XV Latin American Symposium on Chronobiology 2019
Colonia del Sacramento - Uruguay

From the ruler to the smartphone tasks applied to identify sleep deprivation

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ABSTRACT

Sleep-related health disorders and fatigue represent a major public health issue worldwide. It is estimated that 13% of work-related injuries are attributed to sleep problems. Consequences of sleep deprivation and fatigue not only impact the person, but also can have social impact. Numerous objective tests have been designed to assess whether a person is properly rested to safely carry out his/her job. These techniques are focused mainly on the measurement of response time, alertness and sustained attention proxy for sleep deprivation and fatigue, and they should be properly validated. Over the last 35 years, the Psychomotor Vigilance Test has been the gold standard widely used because it can be performed in different environments and due it operational characteristics. However, validity procedures do not report detailed information about specificity, sensitivity, negative and positive predictive value. These data are essential to determine if the test is optimal for it implementation. The purpose of this review is to go over the evolution of the techniques applied to identify sleep deprivation, starting from the basic and analog reaction test to the most current portable and digital techniques.

Keywords: PVT; Sleep Deprivation; Alertness; Fatigue; Performance; Validity

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DOI: 10.5935/1984-0063.20200007

INTRODUCTION

Sleep-related health disorders and fatigue represent a major public health issue worldwide[1,2]. After an extensive analysis on a complete description of fatigue, Phillips (2015)[3] defines fatigue as: "A suboptimal psychophysiological condition caused by exertion […]. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced." Insufficient sleep has a negative impact on different aspects of wakefulness[4].

It is estimated that 13% of work-related injuries are attributed to sleep problems, and workers with sleep problems had a 1.62 times higher risk of being injured than workers without them[5]. In the road safety field, effects of sleep deprivation are responsible for approximately 20% of all serious motor vehicle accidents and up to 43% of commuter train accidents are thought to be due to this problem[2].

In the last 50 years, numerous objective tests have been designed to assess whether a person is properly rested to safely carry out his/her job. These tests have been included in occupational or military safety protocols in order to avoid accidents or catastrophes related to fatigue[6].

Objective tests designed to assess whether a worker is well rested have focused mainly on the measurement of: response time (the minimal time needed to respond to a stimulus), alertness (a cognitive capacity characterized by being fully aware of the self and the surroundings), and attention, specifically sustained attention (the ability to keep the focus of attention on a task or event for a prolonged period of time)[7-9].

Many of the techniques used to measure response time, alertness and sustained attention, as a proxy for sleep deprivation and fatigue, have been widely used and thoroughly validated in experimental and clinical environments[9]. As sleep-related health disorders and fatigue are increasing worldwide and generating occupational and social impact, it is imperative to perform these tests in operational environments to effectively predict sleep deprivation and prevent incidents and accidents[10,11]. Rapidly growing technological developments are constantly producing readily available commercial devices that are increasingly portable and easily implemented in the operational environment; however, it is imperative that these new devices are valid for their application[12]).

The purpose of this non-systematic review is to go over the evolution of the techniques applied to identify sleep deprivation, starting from the basic and analog reaction test to the most current portable and digital techniques.

THEORETICAL BACKGROUND

Alertness is the state of a healthy, well-rested person that allows an individual to sustain his/her attention and give a timely response to any situation[13]. Lack of alertness is one of the most specific symptoms of fatigue or sleep deprivation[8].

Banks et al. (2019) define fatigue as the inability to function at the optimal level, because the physical and mental effort (of all waking activities, not just work) exceeds the existing capacity[14]. The level of fatigue depends on the task performed by the individual (for example, for pilots, their ability to safely operate an aircraft; for cabin crew, their ability to perform safety-related duties)[4].

Sleep deprivation (partial or total) leads to neurobehavioral consequences. Some of them are: degradation of alertness, slower reaction time, decreased vigilance, lapsing, slower problem-solving and reasoning abilities, impaired accuracy and decision-making skills, increased omission and commission errors, reduced psychomotor skills[7, 8, 15, 16]. For example, when sleep is limited to 4-6 hours per night, effects on cognitive performance occur, producing a progressive cognitive dysfunction[12, 17, 18].

An adequate performance refers to achievement of an optimal and effective functioning of cognitive abilities and executive functions like psychomotor vigilance, alertness, memory, reasoning or decision-making among others[13]. One night of sleep deprivation can generate more damage on health than sleep throughout several nights, generating detrimental effects on performance[17]. Cognitive impairment can be measured within the first several minutes of performance, especially on a boring monotonous task[7, 19].

The effects of sleep deprivation on performance are comparable with the effects produced by alcohol consumption; 17 hours awake is equivalent to a blood alcohol content of 0.05, the legal limit for driving in most countries [20]. Specifically, similarities have been observed in the reduction of psychomotor skills[15]. This similarity in effects between fatigue and alcohol highlights the need to develop and implement tools for the detection of sleep deprivation.

The degradation of performance represents the most dangerous effect of sleep loss in the workplace, increasing the possibility of near-accidents and accidents in workers, especially in those with non-traditional shifts (nocturnal or shift workers), which include drivers of professional vehicles, train operators or health personnel[7, 15, 18]. Shift work includes working evenings, nights, or rotating shifts and is often associated with shorter and disrupted sleep periods[21]. Surveys, observational data, and anecdotal incident reports reveal that shift workers often experience sleep episodes[18] and they frequently complain about excessive daytime sleepiness.[10]

Therefore, consequences of sleep deprivation and fatigue not only impact the person, but also can have social consequences such as industrial catastrophes, medical errors, transportation accidents, and security breaches[22]. The relationship between work accidents and the decrease in operational productivity caused by drowsiness or fatigue is difficult to measure[6], yet the effects of sleep deprivation must be studied and quantified to take preventive actions[9].

Subjective evaluation tools like sleep and alertness measurement techniques can provide useful clinical information. However, the lack of sensitivity and specificity make these techniques subject to many influences which can mask the real information[13].

This could be due to unintended bias, motivational factors, demands inherent to the experiment, distractions by environmental stimulation, stress, food intake, posture and activity, room temperature, lighting conditions, drug intake and even purposeful falsification, among others. Also, it has been shown that sleepy subjects cannot reliably self-assess their impairment when they are in a state of drowsiness[10, 13, 23]. The multiple limitations of subjective techniques highlight the dire need for brief, validated and objective measures to evaluate fatigue[9].

A fitness for duty test is optimal when it measures with criterion validity for both risk factors (like fatigue) and job performance. It must have certain characteristics: be valid (measure what it intends to measure as a fatigue-sensitive behavior), reliable (measure the same consistently), specific (minimizing false alarms), generalizable (for all users, taking into account individual differences) and sensitive (predicting unacceptable fatigue levels and minimizing lost events)[12, 24].

It is essential for that test to have the same sensitivity as the laboratory test and to be feasible to apply in the workplace and comply with scientific and operational properties. In particular, it should be easy to use, portable, brief, without effects due to practice or learning and the obtained results must be readily available[24]. These tests must provide feedback to operator about his/her alertness level, that is, if the subject being assessed is able to perform a given task.[18,24-26].

Reaction Time tests, in which subjects simply respond as fast as possible to a stimulus, are sensitive to asses sleep deprivation because they can evaluate changes in the alertness state caused by inadequate sleep, and have proved to be useful to understand the effects of sleep deprivation[9, 26-28]. Woods et all (2015) define the Simple Reaction Time (SRT) as the minimal time needed to respond to a stimulus[29]. A slow response time affects performance, for example by increasing risk for accidental falls and motor vehicle accidents[11].

Sleep deprivation leads to a general slowing of response times. Restricting sleep to 6 hours throughout few nights leads to a slower response time during the day[12]. The same level of sleep restriction sustained for two weeks generates a degree of impairment comparable to two nights of total sleep deprivation (TSD)[17]; and chronic partial sleep deprivation (CPSL) of approximately 5 hours every night results in decreased performance which can lead to accidents[21]. Even more so, chronic sleep deprivation of 4 hours per night may generate a continuous performance impairment and would most likely lead to personal or work-related accidents[17,7-8].

Jafe et al. (2018)[28] emphasize the value of studies focused on performance metrics - such as reaction time - for the understanding of the specific effects sleep duration and sleep deprivation.

RELEVANT TECHNIQUES FOR MEASURING REACTION TIME

The Ruler Drop Method (RDM): It consist in grab a ruler when someone else throws it at an unexpected moment. The falling ruler is the stimulus and grabbing it is the motor (voluntary) response. Shorter the time, the faster is the reaction[30]. This is one of the first analog method to assess reaction time and has also been field-expedient and widely accepted as a valid method for testing reaction time. Aranha et al. (2017), developed a study in school going children comparing the RDM to a mobile-based software application and found that the RDM is a moderate to good method for determining reaction time[28]. It has been used in clinical environment for testing speed visual reaction time in people with and without diabetes[30].

RTclin (University of Michigan, USA, 2010): A similar method to the RDM is the RTclin, a clinical reaction time apparatus designed to emulate a ruler, that measures reaction time. It quantifies the time required to catch a suspended vertical shaft by pinch grip released at random intervals. The subject has to open his hands and catch the device as soon as he perceives it being released and grasps it quickly as possible[28]. It has been used in experimental environments. A study in which 65 healthy adults performed clinical and computerized reaction time tasks (RTclin and RTcomp) under simple and dual-task conditions confirmed that RTclin is a reliable and valid measure of reaction time[31]. Further work is needed before recognition RTclin can be applied in the clinical setting[11].

The Auditory Vigilance Task (Wilkinson, 1970)**:** The stimulus in this task is an auditory tone[32]. The original task, is a one-hour auditory technique in which subjects must listen to spaced tones of 500ms of duration every two seconds[25]. In a shorter duration task (10 minutes), the auditory tone is turned on for 475ms and off for 48ms If no response occurred the counter was reset after 30 000ms[32]. During the Auditory Vigilance Task, subjects have to look at a paper located on the computer screen and no response time feedback is given. The response box had double pole double throw buttons which gave two electrical outputs when pressed: one to the computer to stop the stimulus and one to the digital recorder. It has been demonstrated that the 1h Wilkinson Auditory Vigilance Task is sensitive to one night of sleep deprivation[25]. The 10 minutes Auditory Vigilance Task is sensitive to sleep deprivation, to performance at an adverse circadian phase, and to time on task decrements[32].

The four choice portable cassette recording apparatus (Wilkinson & Houghton, 1975): It is the reaction time task of choice (10 minutes of duration). It consists of four lights arranged in a square and four keys arranged in a similar way. When one of the four lights comes on, the subject must press the button that corresponds geometrically to the activated light. The light goes out and after 120ms any of the four lights come on again, independently of the response. The cycle is repeated in a randomly fashion[25].

Wilkinson Simple Visual Reaction Time (VRT) Task (KE Developments, Ltd., Cambridge, England, 1982): It is a ten-minute auditory task carried out with a portable cassette recording device and a modified tape. It initiates with a visual stimulus, and a four digits clock in milliseconds visually displayed. The subject has to press a microswich that stops the burst of tones on the audio tape and the digital clock, allowing the subject 1.5 seconds to read the value.

The start of the stimulus of the next series of numbers occurs randomly between 1 and 10 seconds after the previous response[26].

It was found that the **Wilkinson VRT Task** and **The four choice portable cassette recording apparatus** are particularly sensitive to the effects of sleep deprivation after only five minutes of testing[25]. Performance on **Wilkinson VRT Task** was sensitive to as little as one night without sleep[25, 26].

Occupational safety performance assessment test (OSPAT) (Romteck, Western Australia, 1998): The test consists in a software task with a duration of 60 seconds. It measures reaction time, sustained attention and motor coordination.[33] OSPAT has been validated for sleep deprivation and it shows to be sensitive to the detection of TSD from a single night (24 hours of prolonged wakefulness)[33].

The gold standard: Psychomotor Vigilance Task

The PVT is one of the most sensitive measures of performance impairment by sleep deprivation[22]. It consists in a visual simple reaction time test based in a sustained attention task for fatigue detection[7,12,34]. The objective of the PVT is to motor response as quickly as possible by clicking a button to the visual stimuli presented on a screen with a random inter-trial interval.[16, 35]. Average reaction time in PVT increases in length overall after a period of sleep deprivation and is associated with eye closure and micro-sleep[7, 36]. It has proven to be a valid test to measure alert reduction as a result of PSD or TSD[34, 37, 38].

Over the last 35 years, the Psychomotor Vigilance Test has been the gold standard widely used because of its advantages over other tests[24, 37, 39]. Some of the most important advantages are that: it can be used not only in experimental and clinical studies, but also in operational environments[35-37]; it is useful for repeated use in within-subject designs[35]; It is a brief test, different versions of PVT can last from 2 minutes to 10 minutes[35, 36, 40]; and it can measure and estimate differences in the aptitude between different subjects[35].

The most used outcomes that the PVT give back are: mean Response Time (RT) (which are valid if they are ≥100ms and ≤500ms); false starts (when the RTs are less than 100ms) and lapses (reaction times greater than 500ms)[9,37,39]. Some others outcomes are: mean1/RT; fastest 10% RT; fastest 10% 1/RT; median RT; slowest 10% RT; slowest 10% 1/RT; lapse probability and other particular outcomes[9].

PVT-192 (Ambulatory Monitoring Inc., Model PVT-192): The first PVT (Ambulatory Monitoring Inc., Model PVT-192) was designed by Dinges and Powell in 1984 as an evolution of the Wilkinson Visual Reaction Test[39,41]. It is a hand-held, self-contained system which consists in a simple reaction time task of 10 minutes of duration and inter-stimulus interval (ISI) that ranges between 2 and 10 seconds[16,40]. The stimulus is composed of a counter that has four digits and can be seen on the screen. To answer the subject has to press the button when the stimulus is received. Each RT is stored on the device and then loaded on a PC[42]. Inter-stimulus intervals, time on task and ISI parameterization represent the "vigilance" aspect of the PVT[9].

It has been demonstrated that the 10min PVT version is valid and highly sensitive to the effects of sleep deprivation (TSD and CPSD) and fatigue because the performance deteriorates faster in sleep deprived than in alert subjects with time on task[7,9,26,43]. This can be seen in the higher RT, number of lapses, mean RT, inverse of the mean RT, the mean of the 10% of the fastest and slowest RT, and in the increase of omission errors and commission errors[8,9,44].

In recent years, shorter variants of the PVT have been developed which have been useful to measure the decrease in performance due to sleep deprivation[8]. Some of these variants are described below:

PVT-A (Basner & Dinges, 2012): This computer version of the PVT has an average duration of 6.5 minutes, which makes it more feasible to use it in operating and clinical settings.[21]

Table 1. Relevant techniques for reaction time and sleep deprivation detection

Task/ Test	Author	Year	Country	Device	Measure	Duration	Enviroment	Validity	Objective
The Ruler Drop Method	Unknown	n/s	n/s	Ruler	Reaction Time	Random	Experimental & Clinical: school going children/ Diabetes and non-diabetes patients	No	Reaction time. Speed visual reaction
RTclin	University of Michigan	2010	USA	Shaft and Pinch Grip	Reaction Time	Random	Experimental & Sport related	Yes	Reaction time
Auditory Vigilance Task	Wilkinson	1970	England	Auditory technique	Reaction Time	1h	Experimental	Yes	Sleep deprivation
The four choice portable cassette recording apparatus	Wilkinson and Houghton	1975	England	Lights and buttons	Reaction Time	10m	Experimental	Yes	Sleep deprivation
Wilkinson Simple Visual Reaction Time (VRT) Task	Wilkinson	1982	England	Cassette recording device and microswitch	Reaction Time	10m	Experimental	Yes	Sleep deprivation
Occupational safety performance assessment test	Romteck	1998	Australia	Portable device	Reaction Time; sustained attention, motor coordination	60 seconds	Sleep deprivation	Yes	Total sleep deprivation

Looking at a computer screen, subjects should respond as quickly as possible to a yellow counter on it; which then shows the response time for 1s. The PVT-A has been validated in experimental environment demonstrating to be highly accurate, sensitive and specific[16,21].

PC-PVT (Khitrov, 2013): In order to improve the traditional PVT interface, a version of PVT for PC, which runs in Windows 7 operating system, was developed consisting of two separate programs, an administrator and a tester. The tester consists of a PVT session that can last from 5 to 10 minutes and uses a five-digit millisecond counter as a stimulus. The answer is granted with the click of the mouse and, after each response, the RT is displayed on the screen for 500ms. The PC-PVT has been validated as a technique for measuring neurobehavioral performance and as a sleep deprivation detection[42].

The emergence of new technologies allowed the development of more portable PVT. This type of devices facilitatesthe use of this technique in operational environments of remote conditions[44].

PalmPVT (Walter Reed Army Institute of Research, 2005): This version of the PVT was developed and validated on personal data assistant devices (PDAs) and runs on a Palm-Os. In a 5-minute duration task, the stimuli are presented on the device screen and the subject must respond on the same screen by pressing a specific button[41]. This version responds as a valid and reliable device for measuring sleep deprivation and fatigue. Regarding results are comparable to the longer values of the PVT-192 despite the different stimulus characteristics[8,41].

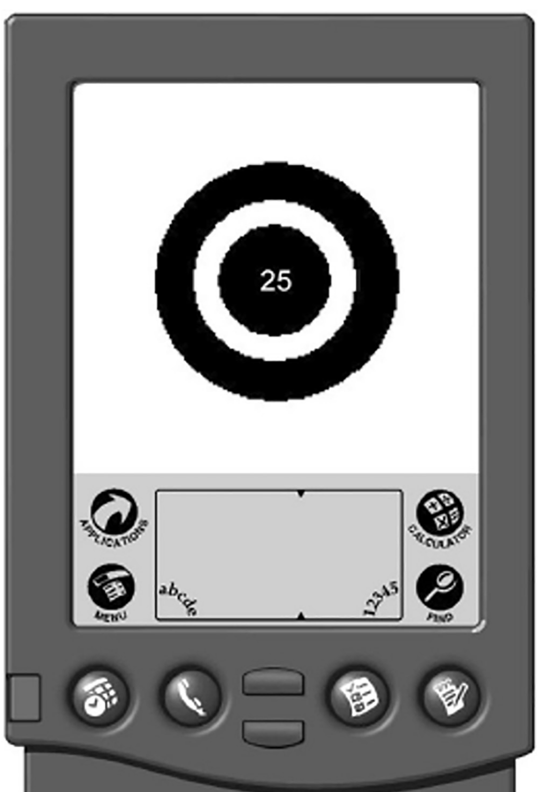

Figure 1. PalmPVT (Walter Reed Army Institute of Research, 2005). Subjects should look at a screen and press a button as soon as the counter stimulus appears.

PVT-B (Basner et. al, 2011)**:** This is the first version of the 10-minute PVT in a 3-minute mode. As in the 10-min version, subjects should look at a screen and press a button as soon as the counter stimulus appears, which stops the counter and the response time can be observed[45]. It was validated in controlled laboratory studies and had demonstrated to be less sensitive to the detection of sleep deprivation due to its short duration[45]. Likewise, the PVT-B grants faster response times, more false starts and less lapses than the traditional PVT performance. Although in general the tool is sensitive and specific for detecting sleep deprivation, especially in environments where it is not possible to run longer tests, a validation process is required in this type of environment[19, 45].

Fitness For Duty (FFD)-PVT (Basner & Rubinstein, 2011): In this 3-minute version, the signal speed is increased (interval between stimuli from 1 to 4 seconds) and the definition of lapse is reduced from the standard definition of ≥500ms to ≥355ms. It was validated against the standard 10-minute PVT in total and partial sleep deprivation paradigms, and it was shown that it reaches similar levels of sensitivity and specificity. It was able to predict performance

on a simulated luggage-screening task. Fitness-for-duty feasibility should be tested in professional screeners and operational environments[24].

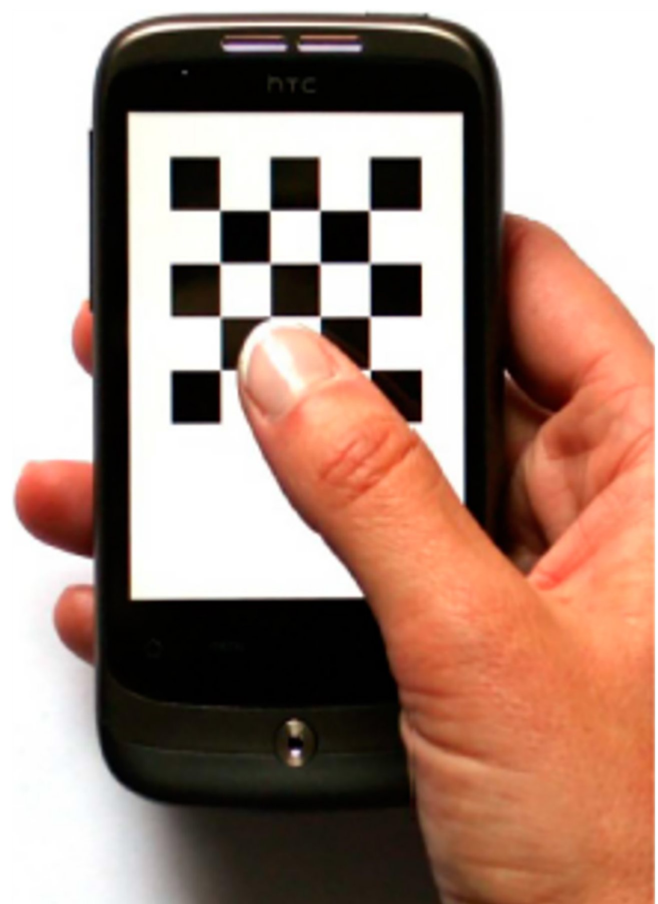

Figure 2. Pvt Touch (Kay et al., 2013) The stimulus and response occur on the same screen. In each trial, the screen starts out blank (white). After a random delay, a high contrast checkerboard pattern appears, at which point the participant provides a response touching the screen).

PVT Touch (Kay et al., 2013): One of the newest and portable adaptations of the PVT is based on touch screen devices because it is currently more familiar and convenient. The stimulus and response occur on the same screen. The test consists of a 5-minute PVT version with random foreperiods from 1 to 10s. In each trial, the screen starts out blank (white). After a random delay, a high contrast checkerboard pattern appears, at which point the participant provides a response touching the screen. It has been compared to traditional PVT, and although the sensitivity is not as high as in the 10-minute tests, it was determined that it is valid for measuring alertness and detecting a deterioration of the performance induced by TSD, with an increase in the number of lapses, average RTs and false starts[38].

PVT for touch screen devices (Arsintescu et al, NASA Ames Research, 2017): Under carefully controlled laboratory conditions, touch screen versions of the PVT yield changes in RT consistent with those recorded by computer versions of the test[44]. A PVT has developed in a touch screen device (fifth-generation iPod) and thirteen participants completed a 5-min PVT in three positions (on a table with index finger, handheld portrait with index finger, handheld landscape with thumb). First session has recorded with a high speed video camera[44]. RTs differed depending on the orientation of the device and the finger used to respond to the stimulus and it was found a substantial response latency between the actual time of an individual's touch response and the time recorded by the touch screen device[44]. About the PVT duration, studies show that, in those PVT of 10 minutes, the performance decreases significantly in the first 2 minutes and in the first 5 minutes. This decrease in performance is observed in the means of the RTs, in the optimal responses and the responses in the span of time. This shows that tests under 10 minutes are sensitive for the detection of sleep loss[18].

It is noteworthy that although some sleep tests (such as Maintenance of Wakefulness Test and Multiple Sleep Latency Test, not described in this review[10, 23]) report sensitivity and specificity values, no such values were found on the PVT validation studies reviewed. In addition, we did not find reports of positive predictive values (to what extent a classifier or diagnostic test is able to detect) or negative predictive values (how many positive results are incorrect among all the negative cases available).

CONCLUSION

The measurement of reaction time is very useful to determine the sleep deprivation and prevent declines in the performance[28].

The PVT is the gold standard test for the detection of TSD and PSL in its different versions with respect to the duration and characteristics of devices[7]. It has evolved from being a 10-minute test developed in large equipment to a 3-minute test that can be performed with a mobile device. These new features make it more feasible to be used in operating environments[24].

Nowadays there are numerous technologies that are used for sleep deprivation assessment, but many lack scientific support that support their use. PVT validation works report to have optimal sensitivity (for the purpose of sleep deprivation), operational validity, predictive validity (ability to predict the performance capacity that is operationally relevant at a future time); reliability; specificity and generalization to be used in clinical and operational settings where tests must be brief, with minimal interference, portable and not intrusive, among other features[6,12]. Although the validity procedures asseverate that the tests meet all these criteria, the exact values are not informed. This detailed data is essential to determine if the test is optimal for it implementation on an specific operational environment[12].

Future developments of PVT task in more portable and practical technologies should report detailed information about specificity, sensitivity, negative and positive predictive value for the detection of sleep deprivation and fatigue in operational environments to avoid accidents[12].

Table 2. Comparison of the characteristics of the different PVT

Task/ Test	Author	Year	Device	Duration	Background	Validity	Objective
PVT-192	Ambulatory Monitoring Inc.	1984	Hand held self-contained system	10m	Experimental, clinical & operational	Yes	Sleep deprivation and fatigue
Palm PVT	Walter Reed Army Institute of Research	2005	PDAs, Palm-Os	5m	Experimental & Operational	Yes	Sleep deprivation & Fatigue
PVT-B	Basner et al.	2011	Computer	3m	Experimental	Yes	Sleep deprivation
Fitness for duty	Basner & Rubinstein	2011	Computer	3m	Experimental & Operational	Yes	Predict performance on a simulated luggage-screening task
PVT-A	Basner & Dinges	2012	Computer	6.5m	Experimental	Yes	
PC-PVT	Khitrov	2013	Computer, Windows 7	5m to 10m	Experimental	Yes	Sleep deprivation & Neurobehavioral performance
PVT Touch	Kay et al.	2013	Touch screen devices	5m	Experimental	Yes	Alertness, deterioration of performance induced by TSD
PVT for touch screen devices	NASA Ames Research	2017	iPod	5m	Experimental	No	Fatigue

10 minutes are sensitive for the detection of sleep loss[18].

ACKNOWLEDGMENTS

This study was supported by a grant from the Agencia Nacional de Promoción Científica y Tecnológica (PICT Start-Up 2013-0710) and the 4th Research Project Accreditation Program (PROAPI), from the Catholic University of Argentina (UCA).

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