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PC-PVT 2.0: An updated platform for psychomotor vigilance task testing, analysis, prediction, and visualization

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HIGHLIGHTS

- Free software for PVT analysis, prediction, and visualization in a Windows 10 PC.
- Average delay of less than 10 ms with the recommended hardware configuration.
- Real-time, individualized PVT predictions for any sleep and caffeine schedule.

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ABSTRACT

Background: The psychomotor vigilance task (PVT) has been widely used to assess the effects of sleep deprivation on human neurobehavioral performance. To facilitate research in this field, we previously developed the PC-PVT, a freely available software system analogous to the "gold-standard" PVT-192 that, in addition to allowing for simple visual reaction time (RT) tests, also allows for near real-time PVT analysis, prediction, and visualization in a personal computer (PC).
New method: Here we present the PC-PVT 2.0 for Windows 10 operating system, which has the capability to couple PVT tests of a study protocol with the study's sleep/wake and caffeine schedules, and make real-time individualized predictions of PVT performance for such schedules. We characterized the accuracy and precision of the software in measuring RT, using 44 distinct combinations of PC hardware system configurations.
Results: We found that 15 system configurations measured RTs with an average delay of less than 10 ms, an error comparable to that of the PVT-192. To achieve such small delays, the system configuration should always use a gaming mouse as the means to respond to visual stimuli. We recommend using a discrete graphical processing unit for desktop PCs and an external monitor for laptop PCs.
Comparison with existing method: This update integrates a study's sleep/wake and caffeine schedules with the testing software, facilitating testing and outcome visualization, and provides near-real-time individualized PVT predictions for any sleep-loss condition considering caffeine effects.
Conclusions: The software, with its enhanced PVT analysis, visualization, and prediction capabilities, can be freely downloaded from https://pcpvt.bhsai.org.

1. Introduction

Previously, we developed the PC-PVT, a freely available package for psychomotor vigilance task [PVT; (Dinges and Powell, 1985)] testing, analysis, prediction, and visualization in a personal computer (PC) for Windows 7 operating system (OS) (Khitrov et al., 2014). Beyond cost, the PC-PVT offers a number of benefits over specialized stand-alone devices as in the "gold standard" PVT-192 [Ambulatory Monitoring Inc., Ardsley, NY (Dinges and Powell, 1985)]: ease of use; testing and analysis integrated into a single system, which minimizes the potential for data loss or corruption because it eliminates the need for manual transfer of records from a data-collection device to a PC for analysis; incorporation of advanced analytical tools, such as real-time individualized performance prediction models; the ability to visualize PVT results immediately after each test; and simplified data storage, organization, and export tasks. Importantly, we demonstrated that

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the PC-PVT could serve as a viable replacement for the PVT-192, because when we compared the accuracy and precision in reaction time (RT) tests between the two systems, the discrepancies [mean latency and standard deviation (SD): ∼8.0 ms (SD = 1.7 ms) for the PC-PVT vs. 3.4 ms (SD = 0.8 ms) for the PVT-192 (Khitrov et al., 2014)] were well below the threshold of clinical and operational significance (Belenky et al., 2003).

To date, the PC-PVT has been accessed more than 1850 times by users in 72 countries, and over the last two years it has been used in 15 published studies (Arnal et al., 2015; Ashton et al., 2017; Azizan et al., 2016a,b; Doty et al., 2017; Huffmyer et al., 2016; Lee and Finkelstein, 2015; Morasch et al., 2015; Morris and Pilcher, 2016; Price, 2017; Roelen and Stuut, 2016; Thompson et al., 2016; Van Auken et al., 2017; Yuda et al., 2017a,b). Here, we describe the PC-PVT 2.0 for Windows 10 OS, which, in addition to an OS upgrade, has four key new functionalities: *1*) the ability to import sleep and caffeine schedules of a study protocol from Microsoft Excel directly into the PVT-testing software, integrating the testing within the study's schedules, *2*) the ability to assign different sleep and caffeine schedules to the same subject in a study, to represent the subject's involvement in different arms of a study, *3*) the ability to generate individualized predictions of performance on the PVT for *any* sleep/wake schedule, while accounting for the effects of caffeine, and *4*) the ability, after each test, to automatically visualize sleep/wake and caffeine schedules, along with PVT measurements and individualized predictions.

In the original version, as in the PVT-192, a study's sleep and caffeine schedules are not inputs to the system. This decoupling of the study schedule from the actual PVT tests requires the user to create a "new" study (or an alternative subject identifier) when the same subject takes part in different arms of a study (e.g., when the same subject is challenged twice with total sleep deprivation [TSD], with and without caffeine consumption). The decoupling also prevents the system from performing consistency checks, for example, to assure that PVT data can only be collected during wakefulness. In addition, the original version of the system uses a now-outdated model that can only predict the effects of TSD challenges, precluding predictions of the most common form of sleep loss, chronic sleep restriction (CSR), and lacking the ability to account for the restorative effects of caffeine on neurobehavioral performance. Finally, the updated software allows for visualization of Microsoft Excel-imported sleep/wake periods as well as caffeine intervention time points for both TSD and CSR challenges, which was not previously possible.

In addition, because any change that affects video rendering, timers, or mouse input may affect PVT RT results, we could not determine in advance how the Windows 10 OS would affect the PVT results. To assess the potential impact of the new OS on RTs, we tested 44 distinct PC hardware system configurations to provide specific hardware recommendations that lead to delays of less than 10 ms.

2. Materials and methods

2.1. System description

We updated the PC-PVT 2.0 software to run on Windows 10 OS. Briefly, the software architecture consists of two separate applications, the Manager and the Tester. The Manager is used to create and configure testing protocols, enter subject information, export data, and access PVT data analyses and predictions (Fig. 1A). By clicking "Create" in the "Active Study" panel, users can configure the testing protocol and import sleep and caffeine schedules from an Excel file (Fig. 1B), and by clicking "Create" in the "Subjects" panel, users can enter subject information and assign the corresponding arm of the imported schedule (Fig. 1C). Double-clicking a subject ID in Fig. 1A displays the analysis window (Fig. 2), which shows PVT data and individualized model predictions superimposed over the sleep/wake and caffeine schedules.

The Tester is used by the subject to perform PVT testing sessions, and closely duplicates the functionality of the PVT-192, except for the use of a gaming computer mouse to respond to visual stimuli.

2.2. Individualized prediction model

The original PC-PVT allows for individualized predictions in studies where subjects are challenged by TSD, but not for those in the more prevalent CSR condition. In addition, its inability to account for the restorative effects of caffeine on PVT performance precludes predictions of the effects of the most widely used stimulant and, therefore, limits the use of the prediction component of the software in studies designed to represent real-world conditions.

We have updated the prediction model to eliminate these limitations. The individualized prediction model in the PC-PVT 2.0 software incorporates the latest capabilities of the Unified Model of Performance [UMP; (Liu et al., 2017)], which were developed after the publication of the original PC-PVT. This includes the capability to automatically learn, nearly in real time, an individual's trait-like response to sleep loss under *any* sleep-deprivation challenge, as well as the ability to account for the restorative effects of caffeine on PVT performance. After each PVT test, the software uses the most recent test data to update the UMP model parameters so that predictions match the PVT results. This process is repeated after each test of a study protocol, as the model progressively learns the subject's response to sleep loss with improving accuracy, yielding a fully individualized model after approximately 25 PVT tests (Liu et al., 2017). Visualization of the individualized model predictions for the entire duration of the protocol after each PVT test allows investigators to assess future alertness levels of each subject, as the study progresses. The UMP has been validated using data from more than 400 subjects in 14 studies, involving 24 distinct sleep-loss conditions (including both TSD and CSR challenges) and 9 caffeine regimens (including both single and repeated caffeine doses, ranging from 100 to 600 mg) (Ramakrishnan et al., 2016a; Ramakrishnan et al., 2016b). It has also been used as the core modeling framework for the *2B-Alert* Web, a freely available Web tool to compare and contrast the effects of different sleep-loss and caffeine schedules on performance in a group of subjects (Reifman et al., 2016).

2.3. Latency characterization

We used the RTBox (Li et al., 2010) as the measuring device to assess the extent to which the accuracy and precision of RTs from the PC-PVT 2.0 matched those of the PVT-192, and the extent to which they varied for different PC hardware system configurations. The RTBox has submillisecond precision and allows for human-factor-independent assessment, because in the experimental setup we considered the difference between the RTs measured by the RTBox (the true value) and by the PC-PVT 2.0, as well as the difference between those measured by the RTBox and by the PVT-192 (Khitrov et al., 2014).

Fig. 3 shows the experimental setup to simultaneously measure RTs in the RTBox and the PC-PVT installed in a given PC hardware system configuration. To simultaneously measure RTs, we placed a light sensor on the PC monitor to detect stimulus onset and a button sensor inside the PC mouse's left button to detect the response made to the stimulus by a human operator. The two sensors are connected to the RTBox, and the monitor and mouse are connected to the PC. Hence, when a stimulus is presented on the monitor and a human operator responds to it by pressing the mouse's left button,

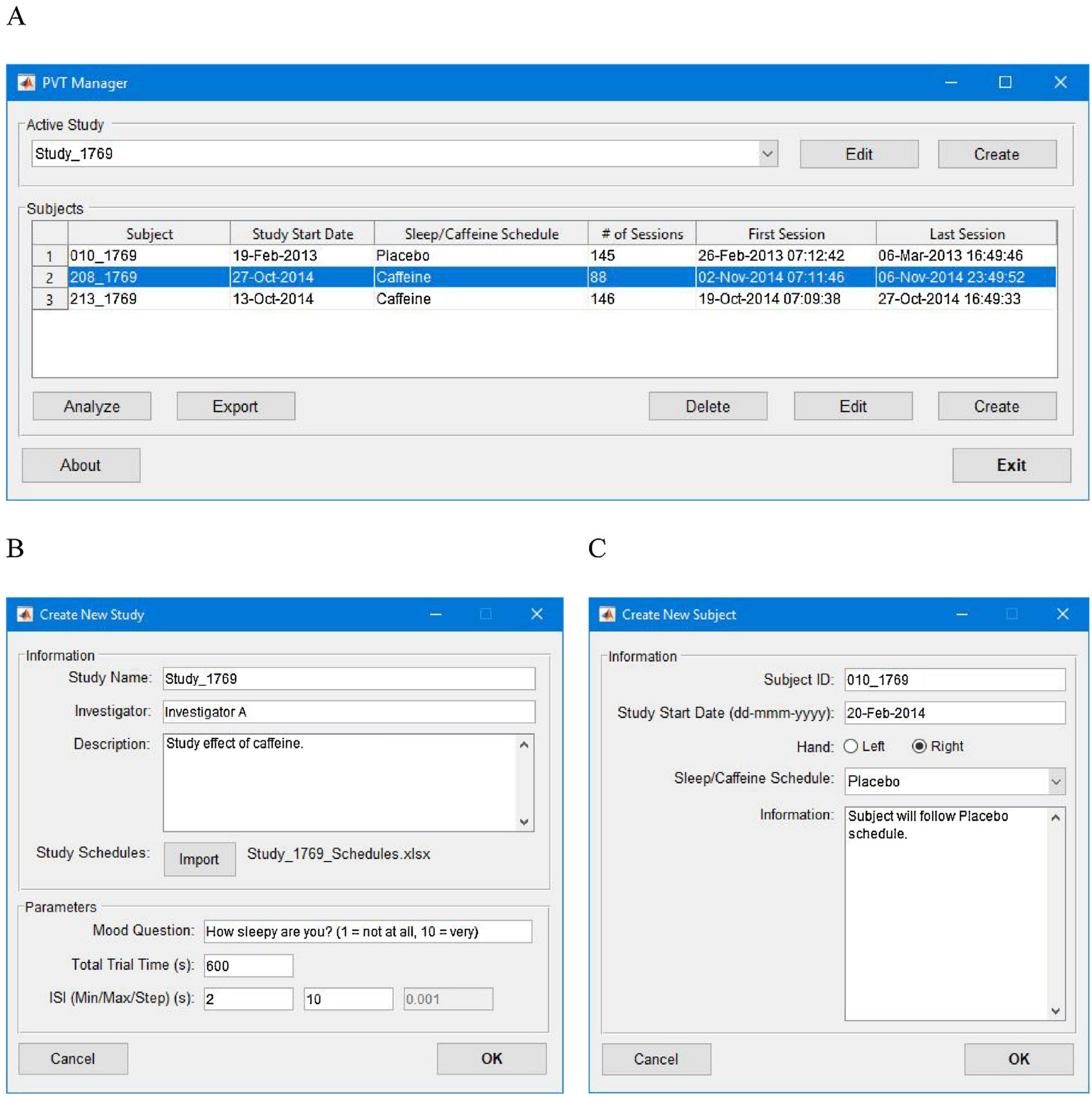

Fig. 1. The Main Manager window. The main PVT Manager window (A) displays the currently active study name and a list of its subjects. Clicking the "Create" button in the "Active Study" panel opens the Create New Study window (B), where a new study is defined and selected as the currently active study. Subjects are added to the current study by clicking the "Create" button in the "Subjects" panel, which opens the Create New Subject window (C). The list of subjects in the PVT Manager (A) shows their assigned sleep/caffeine schedule, as defined in the Create New Subject window (C). It also shows session information to provide an overview of the progress that each subject is making through the study protocol. The buttons below the list of subjects allow for the analysis and export of PVT data and for the management of subjects.

the PC-PVT software computes its RT (t'_2−t'_1) as does the RTBox (t_2−t_1), using its internal clock. The difference between the two RTs provides an estimate of the hardware delay for the tested PC configuration, which is not affected by the human operator. (See Khitrov et al., 2014 for additional information.)

We tested the PC-PVT 2.0 using Windows 10 Enterprise (64-bit) on 10 different Dell, Lenovo, Hewlett Packard, and Apple computers (four desktops and six laptops) produced between 2010 and 2017, including low- and high-end systems using graphical processing units (GPUs) from Intel, NVIDIA, or AMD, built-in or external monitors, and a Dell standard mouse or Logitech G203 Prodigy gaming mouse. We did not test built-in laptop mousepads or buttons because there was no reliable way of attaching the RTBox button-press sensor to these components.

3. Results

We conducted a broad range of experiments (45 in total), where we compared the RTBox against the PVT-192 and against the PC-PVT 2.0 in 44 distinct combinations of PC hardware system configurations (computing device, GPU, monitor, and mouse). Each experiment consisted of 25 min of data collection (5 sessions of 5 min each) per system, covering a wide range of RTs (from ∼160 ms to ∼2500 ms). To obtain the delay of each hardware system (PVT-

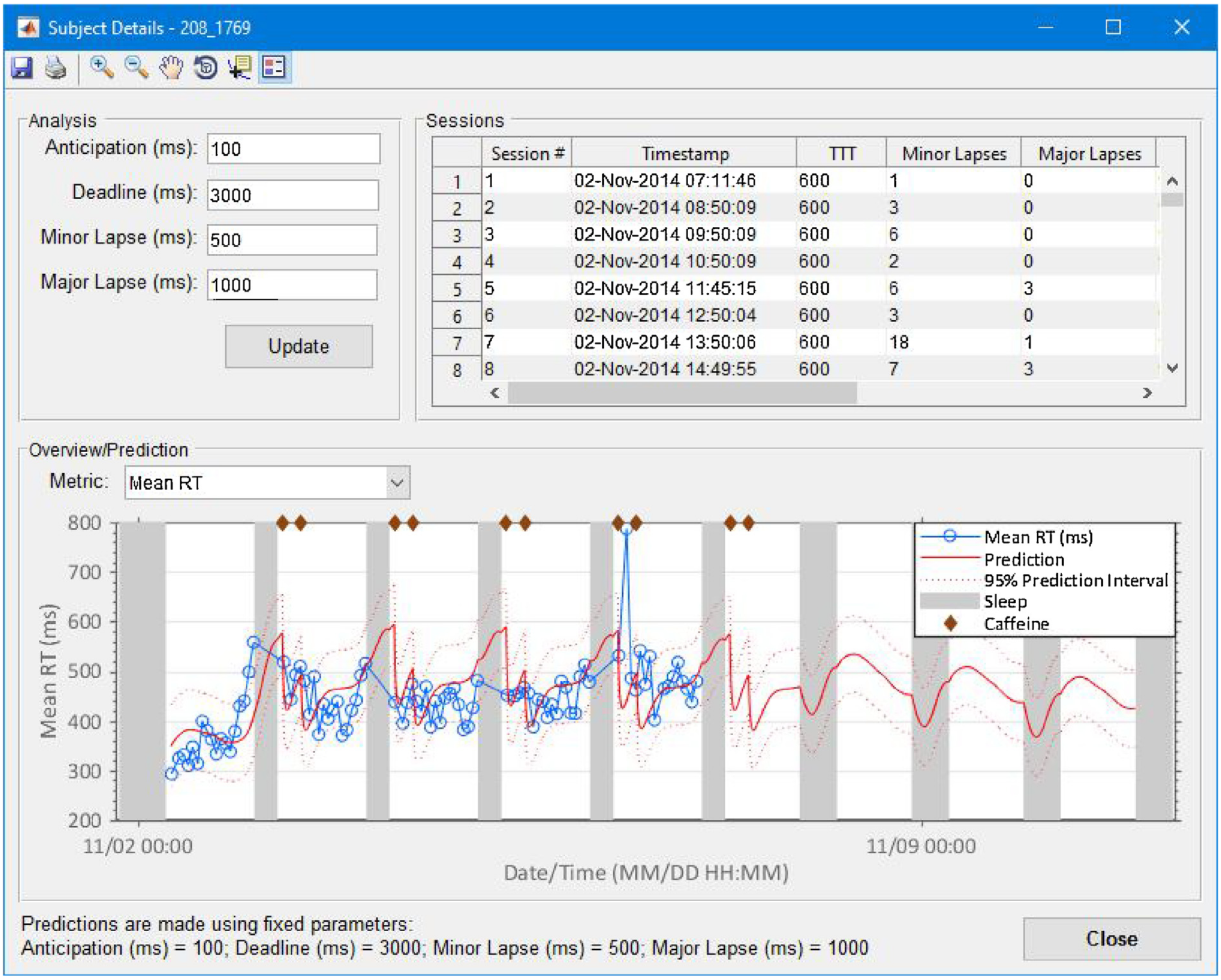

Fig. 2. The Subject Details window displays session data and predictions for a single subject. The "Analysis" panel (top left) is used to configure PVT-dependent parameters. The "Sessions" panel (top right) lists each completed PVT session for the given subject, including the time stamp, configuration parameters, and computed statistics. The "Overview/Prediction" panel (bottom) displays a plot of the currently selected summary statistics (in the example shown, the mean RT, based on the parameters defined in the "Analysis" panel, as appropriate) and outputs from the individualized prediction algorithm (based on the subject's sleep/caffeine schedule and all available PVT data). RT: response time; TTT: total trial time, in seconds.

192 or PC-PVT 2.0 configuration) relative to that of the RTBox, we subtracted the RTs recorded by the RTBox (which measures the true RT with 0.1-ms accuracy) from those recorded by the tested system (see Fig. 3 and Khitrov et al., 2014).

Table 1 shows the 44 combinations of tested PC hardware system configurations, along with their testing results and those for the PVT-192, sorted in ascending order of mean delay over the 25-min data collection period of each experiment relative to the RTBox. All systems exhibited measurement delay, with the PVT-192 yielding the smallest mean delay (4.7 ms) and laptops with a built-in monitor using a standard mouse yielding some of the largest mean delays (from 25.0 to 50.6 ms).

4. Discussion

The PC-PVT 2.0 testing results showed that, while certain hardware components are needed to achieve small latencies, their presence alone does not guarantee such results, because delays seem to depend on more than a single hardware component of a system, where such dependencies can also be manufacturer-specific. Nevertheless, certain hardware configurations resulted in general trends in the testing results, where the use of specific combinations of hardware components consistently assured accuracy (i.e., mean errors) of less than 10 ms, which is comparable to the 4.7-ms delay observed in the PVT-192. Consistent with our previous results (Khitrov et al., 2014), we found that the use of a gaming mouse is necessary to obtain small errors. Each of the 15 configurations with mean errors of less than 10 ms used a gaming mouse (Table 1). Of those, four were desktops, where each used a discrete GPU (AMD or NVIDIA), and eight of the 11 laptops used an external monitor. However, when the only difference in a laptop configuration was the monitor, laptops with an external monitor consistently outperformed those with built-in monitors; the only exception was the Apple MacBook Pro. From this, we make the general recommendation of using laptops with external monitors, which are known to have low input lag (ideally <10 ms). In terms of the precision of the tested hardware configurations, we observed that the average SD over the 22 configurations that used a gaming mouse was ~0.6 ms, supporting the reproducibility of our results when using a high-end computer mouse.

The average delay of 8.5 ms for the top 15 configurations in Table 1 corresponds to a relative error of ~3.5%, assuming an average RT of 240 ms (SD = 29 ms) in sleep-satiated individuals (Rupp et al., 2012). This is similar to the ~2.0% (4.7 ms) error observed with the PVT-192. In any case, these errors are considerably smaller than the intra-subject RT variability of ~29 ms and their fraction

Table 1
Hardware delay statistics, sorted by mean delay time in ascending order. The mean values represent the average differences between reaction times measured by the hardware system and the RTBox (see Fig. 3) over five, 5-min PVT tests.

Device	Type	Year	CPU (Intel Core)	GPU	Monitor	Mouse	Mean (ms)	*SD* (ms)
PVT-192	E	2010	n/a	n/a	n/a	n/a	4.7	1.2
Dell Optiplex 7050	D	2017	i7-6704	Quadro P1000[b]	External	G	5.4	0.6
Apple MacBook Pro	L	2015	i7-4980HQ	Radeon R9 M370X[a]	Built-in	G	6.9	0.5
Dell Latitude 5280	L	2017	i5-7300U	HD 620[c]	External	G	7.3	0.5
Lenovo Legion Y520	L	2017	i7-7700HQ	GeForce 1050 Ti[b]	External	G	8.3	0.5
Dell Precision M4800	L	2014	i7-4900MQ	Quadro K2100 M[b]	External	G	8.4	0.4
HP Envy Notebook	L	2017	i7-7500U	HD 620[c]	External	G	8.5	0.6
Dell Optiplex 9010	D	2013	i7-3770	Radeon HD 7470[a]	External	G	8.5	0.4
Dell Precision M4800	L	2014	i7-4900MQ	HD 4600[c]	External	G	8.6	0.6
Dell Precision M4500	L	2010	i5-540M	Quadro FX 880 M[b]	External	G	8.6	0.7
Lenovo Legion Y520	L	2017	i7-7700HQ	HD 630[c]	External	G	9.2	0.9
Dell Precision M4800	L	2014	i7-4900MQ	Quadro K2100 M[b]	Built-in	G	9.3	0.4
Dell Precision M4500	L	2010	i5-540M	Quadro FX 880 M[b]	Built-in	G	9.3	1.1
Dell Optiplex 9020	D	2015	i7-4790	Radeon R5 240[a]	External	G	9.4	0.4
Dell Optiplex 7040	D	2016	i7-6701	Quadro P1000[b]	External	G	9.5	0.5
Apple MacBook Pro	L	2015	i7-4980HQ	Radeon R9 M370X[a]	External	G	9.9	0.5
Dell Optiplex 7040	D	2016	i7-6700	HD 530[c]	External	G	23.3	0.5
Dell Optiplex 7050	D	2017	i7-6703	HD 530[c]	External	G	23.6	0.5
Dell Precision M4800	L	2014	i7-4900MQ	HD 4600[c]	Built-in	G	24.2	1.0
Lenovo Legion Y520	L	2017	i7-7700HQ	GeForce 1050 Ti[b]	External	S	24.9	2.9
Apple MacBook Pro	L	2015	i7-4980HQ	Radeon R9 M370X[a]	Built-in	S	25.0	2.4
Dell Precision M4800	L	2014	i7-4900MQ	HD 4600[c]	External	S	25.2	2.4
Dell Latitude 5280	L	2017	i5-7300U	HD 620[c]	External	S	25.6	2.4
Lenovo Legion Y520	L	2017	i7-7700HQ	HD 630[c]	External	S	25.6	2.7
Dell Precision M4800	L	2014	i7-4900MQ	Quadro K2100 M[b]	External	S	25.9	2.0
Dell Precision M4800	L	2014	i7-4900MQ	Quadro K2100 M[b]	Built-in	S	26.0	2.3
HP Envy Notebook	L	2017	i7-7500U	HD 620[c]	External	S	26.2	2.6
Dell Optiplex 7040	D	2016	i7-6701	Quadro P1000[b]	External	S	26.4	2.4
Dell Precision M4500	L	2010	i5-540M	Quadro FX 880 M[b]	Built-in	S	26.5	2.5
Dell Optiplex 7050	D	2017	i7-6704	Quadro P1000[b]	External	S	26.5	2.4
Dell Precision M4500	L	2010	i5-540M	Quadro FX 880 M[b]	External	S	26.6	2.6
Apple MacBook Pro	L	2015	i7-4980HQ	Radeon R9 M370X[a]	External	S	26.8	2.2
Dell Optiplex 9010	D	2013	i7-3770	Radeon HD 7470[a]	External	S	26.9	2.3
Dell Optiplex 9020	D	2015	i7-4790	Radeon R5 240[a]	External	S	26.9	2.4
Dell Latitude 5280	L	2017	i5-7300U	HD 620[c]	Built-in	G	28.0	0.5
HP Envy Notebook	L	2017	i7-7500U	HD 620[c]	Built-in	G	28.8	0.6
Lenovo Legion Y520	L	2017	i7-7700HQ	GeForce 1050 Ti[b]	Built-in	G	31.6	0.5
Lenovo Legion Y520	L	2017	i7-7700HQ	HD 630[c]	Built-in	G	34.1	0.5
Dell Optiplex 7040	D	2016	i7-6700	HD 530[c]	External	S	40.7	2.4
Dell Optiplex 7050	D	2017	i7-6703	HD 530[c]	External	S	41.5	2.3
Dell Precision M4800	L	2014	i7-4900MQ	HD 4600[c]	Built-in	S	42.8	2.4
Dell Latitude 5280	L	2017	i5-7300U	HD 620[c]	Built-in	S	43.7	2.7
HP Envy Notebook	L	2017	i7-7500U	HD 620[c]	Built-in	S	45.9	2.1
Lenovo Legion Y520	L	2017	i7-7700HQ	HD 630[c]	Built-in	S	48.6	2.4
Lenovo Legion Y520	L	2017	i7-7700HQ	GeForce 1050 Ti[b]	Built-in	S	50.6	2.4

D, Desktop computer; E, Electronic device; External, Dell U2415; G, Logitech G203 Prodigy gaming mouse; L, Laptop computer; S, Dell standard mouse;
[a] AMD discrete GPU.
[b] NVIDIA discrete GPU.
[c] Intel integrated GPU. The PC-PVT 2.0 User's Guide provides the minimum system requirements, for both software and hardware.

should decrease in studies involving sleep deprivation, as average RTs increase with sleep loss. Reassuringly, the average delay obtained in the top 15 configurations running Windows 10 OS was nearly equivalent to that in the original PC-PVT running Windows 7 OS (8.5 ms vs. 8.0 ms).

The PC-PVT 2.0 could also be used in hardware configurations whose delay is unknown, as long as the same hardware configuration is used in all studies and the objective is to obtain relative performance. However, such an approach would not work if one is interested in mapping PVT results to some absolute threshold. Alternatively, one could separately characterize the delay in a given hardware configuration and subtract the delay from the PC-PVT results. By testing a large number of PC configurations, we were able to bypass the need to separately characterize each new configuration and thereby make general recommendations.

An important aspect of our assessment of the delays introduced by different hardware system configurations, is that the results are independent of human operation. In contrast to other approaches that require subjective judgment, such as those that use a high-speed camera to detect RT delays (Arsintescu et al., 2017), the use of the RTBox allowed us to test the hardware system configurations in a "closed-loop" protocol (Fig. 3). This led to very small variability (i.e., SD values) in the measured RT differences, with a level of precision ranging from 0.4 to 2.9 ms and an average precision of 1.5 ms, over the 44 configurations in Table 1. This small variability is attributed to multiple sources in both the hardware and software, such as the monitor input lag, video card, mouse, device drivers, polling rates, interrupts, power states, and OS multitasking.

The capability of the updated software to make individualized predictions of alertness nearly in real time and allow for visualization of the predictions, while considering any sleep-loss challenge and caffeine-dosing regimen, opens opportunities to perform new types of sleep-loss studies not previously possible. For example, we could design a *dynamic* protocol where we use the results of the individualized model predictions as the study progresses to perform tailored caffeine interventions for each subject by providing, for instance, different doses of caffeine for different subjects

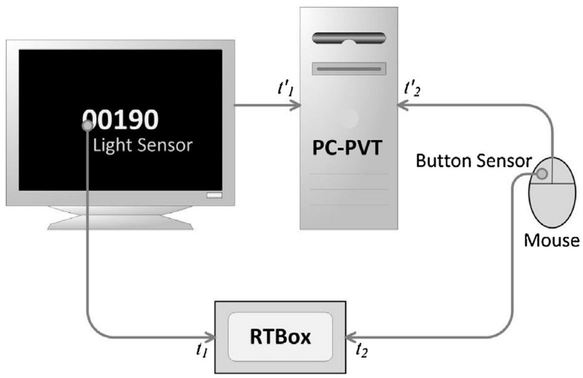

Fig. 3. Experimental setup to simultaneously measure reaction times in the RTBox and the PC-PVT installed in a given computer hardware system configuration. The PC-PVT software uses an LCD monitor for stimulus presentation and a mouse for recording the response to the stimulus. A light sensor connected to the RTBox is also attached to the LCD monitor to detect the onset of stimulus presentation, at which point the RTBox and the PC-PVT record the respective start times t_1 and t'_1. A button sensor connected to the RTBox is attached to the mouse's left button. Hence, when a human operator presses the left button in response to a stimulus, this simultaneously triggers the RTBox and the PC-PVT to record the respective end times t_2 and t'_2. The difference between the PC-PVT reaction time (t'_2–t'_1) computed by the software and the RTBox reaction time (t_2–t_1) computed by its internal clock, with an accuracy of 0.1 ms, constitutes the delay of the PC hardware system configuration being tested. We used a similar procedure to characterize the delay of the PVT-192 hardware.

so that they all meet a specified alertness level at a desired time for a desired duration. This could be achieved by editing an active study, using the "Active Study" panel in the PVT Manager window to import new caffeine-dosing schedules, and then editing each subject in the study to assign the appropriate caffeine schedule, using the "Subjects" panel in the same window (Fig. 1A).

5. Conclusion

We have updated the freely available PC-PVT software to conduct simple visual RT testing in a PC running Windows 10 OS. In addition, the PC-PVT 2.0 provides the capability to couple PVT tests of a study protocol with the study's sleep and caffeine schedules, visualize test results overlaid on the schedules, and make nearly real-time individualized predictions of PVT performance for each study volunteer challenged by *any* sleep-loss condition, while accounting for the beneficial effects of caffeine. We showed that, to achieve minimal delays (<10 ms) comparable to those of the hand-held PVT-192, the PC-PVT 2.0 should *always* run on hardware configurations with a gaming mouse. In addition, for desktops, the system should use a discrete GPU and, for laptops, the system should use an external monitor.

Software availability

The PC-PVT 2.0 software is freely available and can be downloaded from https://pcpvt.bhsai.org.

Disclaimer

The opinions and assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the U.S. Army or of the U.S. Department of Defense. This paper has been approved for public release with unlimited distribution.

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