scientific reports

Check for updates

OPEN

A novel mobile application to examine impaired vigilance through digital means

Purbanka Pahari[1,3]✉, Lisa Schmitz[4,5], Elena Richert[1,4,6], Kamilla Rún Jóhannsdóttir[4,6], Hlín Kristbergsdóttir[4,6], Henri Korkalainen[1,2], Juha Töyräs[1,7,8], Timo Leppänen[1,2,8], Sami Nikkonen[1,2], Erna Sif Arnardottir[4] & Anna Sigridur Islind[5]

The psychomotor vigilance task (PVT) is a three to thirty-minute test widely used to measure alertness and vigilance. However, only a few comprehensively validated PVTs are currently available through digital means, e.g., mobile devices. Thus, the present study aimed to investigate the usefulness of a novel three-minute PVT (PVT_{SR}) delivered through a touchscreen mobile device. The present study comprised 41 healthy or undiagnosed with obstructive sleep apnea participants recruited through local advertisement in Reykjavik, Iceland between 2021 and 2022. First, participants completed an in-lab ten-minute standard PVT (PVT_{std}) on a computer with the Inquisit software at Reykjavik University Sleep Institute. Later, the same participants completed a three-minute PVT_{SR} in the Sleep Revolution mobile application at home. With a paired sample t-test, differences between the PVT outputs, i.e., mean reaction time (RT) and median RT, were compared between PVT_{std} and PVT_{SR}. In addition, effect sizes and Pearson correlations between the PVT_{std} and PVT_{SR} outcomes were evaluated. The average mean RT (PVT_{std}: 350.2 ms; PVT_{SR}: 424.1 ms) and median RT (PVT_{std}: 334.4 ms; PVT_{SR}: 415.2 ms) were significantly ($p < 0.001$) shorter in PVT_{std} compared to PVT_{SR}. The effect sizes for mean RT and median RT were 0.70 and 0.79, respectively. In addition, the correlations of mean RT ($r = 0.96$, 95% confidence interval (CI): 0.92–0.98) and median RT ($r = 0.94$, 95% CI: 0.89–0.97) between PVT_{std} and PVT_{SR} were high. Although median and mean reaction times were systematically higher when measured with the mobile application, there was a strong correlation between the methods' outcomes. After accounting for this systematic increase, the novel PVTSR approach shows potential for evaluating impaired vigilance. With future fine-tuning to adjust for the systematic delay, this readily available three-minute test could enable long-term follow-up of impaired vigilance in participants' homes.

Keywords Impaired vigilance, PVT, Reaction time, Mobile application

Adequate sleep is pivotal to remain vigilant during the day and sustain a healthy lifestyle. However, about 25% of the general population are not satisfied with their sleep quality, 10–15% have a sleep disorder manifestation causing adverse daytime symptoms, and 6–10% suffer from insomnia[1]. The consequences of inadequate sleep are broad; the most common impacts of sleep deprivation are impaired vigilance, poor cognitive performance, and inability to sustain attention[2,3]. In addition, reduced vigilance and cognitive impairment have been associated with increased morbidity and are risk factors for traffic and occupational accidents[4–6]. Therefore, the detection of impaired vigilance would be beneficial to improve work productivity and the overall quality of life.

Vigilance is defined as the ability to sustain attention during a certain task over a prolonged period[7]. The psychomotor vigilance task (PVT) is the most widely used test to estimate impaired alertness or vigilance and is considered a good indicator of fatigue and cognitive impairment[8,9]. PVT is based on individuals' reaction time to a particular visual stimulus[10] and the reaction time over 500 milliseconds is considered as a lapse. Generally, the in-lab PVT takes ten to thirty minutes, however, the standard 10-minute PVT protocol is the

[1]Department of Technical Physics, University of Eastern Finland, Kuopio, Finland. [2]Diagnostic Imaging Center, Kuopio University Hospital, Kuopio, Finland. [3]Department of Psychiatry, Population Health and Neurology, NYU Langone Health, NYU Grossman School of Medicine, 180 Madison Avenue, 7th floor, New York, NY 10016, USA. [4]School of Technology, Reykjavik University Sleep Institute, Reykjavik University, Reykjavik, Iceland. [5]Department of Computer Science, Reykjavik University, Reykjavik, Iceland. [6]Department of Psychology, Reykjavik University, Reykjavik, Iceland. [7]Science Service Center, Kuopio University Hospital, Kuopio, Finland. [8]School of Electrical Engineering and Computer Science, The University of Queensland, Brisbane, Australia. ✉email: purbanka.pahari@nyulangone.org

most commonly utilized in clinical practice[11]. However, the 10-minute in-lab PVT can be considered too long and time-consuming, especially when completed multiple times over a follow-up period (e.g. daily or weekly). Therefore, there is a need for a shorter PVT version, that is easily available to everyone without hospital visits[12]. Although 5-minute and 3-minute PVTs exist, only a few of them are comprehensively validated[8,13]. Therefore, the present study aimed to assess the usefulness of the novel 3-minute PVT (PVT_{SR}) delivered through the Sleep Revolution mobile application[14] by comparing its outcomes to those of the standard 10-minute PVT (PVT_{std}). We hypothesize that the easily accessible and mobile application-based PVT_{SR} can be used as an alternative for longer in-lab PVT versions to estimate impaired vigilance.

Methods

Study design

This study was part of a larger three-month pilot sleep study at Reykjavik University. In the current study, participants (n = 59) were recruited through a local advertisement in Reykjavik between November 2021 and May 2022 (Fig. 1). Before participating in the main sleep study, participants completed a screening questionnaire including an in-depth introduction to the study and then followed by the signing of an informed consent form. After which the researchers contacted and asked them to complete an online questionnaire including information about the participants' background, demographic information, lifestyle, and sleep quality. All questionnaires and the digital informed consent form were collected and managed using REDCap (Research Electronic Data Capture); ergo online[15]. In the next phase, participants arrived at Reykjavik University, where their height and weight were measured, and the participants completed the 10-minute in-lab PVT test (PVT_{std}) on a computer. After the PVT_{std}, a three-night sleep study (Nox A1, Nox Medical, Reykjavik, Iceland) with self-applied polysomnography (SAS) was conducted at participants' homes[16]. During this visit, the participants got access to the Sleep Revolution mobile application to perform the 3-minute PVT test (PVT_{SR}) at home. The participants were instructed to take the PVT_{SR} at mobile application once every week during the three-month follow-up period and thus, they completed multiple PVT_{SR}s during the follow-up. Participants were also instructed to answer the sleep diary twice a day, in the morning and evening every day for the three months. The automated reminders were sent twice per day as a digital nudge through the mobile application (i.e., notification through SR application) to participants to motivate them to complete the diary regularly[17]. The participants were only allowed to answer on the current day to ensure they reported their real-time experience. At the end of the three-month follow-up, 45 participants re-visited the lab at Reykjavik University and completed the second in-lab PVT_{std}. In addition, a few participants were removed (n = 4) due to missing mobile application information and therefore, the final study population consisted of data from the first set of both PVT tests (PVT_{std} and PVT_{SR}) of 41 participants.

The average apnea-hypopnea index (AHI), average oxygen desaturation index (ODI), average arousal index (ArI), and average oxygen saturation (SpO_2) were determined from three-night sleep measurements using Noxturnal version 6.2.2 software (Nox Medical, Reykjavik, Iceland). The participants were divided into three groups based on the obstructive sleep apnea (OSA) severity (healthy: AHI < 5, mild: 5 ≤ AHI < 15, moderate-to-severe: AHI ≥ 15), and PVT outcomes were separately evaluated within each OSA severity group (Fig. 1). The study protocol was approved by the Icelandic National Bioethics Committee (ref. no. 21–070), and participants read and signed an informed consent before their participation. All methods were performed in accordance with relevant guidelines and regulations.

Psychomotor vigilance task (PVT)

Standard in-laboratory PVT (PVT_{std})

During the first visit to Reykjavik University, participants (n=59) completed a 10-minute PVT test (PVT_{std}) on a computer using Inquisit software (Millisecond, Seattle, USA). The visits' Start times were fixed to 10:00 am or 12:00 pm to control the effects of circadian rhythm. The lab conditions were standardized, and a researcher was always present to supervise the participants during the test. Up to two participants took the test simultaneously; participants were shielded from possible visual distractions and wore noise-canceling headphones during the test, and the background of the computer screen was light gray. All participants had similar screen sizes and keyboards, and all the instructions were presented on the screen during the PVT_{std}. The PVT_{std} was set for an 11-minute, however, the first minute was considered a habituation phase for the participants and therefore removed from the calculations. As the PVT_{std} time was fixed to an exact 10-minute test, it included varied number of visual stimuli, about 100-120 (i.e., red stopwatch) occurring at 2–10 s intervals during which the participants were instructed to keep their index finger on the spacebar and tap it as soon as the red stopwatch appeared (Fig. 2). The participants got feedback that lasted for 1000 ms after each response indicating their reaction time or a short error message as 'pressed too early' lasting for 300 ms if they tapped the spacebar before the stimulus appeared.

Sleep revolution mobile application PVT (PVT_{SR})

During the three-month follow-up, participants were asked to complete a 3-minute version of the PVT in the Sleep Revolution mobile application (PVT_{SR}) at home anytime during the day. As there were no restrictions, participants took multiple tests during the follow-up period, however, only the first test was considered for this study. The PVT_{SR} started with a completely black screen, and participants were instructed to tap the touchscreen of their mobile device as fast as possible when the pattern appeared on the screen. Although the PVT_{SR} visual stimuli and the response mode (i.e., spacebar vs. touchscreen) are different than those in PVT_{std}, the foundation of both PVTs is similar. The screen size also varied for each participant based on their mobile device (Fig. 3).

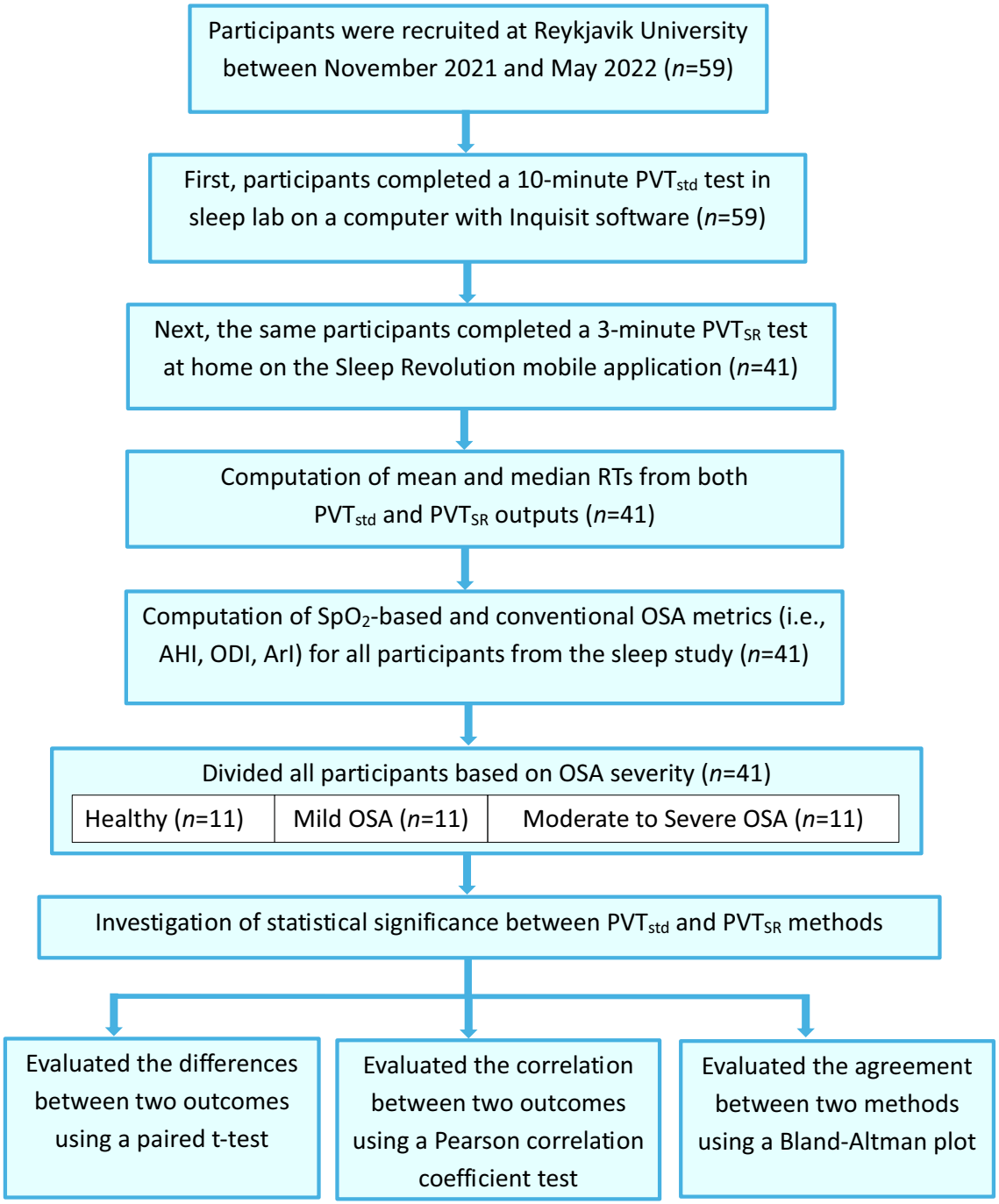

Fig. 1. Flowchart of the study, computed methods, and data division. RT: reaction time; SpO_2: oxygen saturation; OSA: obstructive sleep apnea; AHI: apnea-hypopnea index; ODI: oxygen desaturation index; ArI: arousal index; Healthy: AHI < 5; Mild OSA: 5 ≤ AHI < 15; Moderate-to-Severe OSA: AHI ≥ 15.

Statistical analysis

The mean and median reaction times (RTs) were calculated from both PVT versions and the statistical significance of differences was evaluated with a paired t-test. The Pearson correlation was evaluated between the two methods. The reaction times were used as continuous data during the statistical test. Finally, the Bland-Altman plot[18] was used to illustrate the agreement between the two methods. All calculations and statistical comparisons were performed with MATLAB (R2022b, MathWorks, Natick, MA, USA).

Results

The final study population included 41 participants (56% females), with a mean BMI of 28.7 kg/m^2 (range: 20.0–38.2 kg/m^2) and a mean age of 50.7 years (range: 23.0–74.0 years). 11 participants had no OSA (AHI < 5),

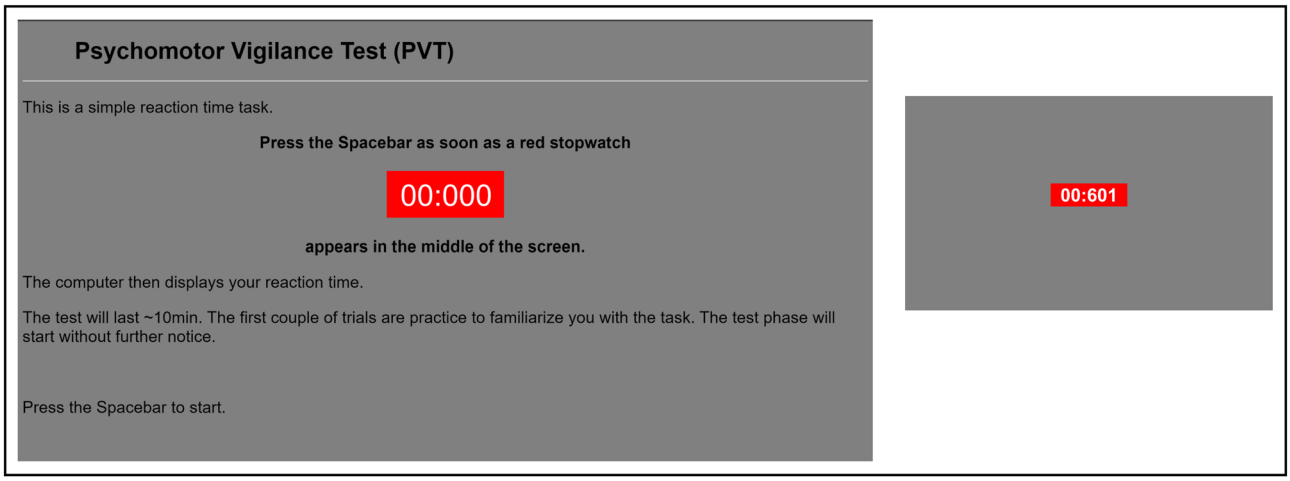

Fig. 2. Screenshot from PVT_{std} study.

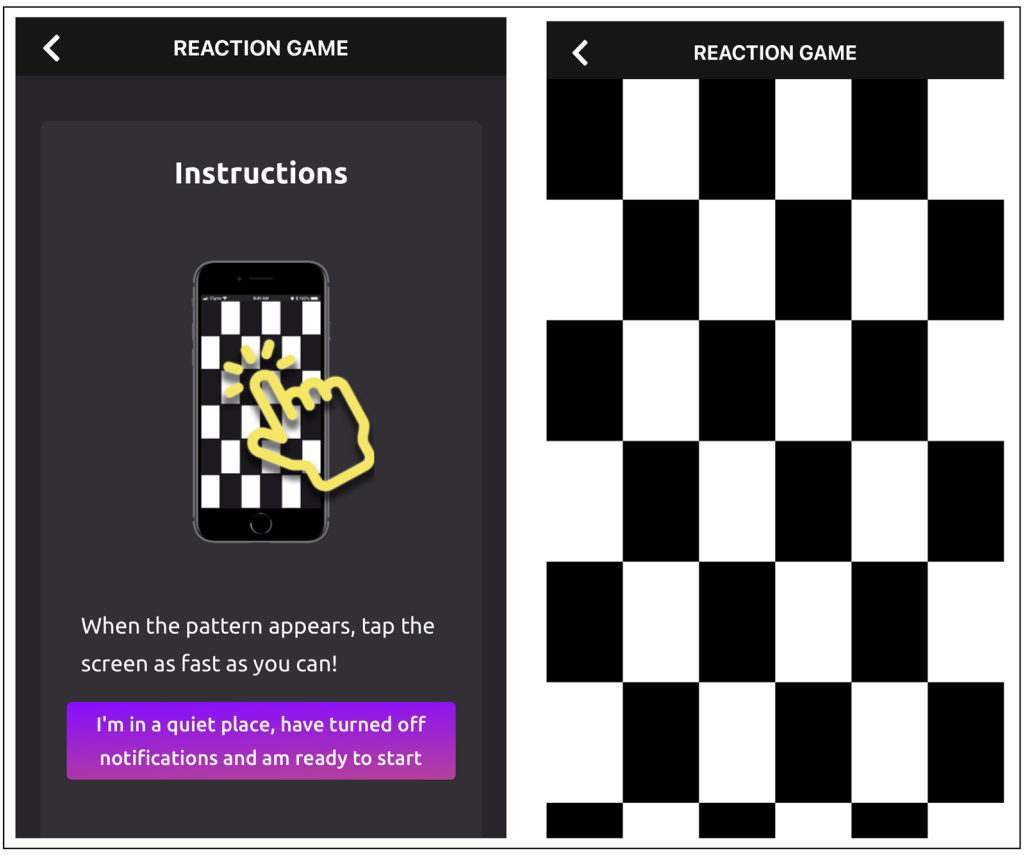

Fig. 3. Screenshot from PVT_{SR} study.

15 participants had mild OSA ($5 \leq AHI < 15$), and the remaining 15 participants belonged to the moderate-to-severe OSA group ($AHI \geq 15$). The mean AHI, ODI, and ArI were 15.4 events/hr, 12.4 events/hr, and 13.6 events/hr, respectively (Table 1).

Among all participants, the average mean RT was significantly shorter in PVT_{std} compared to PVT_{SR} (350.2 ms vs. 424.1 ms, $p = 0.02$, effect size = 0.70, Table 2). Similarly, the average median RT was significantly shorter in PVT_{std} compared to PVT_{SR} (334.4 ms vs. 415.2 ms, $p = 0.01$, effect size = 0.79, Table 2). When participants were divided into OSA severity groups, the mean and median RTs and the difference between PVT_{std} and PVT_{SR} increased as a function of OSA severity (Table 2; Fig. 4). Nevertheless, the findings related to reaction times

Parameters	All ($n=41$, female = 23)
Age (years)	50.7 [23.0–74.0]
Body mass index (BMI) (kg/m^2)	28.7 [20.0–38.2]
Apnea-hypopnea index (AHI) (events/hr)	15.4 [0.4–59.2]
Oxygen desaturation index (ODI) (events/hr)	12.4 [0.0-50.9]
Arousal index (ArI) (events/hr)	13.6 [0.0–31.8]

Table 1. Demographic and polysomnographic information presented as mean [minimum to maximum range].

Parameters	PVT_{std}		PVT_{SR}		T-test	Effect size	Pearson correlation	
	Average [min-max]	SD	Average [min-max]	SD	*p*-value	*d*	*r* [95% CI] *p*-value	
Mean RT (ms)								
All ($n=41$)	350.2 [274.4–815.1]	92.98	424.1 [234.1–1504.7]	188.75	0.02	0.70	0.96 [0.92–0.98]	<0.001
Healthy ($n=11$)	326.4 [274.4-378.3]	40.02	381.7 [234.1–470.5]	74.98	0.04	0.88	0.96 [0.85–0.99]	<0.001
Mild OSA ($n=15$)	350.1 [286.6-451.5]	55.47	415.8 [301.3–572.2]	75.45	0.01	0.96	0.98 [0.94–0.99]	<0.001
Moderate-to-Severe OSA ($n=15$)	367.7 [279.6-815.1]	170.75	463.5 [291.7-1504.7]	365.51	0.01	0.78	0.97 [0.87–0.99]	<0.001
Median RT (ms)								
All ($n=41$)	334.4 [264.5–691.0]	76.95	415.2 [234.1–1504.7]	189.73	0.01	0.79	0.94 [0.89–0.97]	<0.001
Healthy ($n=11$)	315.5 [264.5–371.0]	40.02	372.9 [234.1-461.4]	71.74	0.03	0.95	0.96 [0.85–0.99]	<0.001
Mild OSA ($n=15$)	335.2 [271.0-423.0]	50.77	405.4 [301.3-572.1]	77.17	0.006	1.05	0.98 [0.95–0.99]	<0.001
Moderate-to-Severe OSA ($n=15$)	347.5 [269.0-691.0]	136.93	456.1 [292.9-1504.7]	367.18	0.01	0.79	0.95 [0.79–0.99]	<0.001

Table 2. Results from standard PVT test (PVT_{std}) and PVT test at sleep revolution mobile application (PVT_{SR}) and statistical significance of differences between them. RT: reaction time; OSA: obstructive sleep apnea; SD: standard deviation; CI: confidence interval; healthy: AHI < 5; Mild OSA: 5 ≤ AHI < 15; Moderate-to-Severe OSA: AHI ≥ 15; AHI: apnea-hypopnea index.

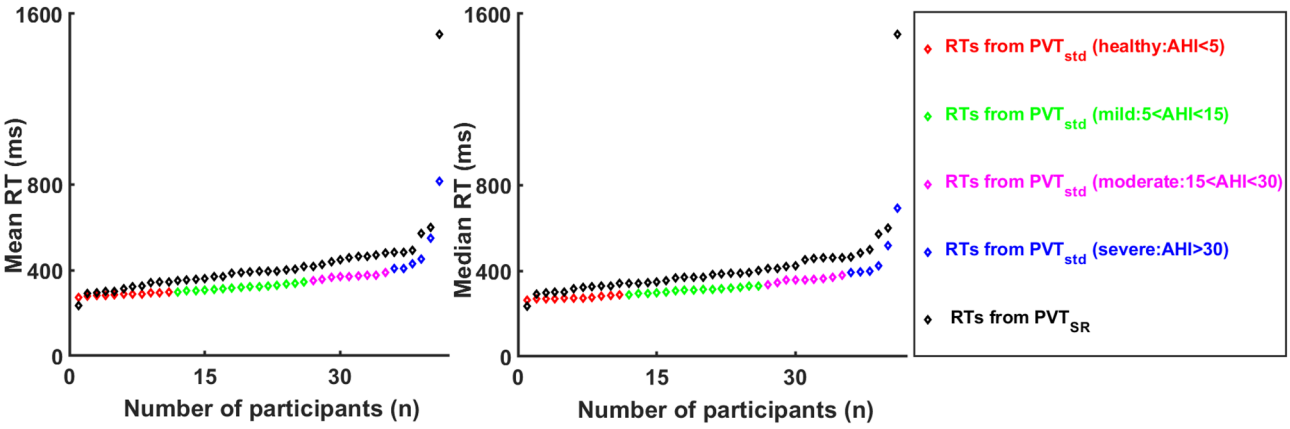

Fig. 4. The mean and median reaction times of each participant in both psychomotor vigilance tests (PVT_{std} and PVT_{SR}) based on their obstructive sleep apnea severity groups. AHI: apnea-hypopnea index, RT: reaction time.

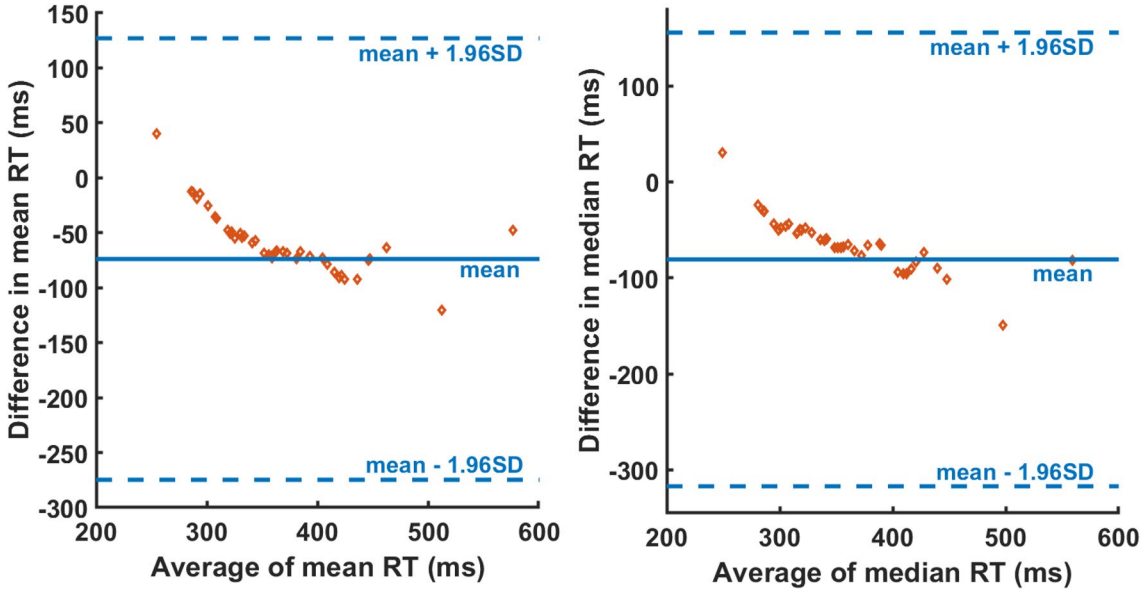

Fig. 5. Bland Altman plot for psychomotor vigilance tests (PVTs). Differences were calculated as PVT_{std} – PVT_{SR}. RT: reaction time, SD: standard deviation.

between the two PVTs were similar in all OSA severity groups; reaction times were systematically shorter in PVT_{std} compared to PVT_{SR} (Table 2; Fig. 4).

Among all participants, the Pearson correlation coefficient between the two methods was very high for both mean RT ($r = 0.96$, $p < 0.0001$) and median RT ($r = 0.94$, $p < 0.0001$). In the Bland-Altman plot, the differences in the RTs were rather close to the mean indicating a strong agreement between the two methods and further supporting the correlation between the two methods (Fig. 5). However, systematic and proportional errors were observed. The difference between two PVTs increased when the reaction time increased (Fig. 5). When participants were grouped based on OSA severity, the correlation between the two methods remained high ($r = 0.95$–0.98) for both median and mean RTs (Table 2).

Discussion

In this study, we aimed to study the differences in median and mean reaction times between the 10-minute-based standard PVT_{std} and the 3-minute-based mobile application-based PVT_{SR}. We observed that the median and mean RTs were always 50–70 ms longer on average in the PVT_{SR} compared to the PVT_{std}. The novel PVT_{SR} method, despite showing significantly longer median and mean RTs compared to PVT_{std}, demonstrated a statistically significant correlation with PVT_{std}.

The systematically higher RTs in PVT_{SR} than PVT_{std} could be due to multiple reasons. First, participants needed to tap the spacebar on the keyboard in the PVT_{std}. In contrast, participants were required to tap on the touchscreen in the mobile application (PVT_{SR}), and tapping on a mobile touchscreen might take longer than tapping on a keyboard[19]. Second, the PVT_{std} test was conducted in a calm, silent laboratory setting, whereas the PVT_{SR} was performed in a more comfortable and relaxed home environment, which, being rich in stimuli, may have been more distracting and contributed to longer reaction times[20]. In addition, there was no control for what finger particiapnts use; previous study also showed that using the index finger to tap resulted in the fastest task completion time compared to all other fingers[19]. Third, another key difference between the standard PVT and the SR app is that the PVT_{std} provides live feedback (e.g., a timer display), which the PVT_{SR} app lacks; this absence may affect engagement and performance, potentially contributing to longer reaction times. Therefore, other factors, such as device screen size and thumb or index finger use, feedback differences could account for longer response time in PVT_{SR}.

Our results align with an earlier study, which reported that the response times are longer in a 3-minute PVT than in a 10-minute PVT[12]. However, when they corrected the systematic error by a scaling factor of 0.75, the response times became similar to the standard 10-minute PVT test[12]. Although we did not include scaling factors in our results, we also investigated with adjusted scaling factors to observe whether that makes any difference in PVT_{SR} response time. We adjusted our results with a scaling factor of 0.70, which makes the difference between the response time of PVT_{std} and PVT_{SR} small. For instance, the mean reaction time for all participants in PVT_{std} was 350.2 ms, and after adding a scaling factor of 0.70, the mean reaction time for all participants in PVTSR decreased to 349.1 ms. The response time for PVT_{SR} for the OSA severity groups became ± 10 ms less than in PVT_{std}. Thus, systematic delays or device errors in sleep revolution applications can also be a reason for longer PVT_{SR} response times in our analysis. We also observed that the agreement between the PVTs deteriorated along worsening OSA severity. The difference between the two PVTs in median RTs was 57.4 ms in healthy participants, while the difference increased to 70.2 ms in mild and further to 108.6 ms in participants with moderate to severe OSA (Table 2). The Bland-Altman plot (Fig. 5) shows that the discrepancy between

the two methods increasesfor participants with higher reaction times. This pattern suggests that the methods diverge more as reaction times get longer, which could be important when interpreting results or choosing a measurement method for participants who tend to have lower vigilance. However, despite these increases in differences in RTs the correlation between the two PVTs for all groups was high and the pattern of increased RTs with increased OSA severity was captured well with both PVT tests.

In general, the present results indicate that our PVT_{SR} method is adequate for measuring vigilance and capturing the pattern of increased response time due to the progression of OSA severity similar to the standard PVT. Moreover, the test is available through any smartphone, which makes its usage easy and cost-effective, allowing, e.g., measurements among larger patient groups, estimation of changes in vigilance over time, and following how OSA treatment affects vigilance. Importantly, the PVT_{SR} is not intended to replace the standard in-lab PVT but rather to expand its applicability and enable long-term follow-up monitoring of vigilance. It can also guide individuals to keep track of their habitual sleep behaviors on their path to optimal sleep health[2].

Our study had a few limitations to acknowledge. First, the PVT_{std} was performed at the lab, while PVT_{SR} was performed in a home environment. For instance, while the in-lab PVT was more controlled, the PVT_{SR} test was not restricted to any specific time, space, or environment[20]. Participants could have taken the test anytime during the week and multiple times during the study period. Secondly, the PVT methods differed; PVT_{std} involved keyboard tapping, while PVT_{SR} used mobile screen tapping, and only PVT_{std} provided live feedback to the participants. These factors can impact the reaction times determined by using the two different methods for PVTs. In addition, we had limited information on whether there was a delay due to the test administration hardware and software platforms in the Sleep Revolution application, and thus, we did not assess any system delay in the PVT_{SR}. System delays or device errors can affect reaction times[12], and this fact might have also impacted the present analysis. Lastly, the errors and systematic discrepancies between the two methods warrant further investigation. Consequently, it is premature to confidently assert that the proposed method can fully replace the structured laboratory test. Nevertheless, our objective was not to replace the standard method, but the proposed approach appears promising and enables conducting the PVT multiple time over longer period which would be infeasible with the laboratory test. However, the test warrants further exploration, ideally with a larger sample size and more comprehensive statistical analyses beyond mean and median evaluations. Moreover, despite the differences, our objective was to study the participants' performance in both PVT_{std} and PVT_{SR} and investigate if the novel mobile application-based method can detect deterioration of vigilance.

Conclusions

Despite observed systematic and proportional errors, the novel PVT_{SR} method demonstrated a strong correlation with the standard PVT. Future studies could mitigate these errors by estimating systematic delays. As a quick, three-minute mobile application-based test accessible for home use, PVT_{SR} effectively captured the decline in daytime vigilance related to OSA severity, underscoring its potential for long-term monitoring of impaired vigilance.

Data availability

The data include participants' personal information and medical records; therefore, the data can only be shared within the confinements of the Iceland legislation and ethical conventions. Dr. Anna Sigridur Islind should be contacted for the data-sharing request. Reasonable requests concerning data sharing will be individually assessed.

Received: 24 March 2025; Accepted: 4 October 2025
Published online: 07 November 2025

References

1. Laval, U., City, Q., Morin, C. M. & Benca, R. Chronic insomnia. *www.thelancet.com* **379**, 1129–1170. https://doi.org/10.1016/S0140 (2012).
2. Batool-Anwar, S. et al. Obstructive sleep apnea and psychomotor vigilance task performance. *Nat. Sci. Sleep.* **6**, 65. https://doi.org/10.2147/NSS.S53721 (2014).
3. Ferini-Strambi, L., Lombardi, G. E., Marelli, S., Galbiati, A. & Address, M. Neurological deficits in obstructive sleep apnea. *Curr. Treat. Options Neurol.* **19**, 16. https://doi.org/10.1007/s11940-017-0451-8 (1940).
4. Barbe, F. et al. Automobile accidents in patients with sleep apnea syndrome. *Am. J. Respir. Crit. Care Med.* **158**, 18–22. https://doi.org/10.1164/AJRCCM.158.1.9709135 (1998).
5. Brookings, J. B., Wilson, G. F. & Swain, C. R. Psychophysiological responses to changes in workload during simulated air traffic control. *Biol. Psychol.* **42** (3), 361–377. https://doi.org/10.1016/0301-0511(95)05167-8 (1996).
6. Cassel, W. et al. Risk of traffic accidents in patients with sleep-disordered breathing: reduction with nasal CPAP. *Eur. Respir. J.* **9**, 12 (1996).
7. Parasuraman, R., Warm, J. S. & Dember, W. N. Vigilance: taxonomy and utility. *Ergon. Hum. Factors: Recent Res.* **1987**, 11–32. https://doi.org/10.1007/978-1-4612-4756-2_2 (1987).
8. Basner, M., Mcguire, S., Goel, N., Rao, H. & Dinges, D. F. A new likelihood ratio metric for the psychomotor vigilance test and its sensitivity to sleep loss. *J. Sleep Res.* **24**, 702–713. https://doi.org/10.1111/jsr.12322 (2015).
9. Lee, I. S., Bardwell, W. A., Ancoli-Israel, S. & Dimsdale, J. E. Number of lapses during the psychomotor vigilance task as an objective measure of fatigue. *J. Clin. Sleep. Med.* **6** (2), 163. https://doi.org/10.5664/jcsm.27766 2010).
10. Dinges, D. F. & Powell, J. W. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behav. Res. Methods Instrum. Comput.*. **17** (6), 652–655 (1985).
11. Belenky, G. et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. *J. Sleep Res.* **12**, 1–12. https://doi.org/10.1046/j.1365-2869.2003.00337.x (2003).
12. Grandner, M. A., Watson, N. F., Kay, M., Ocaño, D. & Kientz, J. A. Addressing the need for validation of a touchscreen psychomotor vigilance task: important considerations for sleep health research. https://doi.org/10.1016/j.sleh.2018.08.003 (2018).

13. Loh, S., Lamond, N., Dorrian, J., Roach, G. & Dawson, D. The validity of psychomotor vigilance tasks of less than 10-minute duration. *Behav. Res. Methods Instrum. Comput.* **36**, 339–346. https://doi.org/10.3758/BF03195580 (2004).
14. Sveinbjarnarson, B. F., Schmitz, L., Arnardottir, E. S. & Islind, A. S. *The Sleep Revolution Platform: a Dynamic Data Source Pipeline and Digital Platform Architecture for Complex Sleep Data* (Springer Science and Business Media, 2013). https://doi.org/10.1007/s40675-023-00252-x.
15. Harris, P. A. et al. Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *J. Biomed. Inform.* **42**, 377–381. https://doi.org/10.1016/J.JBI.2008.08.010 (2009).
16. Rusanen, M. et al. Self-applied somnography: technical feasibility of electroencephalography and electro-oculography signal characteristics in sleep staging of suspected sleep-disordered adults. *J Sleep. Res.* https://doi.org/10.1111/jsr.13977 (2023).
17. Schmitz, L., Richert, E., Arnardottir, E. S. & Islind, A. S. *Nudging with Dignity: a Critical Examination of When and How to Use Digital Nudging* (Springer, 2024).
18. Bland, J. M. & Altman, D. G. *Statistical Methods For Assessing Agreement Between Two Methods of Clinical Measurement* (Wiley, 2024).
19. Asakawa, D. S., Dennerlein, J. T. & Jindrich, D. L. Index finger and thumb kinematics and performance measurements for common touchscreen gestures. *Appl. Ergon.* **58**, 176–181. https://doi.org/10.1016/j.apergo.2016.06.004 (2017).
20. Evans, G. W. (ed) *Environmental Stress* 25 (CUP Archive, 1984).

Author contributions

P.P. contributed to the study design, data analysis, and interpretation of the results, and wrote the first draft of the manuscript. L.S., E.R., K.R.J, and H.K. contributed to the data collection of the study and writing of the manuscript. H.K., J.T., T.L., and S.N. contributed to the data interpretation and writing of the manuscript. E.S.A. and A.S.I. contributed to the design of the mobile application, study design, data collection, data interpretation, and writing of the manuscript. All authors have reviewed the manuscript critically and accepted the latest version to be submitted.

Funding

This work was funded by the European Union's Horizon 2020 Research and Innovation Programme (grant 965417), the Icelandic Research Fund, the Research Committee of the Kuopio University Hospital Catchment Area for the State Research Funding (projects 5041767, 5041794, 5041805, and 5041803), and the Respiratory Foundation of Kuopio Region and Respiratory Diseases Research Foundation.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to P.P.