}/t_{pi(F)}$	< 0.01**	28.920 1, 18	0.616	0.063	3.937 1, 18	0.179
$t_{b1}/t_{pi(F)}$	< 0.01**	9.326 1, 18	0.354	< 0.01**	15.307 1, 18	0.474
$t_{a2}/t_{pi(F)}$	0.290	1.190 1, 18	0.062	0.135	2.449 1, 18	0.135
$t_{b2}/t_{pi(F)}$	< 0.01**	33.737 1, 18	0.707	0.285	1.235 1, 18	0.081

$^{*}p < 0.05$; $^{**}p < 0.01$

Table 8 Within-subject effects across periods and difficulties by repeated measures ANOVA for adults

Measures	Effects of period			Effects of difficulty		
	p	F $df1, df2$	η^2	p	F $df1, df2$	η^2
$sVRI_{(F)}$	0.035*	5.295 1, 16	0.249	0.084	3.390 1, 16	0.175
$AUC_{(F)}$	< 0.01**	22.689 1, 16	0.586	0.038*	5.095 1, 16	0.242
$IPA_{(F)}$	0.193	1.850 1, 16	0.104	0.115	2.776 1, 16	0.148
$t_{pi(F)}$	< 0.01**	59.54 1, 16	0.998	< 0.01**	21.71 1, 16	0.576
$t_{pi}(W)$	< 0.01**	23.25 1, 16	0.592	0.027*	5.89 1, 16	0.269
$t_1/t_{pi(F)}$	< 0.01**	23.355 1, 16	0.593	< 0.01**	14.708 1, 16	0.479
$t_{a1}/t_{pi(F)}$	0.033*	5.415 1, 16	0.253	< 0.01**	13.533 1, 16	0.458
$t_{b1}/t_{pi(F)}$	< 0.01**	22.005 1, 16	0.579	< 0.01**	15.253 1, 16	0.488
$t_{a2}/t_{pi(F)}$	0.030*	5.67 1, 16	0.967	0.018*	6.89 1, 16	0.301
$t_{b2}/t_{pi(F)}$	< 0.01**	14.005 1, 16	0.483	< 0.01**	14.586 1, 16	0.493

$^{*}p < 0.05$; $^{**}p < 0.01$

The common measures t_{pi}, t_{b1}/t_{pi} were significant across both periods and difficulties for the adults and adolescents, which implied that adults and adolescents may have responded to stress in a similar way, i.e., increasing heart rate and b_1 time ratio. The measure $sVRI$ was significant only across periods for both the adults and adolescents, which indicated that this index may only be applicable as a measure of whether the sympathetic nervous system was excited. Due to the limited external stimuli in this study, the activation of the SNS can be taken as the evidence of cognitive load on the subjects.

The uncommon measures here may reveal the differences between adults and adolescents under similar stress conditions. The measures t_2/t_{pi}, t_3/t_{pi} for the adolescents and AUC, t_{a1}/t_{pi}, t_{a2}/t_{pi}, and t_{b2}/t_{pi} for the adults both showed significance across periods and difficulties, and the adolescent measures AUC, t_1/t_{pi}, t_{a2}/t_{pi}, and t_{b2}/t_{pi} showed significance only across periods. Some possible explanations for these differences are as follows:

(1) The adolescents put as much mental effort as possible into the experiment even if the task demand was low, which led to significance only across periods and roughly the same distribution of AUC, t_1/t_{pi}, t_{a2}/t_{pi}, and t_{b2}/t_{pi} across different difficulties.

(2) The cardiovascular system and autonomic nervous system in the adults were more mature and had higher vascular stiffness than the adolescents. This difference might have caused the t_3/t_{pi}, which is related to the time ratio of the retrograde flow, to be not significant across periods or difficulties for the adults.

It should be noted that some measures showed different significance levels in the adults and adolescents. We may design different indices for them to perform cognitive load assessments in the context of teaching methods and material design. Based on the existing research, HRV, respiration interval, pupil size and skin conductance show significant differences across difficulties and periods (Brouwer et al. 2014). With the exception of skin conductance, these measures are not sensitive enough. Our exploration of PPG morphometrics might help to add more sensitive indicators to monitor cognitive load. The cognitive load effects on PPG morphometrics were analyzed and compared between adolescent and adult students. This study might help us understand more about the physiological responses to cognitive load in adolescents and can be used as a supplement to related research fields at the theoretical level. Additionally, we successfully migrated the laboratory measurements to a real-world situation through the verification experiment of portable wearable devices, providing an experimental basis for the subsequent measurement of physiological signals in real-world contexts to measure cognitive load.

The portable wearable device can greatly reduce the cost and difficulty of collecting physiological signals. The portable device collects physiological signals in real time in a real context. Although the accuracy of the data collected by portable wearable devices is lower than that by laboratory instruments, wearable devices are more convenient and can greatly expand the sample size and data volume, which is not possible using traditional laboratory equipment. The development of wearable physiological signal measurement technology can greatly improve the ubiquity of relevant studies or applications.

Limitations

Although the experimental results showed the possibility of cognitive load measurement using PPG in adolescents and adults, this study still had the following limitations:

(1) The dataset used in this study involved only adolescents with an average age of 16.8 and adults with an average age of 22.4. We may further expand the age range and the quantity of the subjects to observe alterations in the stress responses with age.

(2) We note that $t_{pi(W)}$ was not as accurate as $t_{pi(F)}$. The measures from wearable wristwatches might not be usable. Further evaluation of wearable devices with different precisions is needed for ubiquitous and daily applications. The experimental conditions can still be improved to be more adaptive for circumstances in daily life.

(3) Regarding the SNS activity measures, *sVRI* was only significant across periods, and *IPA* showed no significance, which implied that *sVRI* was a more effective measure than *IPA*, which may be used as an indicator of exercise (Wang et al. 2009). The level of SNS activation might have no indicators among PPG morphometrics. In other words, the PPG morphometric measures may not reflect the level of pure SNS activities unlike EDA measures. Nevertheless, there are some sensitive measures, such as t_2/t_{pi}, t_{b1}/t_{pi}, that can show cognitive load or stress levels. However, we still need to validate their correlation with SNS activities in future work.

(4) In addition, the performance and sensitivity of PPG morphometric measures during cognitive task performance between adolescents and adults were compared, and cardiovascular and cognitive neuroscience theories are still needed to further explore and explain the mechanism.

Conclusions

In this paper, we comprehensively analyzed the PPG morphometrics in the context of cognitive load assessment and compared them between adolescent and adult students. The experiment, based on two levels of task difficulty and two stages of testing periods, showed that there were differences in the levels of significance between adolescents and adults. For example, the measures t_2/t_{pi} and t_3/t_{pi} did not show significance on any effect in the adults, although they showed significance in the adolescents. Our findings also suggested that measures such as *sVRI*, *AUC*, t_{pi}, and t_1/t_{pi} might be sensitive, reliable, and usable indices for cognitive load assessment. However, *sVRI*, *AUC*, and t_1/t_{pi} do not currently distinguish cognitive load from stress despite their differences based on experimental results in both adults and adolescents. These measures may reflect but cannot distinguish the level of pure SNS activities. In future work, we will focus on the current limitations of this method and study its extension for ubiquitous applications.

Acknowledgements This work was supported by Institute for Future Education and Evaluation Tsinghua University (2019IFEE003). We thank all the volunteers for their participation in our experiment. We thank all the reviewers for their insightful comments and helpful suggestions for improving the initial draft of this manuscript.

Author contributions XQ, JW contributed equally as first coauthors. YL, YZ contributed conception and design of the study; XQ and JS conducted experiments and organized the database; JW performed the statistical analysis; JW and QX wrote the first draft of the manuscript; JW and QX wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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