REVIEW ARTICLE

Field Assessment and Enhancement of Cognitive Performance: Development of an Ambulatory Vigilance Monitor

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LIEBERMAN HR, KRAMER FM, MONTAIN SJ, NIRO P. *Field assessment and enhancement of cognitive performance: development of an ambulatory vigilance monitor.* **Aviat Space Environ Med 2007; 78(5, Suppl.):B268–75.**

Introduction: Limited opportunities to study human cognitive performance in non-laboratory, ambulatory situations exist. However, advances in technology make it possible to extend behavioral assessments to the field. One of the first devices to measure human behavior in the field was the wrist-worn actigraph. This device acquires minute-by-minute information on an individual's physical activity and can distinguish sleep from waking, the most basic aspect of behavior. ***Methods:*** Our laboratory developed a series of wrist-worn devices, not much larger than a watch, which assess reaction time, vigilance and memory. The devices concurrently assess motor activity with greater temporal resolution than standard actigraphs. They also continuously monitor multiple environmental variables including temperature, humidity, sound, and light. ***Results:*** These monitors have been employed during training and simulated military operations to collect behavioral and environmental information that would typically be unavailable under such circumstances. Development of the vigilance monitor, and how each successive version extended capabilities of the device are described. Data from several studies are presented, including studies conducted in harsh field environments during a simulated infantry assault, an officer training course. ***Discussion:*** The monitors simultaneously documented environmental conditions, patterns of sleep and activity and effects of nutritional manipulations on cognitive performance. They provide a new method to relate cognitive performance to real world environmental conditions and assess effects of various interventions on human behavior in the field. They can also monitor cognitive performance in real time, and if it is degraded, attempt to intervene to maintain it.

Keywords: actigraph, sleep, reaction time, motor activity, light, sound.

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NOVEL TECHNOLOGIES for assessing human behavior rarely emerge. Tests of cognitive performance and questionnaires, the most common behavioral assessment techniques, have been available since the emergence of psychology in the 19th century. While technologies employed to conduct such testing have substantially improved since the advent of mini- and microcomputers, the underlying parameters assessed have not changed. For example, tests of reaction time, sensory capabilities, and memory emerged in the 19th century and are still widely employed. One of the few novel technologies for the assessment of human behavior developed recently is the ambulatory activity monitor, also known as the actigraph. This technology required availability of microcircuits, specifically solid-state memory, but not microprocessors. Descriptions of several of the initial devices can be found in publications and patents dating from the 1970s and 1980s (3,19,24).

Activity monitors continuously assess human motor activity and are usually worn on the wrist, leg, or waist. The initial devices were simple and consisted of little more than a piezoelectric crystal, minimal signal processing circuitry, and very limited solid-state memory (less than 1000 8-bit bytes) (3). Current devices now automatically record motor activity and other parameters over several days or weeks in individual epochs lasting for periods of a second to several minutes. The most advanced have 8 MB of memory and internal microprocessors that are similar in computing power to Pentium processors. Actigraphs were developed to address limitations of other technologies used to assess human behavior, especially the unsuitability of traditional methods for studying ambulatory human behavior. They provided an opportunity to study a new, previously unmeasurable aspect of human behavior, spontaneous motor activity, for long periods of time as individuals go about their daily activities (20,23).

Ambulatory Assessment of Human Cognitive Performance in the Field

Conventional tests of cognitive performance are administered using paper and pencil to fill out forms, computers to present stimuli and record responses, or with mechanical devices such as pegboards. These tests

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Operational Applications of Cognitive Performance Enhancement Technologies was supported through the Office of Naval Research (ONR), Arlington, VA; the U.S. Army Medical Research and Materiel Command (USAMRMC), Ft. Detrick, MD; the Eye-Com Eye-tracker Research Program, Reno, NV; and through an unrestricted educational grant from Cephalon, Inc.

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measure functions such as reaction time, vigilance, attention, learning, memory, manual dexterity, and sensory function. Scientists rely on such tests to assess mental performance, but there are numerous problems associated with employing them, especially in the field. One limitation is that volunteers must stop all ongoing activities to participate in testing. Another is that the equipment employed to administer them is often not portable. Cognitive tests can now be administered on notebook computers and personal digital assistants (PDAs), a significant advance in portability and convenience (9,16). Unfortunately, these devices have limited battery life, the displays can be difficult to see, particularly in outdoor conditions, they have inadequate keyboards, are not waterproof, and are fragile. Using such instrumentation to study individuals in their natural environment can be intrusive and impractical.

Activity monitors have advantages over conventional technologies. They are much smaller than a personal computer or PDA, have a longer battery life, can be waterproofed, and if used to assess behavior, it is not necessary to halt the ongoing activities of the wearer. Actigraphs can measure duration of waking vs. sleep state, information that can predict cognitive performance (1,8). Although lacking the accuracy and resolution of polysomnography (electrophysiological sleep assessment), the gold standard for assessment of sleep state, activity monitors are used to assess sleep status in a variety of fields, including academic psychology and military, environmental, and clinical medicine (20,23). They have been used extensively to quantify human energy expenditure, although accuracy of the devices for this application is not established (2,5,6,18).

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The Evolution of the Vigilance Monitor

Although actigraphs are valuable tools for assessing ambulatory behavior, they do not directly assess cognitive function. Indirect inferences regarding cognitive state of an individual wearing an actigraph are possible, since virtually all cognitive behaviors cease when an individual is sleeping. However, actigraphs provide no direct information regarding cognitive performance of humans. Therefore, we have modified the actigraph to permit direct assessment of cognitive performance. Actigraph technology was integrated with conventional methods for assessing cognitive performance by combining in a single device the capability to present various stimuli and record responses with the ability to monitor activity. Because microelectronic and sensor technology has advanced rapidly since initial development of actigraphs, environmental sensors could be also be integrated into the device. Sensors to provide information on environmental factors related to human behavior, specifically light, sound, and ambient temperature, were included and, subsequently, a humidity sensor was added.

The first generation, integrated vigilance monitor, actigraph, and environmental monitor was designed and assembled at our laboratory, the U.S. Army Research Institute of Environmental Medicine (USARIEM) (**Fig. 1**) (10–12). As we lacked facilities to build a device from individual components, an off-the-shelf data-logger microcomputer was used as the core of the device. The data-logger (Tattle-Tale Model 5F, Onset Computer Corp., North Falmouth, MA) was designed for portable data logging. It contained an 8-bit microprocessor, RS-232 interface, analog-to-digital converter, and 128 KB of memory. The microprocessor was a variant of the Motorola 6801, manufactured for Onset by a third party. This processor is roughly equivalent to a first generation microcomputer, such as an Apple II. The Tattle-Tale motherboard allowed attachment of a daughterboard containing custom circuitry from third party developers. We designed such a daughterboard, which contained a solid-state accelerometer, temperature sensor, light and sound sensor (microphone), 3 LEDs, a miniature speaker, and two push buttons. To the best of our knowledge no such battery powered, portable device had previously been constructed (10).

Processing input from multiple sensors in real time, presenting stimuli (auditory or visual), and recording responses from the wearer, all under real-time software control, provided a previously unavailable capability for studying and modifying human behavior and motor activity. As typically configured, the first generation device recorded seven channels of data (**Fig. 2**). Its ability to assess vigilance and reaction time are illustrated in Fig. 2D. Vigilance was assessed by presenting a series of auditory stimuli at random times and recording, by button-press, responses (or lack thereof), and their latency with millisecond accuracy. Since the device is fully programmable, it could assess a wide variety of cognitive functions including learning, memory, pattern recognition, and reasoning.

Once this device was constructed, a variety of applications, some not *envisioned* when it was initially conceived, became possible. One application was to evaluate, in real time, responses of the wearer to stimuli, and use the monitor to actively modify those responses. For example, when an individual does not respond to stimuli presented, their intensity and frequency can be increased until a response occurs (10–12). In the data shown in Fig. 2D, to increase the likelihood a volunteer would respond to the vigilance test stimuli, each stimulus presentation actually consisted of three consecutive tones, separated by several seconds, each louder then the previous tone (13). When a volunteer responded to a tone, presentation of the other tones in that series was canceled. This reinforced rapid responding, as once the volunteer responded he avoided subsequent tones in the series. Furthermore, the device can be programmed to increase the vigilance of the volunteer by measuring it directly in real time, and then providing feedback to the user when an unsatisfactory (slow) or no response is detected.

Automated Enhancement of Cognitive Performance

Since the vigilance monitor measures motor activity like an actigraph, data from activity channels, such as low activity indicating sleep, can be used alone or integrated with volunteer response data to modify vigilance or patterns of sleep and activity. The device can be programmed to only present stimuli when low activity levels are present, thereby being less intrusive. For ex-

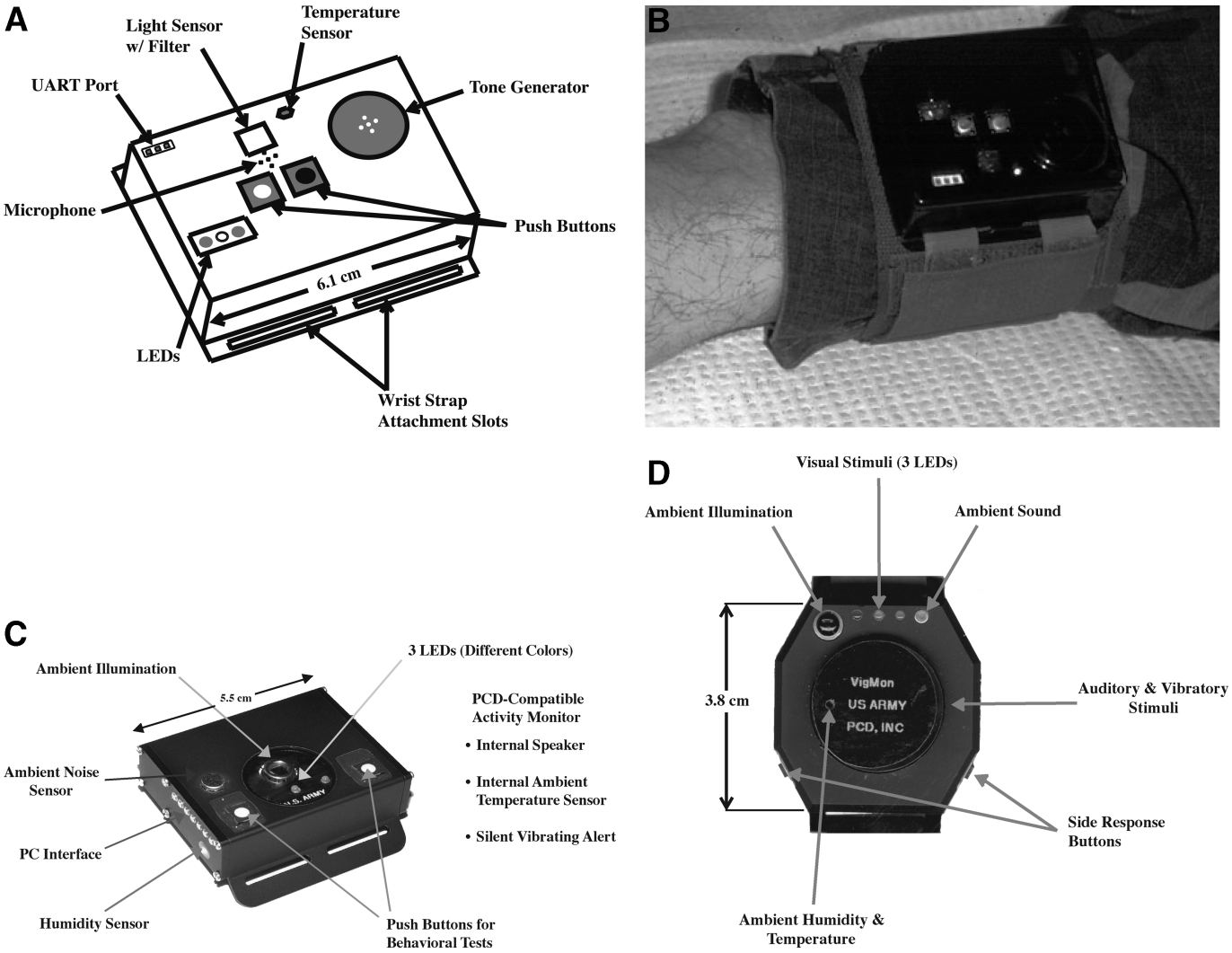

Fig. 1. A and B) Schematic and picture of the first generation vigilance monitor. C) Second generation vigilance monitor with all sensors, output devices, and push buttons identified. D) Third generation vigilance monitor with all sensors, output devices, and push buttons identified.

ample, if the device was being employed to keep a sentry alert, it could be programmed to only present vigilance stimuli when he/she was inactive. The capability was validated in a study in which volunteers were required to stay awake overnight. In one group (n = 20), auditory stimuli were presented randomly. In another group (n = 20), stimuli were presented when the accelerometer detected a period of inactivity. In the later group, reaction time assessed by the monitor was significantly faster (**Fig. 3**) over the course of the night (t = 2.23, p = 0.026).

Vigilance monitors can be employed to accomplish a variety of initially unanticipated objectives. For example, the device can modify circadian rhythms of sleep/activity by permitting sleep during pre-programmed intervals and maintaining vigilance/wakefulness at other times. Another use would integrate behavioral and environmental sensing capabilities. For example, in hot environments, motor activity, an indicator of work load, ambient temperature, and responsiveness to stimuli, could be evaluated by an algorithm that would sound a warning if the individual appeared to be at risk. High levels of activity could trigger an alarm to reduce exertion of the wearer or, alternatively, test behavioral responsiveness to external stimuli, and then act if alertness falls to unacceptable levels (10).

The first generation device lacked some desirable features. One was the ability to present somatosensory stimuli, in particular to vibrate, like cellular telephones and pagers, which would permit behavior to be studied and modified in noisy environments or in individuals wearing helmets, where an auditory stimulus might be masked. In some environments, such stimuli are difficult to ignore compared with moderate intensity auditory or visual stimuli (17). Other limitations of the first generation device were its relatively large size, limited memory, and difficulty making it waterproof. Furthermore, as it employed a non-standard accelerometer, it could not assess sleep using a validated algorithm based on polysomnography (4,21).

We collaborated with Precision Control Devices (PCD), Ft. Walton Beach, FL, to design a second generation vigilance monitor to eliminate these deficiencies (Fig. 1C). The second generation device is waterproof, can generate vibratory stimuli, and includes an additional environmental channel for monitoring ambient

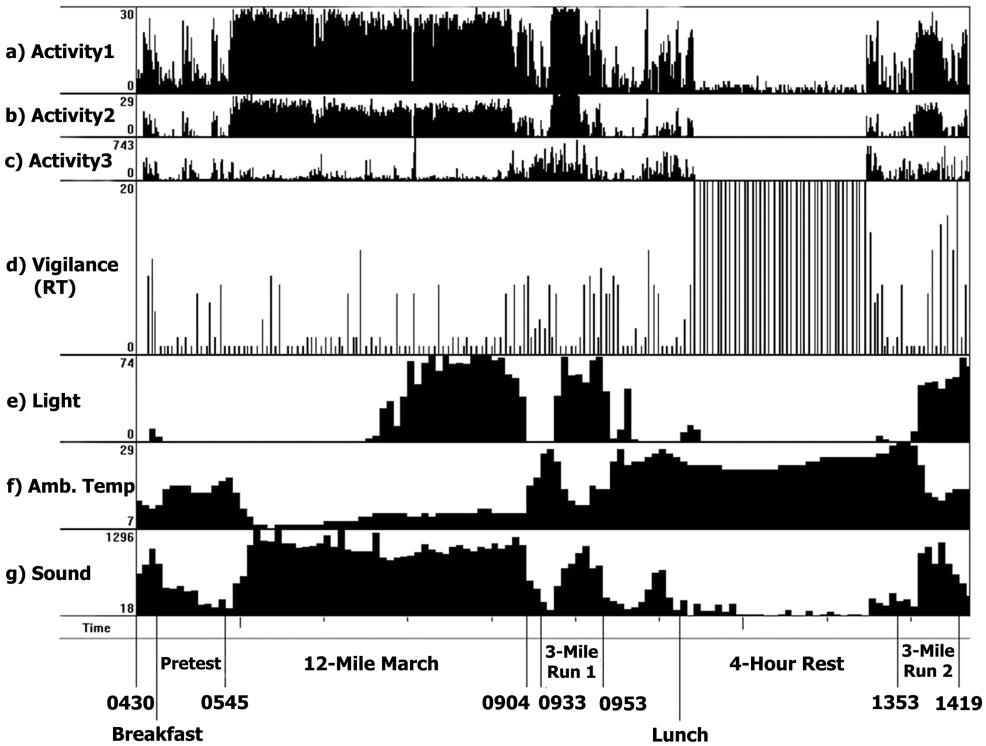

Fig. 2. Representative vigilance monitor data from one volunteer continuously collected over the 10 h of a study designed to evaluate a carbohydrate beverage during a military field exercise (13). The seven channels of data acquired are labeled individually on the y-axis. Activities in which the volunteer was participating and clock hours are indicated on the lowest x-axis. A–C) These three channels, Activity 1–3, are sensing physical motion (acceleration) and data collected are similar to a standard actigraph. The vertical height of each line plotted on the x-axis represents the number of movements detected in 1 min. Each channel was optimized to detect motion with different physical characteristics (see 11). D) This channel, labeled Vigilance (RT), displays the responses of the subject, in seconds, to presentation of a sequence of tones (about 20/h) at random intervals. The height of each bar represents speed of response to the tone. When a bar reaches the top of its graph this indicates the subject did not respond to that stimulus. E) This channel, labeled light, is the illumination level recorded at the wrist of the subject in arbitrary units. F) The Amb. Temp channel continuously records ambient temperature in degrees Celsius. G) This channel continuously records ambient sound levels in arbitrary units.

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humidity. This capability was added since it is an important predictor of ability to work in hot environments. The second generation monitor uses the PIC 16F877 microprocessor (Microchip Technology, Chandler, AZ), equivalent to a 486-based microcomputer.

This second generation device (Fig. 1C) is smaller (5.6 cm × 4.3 cm × 1.6 cm; 53 g) than the first generation vigilance monitor and contains 10 MB of non-volatile memory. A major advantage of the second generation device is it can sample activity to the identical specifications of PCD actigraphs. When sampled in this manner, activity can be used to distinguish sleep from waking, since algorithms to accomplish this have been validated using polysomnograpy (4,21). Although the second generation device is smaller than the first generation device, some volunteers find it to be uncomfortable to wear for long periods of time (many days) and it is subject to physical damage when volunteers are in harsh environments. Since volunteers can, of course, take the devices off once they have left the laboratory, we hypothesized that compliance with study requirements could be encouraged by providing a more tolerable device.

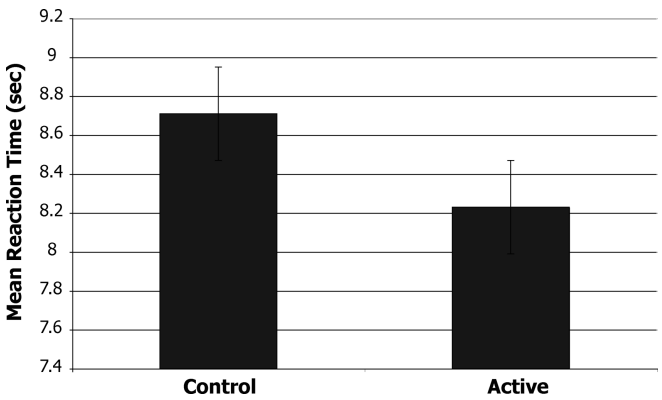

Fig. 3. Mean (± SEM) auditory reaction time assessed with the vigilance monitor in volunteers required to stay awake overnight ($t = 2.23$; $p = 0.026$).

PCD has now produced a third generation monitor which is significantly smaller than the second generation device (Fig. 1D). It is octagonal in shape, has 8 MB of memory, and weighs only 48 g, yet preserves all the functions of the second generation device. Its dimensions are 3.8 cm × 3.8 cm × 1.2 cm, and its size and shape make it more acceptable to the wearer since it is not much larger than a wristwatch (Fig. 1D). To achieve software compatibility with the first PCD-manufactured vigilance monitor, another Microchip Technology microprocessor in the same family was used, the PIC 18LF6720. It is equivalent to a Pentium microprocessor. With 8 MB of data memory it could record 48 d of data in 9 channels every 10 s. Unfortunately, the battery would not last that long.

Research Applications

Although vigilance monitoring is only beginning to emerge as a practical research tool, a number of studies have employed it. Most have been conducted in the field, although the device is also in use in the laboratory. One study (13) assessed the effects of a nutritional intervention on soldiers engaged in a training exercise. The exercise was conducted to test whether providing supplemental energy as a carbohydrate beverage would improve vigilance and physical performance. This study was designed in collaboration with the participating military unit, the 75th Ranger Regiment, to simulate a brief, but intense, light infantry mission, so the test was realistic with regard to the unit's operational requirements. In that study, the vigilance monitor was the primary dependent measure and was used to assess soldier cognitive performance continuously for 10 h in the field. It successfully documented the beneficial dose-related effects of the carbohydrate beverage on vigilance compared with a placebo beverage (**Fig. 4A**) (13).

The ability of the monitor to reliably document changes in cognitive performance was confirmed by results of a mood questionnaire that was administered periodically during the study. The questionnaire demonstrated changes in self-reported mood state across treatment conditions and time consistent with changes in vigilance detected by the vigilance monitor (**Fig. 4B**).

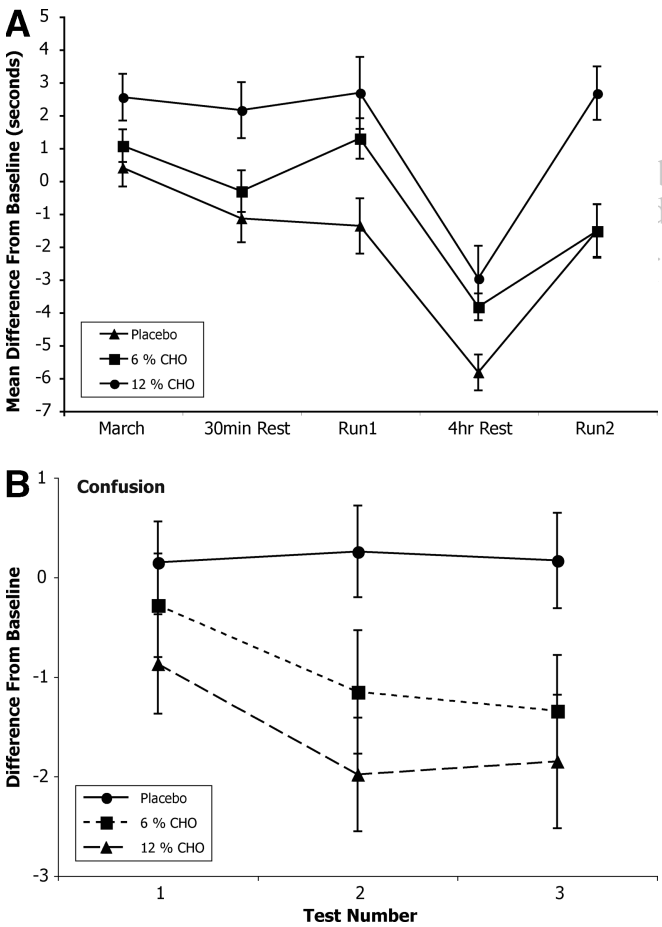

Fig. 4. A) Mean (± SEM) differences from baseline in auditory vigilance reaction times over 10 h of a field study designed to evaluate effects of carbohydrate supplementation on cognitive performance (13). Each subject's performance was summed over five time periods. Because values plotted are differences from baseline, the higher the number on the y axis, the better performance. B) Mean (± SEM) differences from baseline on the Confusion subscale of the Profile of Mood States (13). Lower numbers on the y axis indicate reduced self-reported confusion.

The functionality of the monitors has been evaluated in different training environments. The data shown in **Fig. 5** were collected from a volunteer engaged in an intense 8-d field exercise, a part of U.S. Marine Infantry Officer Training, which was conducted in a hot, humid environment (14). Patterns of rest and activity, and environmental conditions were documented by the monitor (Fig. 5). Vigilance data were also acquired, although only for brief periods of time (Fig. 5G).

Ambient Sound, Light, and Temperature

To understand the effects of environmental factors on human cognitive performance, the vigilance monitor includes a suite of onboard sensors. Ambient light levels, sound, and temperature can be continuously assessed. These parameters were selected since they are important determinants of human behavior. The pattern and intensity of sound in the environment influences human patterns of rest, activity, and other behaviors. To the best of our knowledge, ambulatory field studies investigating the relationship of ambient sound levels and human behavior patterns have not been conducted because of the lack of suitable devices to assess both parameters simultaneously. Humans are sensitive to a wide variety of auditory stimuli, and loud or even moderate volume irregular sounds can severely disrupt sleep. The vigilance monitor has a microphone mounted inside and information on background sound levels the wearer experiences can be continuously monitored. Fig. 2 illustrates the relationship between ambient noise levels and behavior. When volunteers were napping during the 4-h rest period, noise levels (Fig. 2G) were substantially less than any other period of the study. Vigilance performance during this period was significantly degraded (Fig. 2D) (13). Minute-by-minute information on quality and quantity of sleep and simultaneously recorded ambient patterns of sound may be useful for developing appropriate strategies to increase sleep in the field.

Light is another key factor regulating human behavior, including rest and activity cycles and circadian rhythms underlying these behaviors. We included a light sensor so information regarding the duration and amplitude of individual exposure to light can be continuously acquired (Fig. 2E). Commercial versions of actigraphs with light sensors have been available for some time (7). However, individual variations in light exposure and their effects on circadian rhythms and performance in the field have not been investigated. In a study conducted at Camp Parks, CA, with medical reservists as volunteers, we collected data using the monitors and a stationary weather station with an onboard radiometer (11). **Fig. 6** presents data on mean ambient exposure to light from four reservists and also from the weather station's sensor. The vigilance monitor appears to have accurately tracked ambient illumination. Daily patterns of light exposure of volunteers were

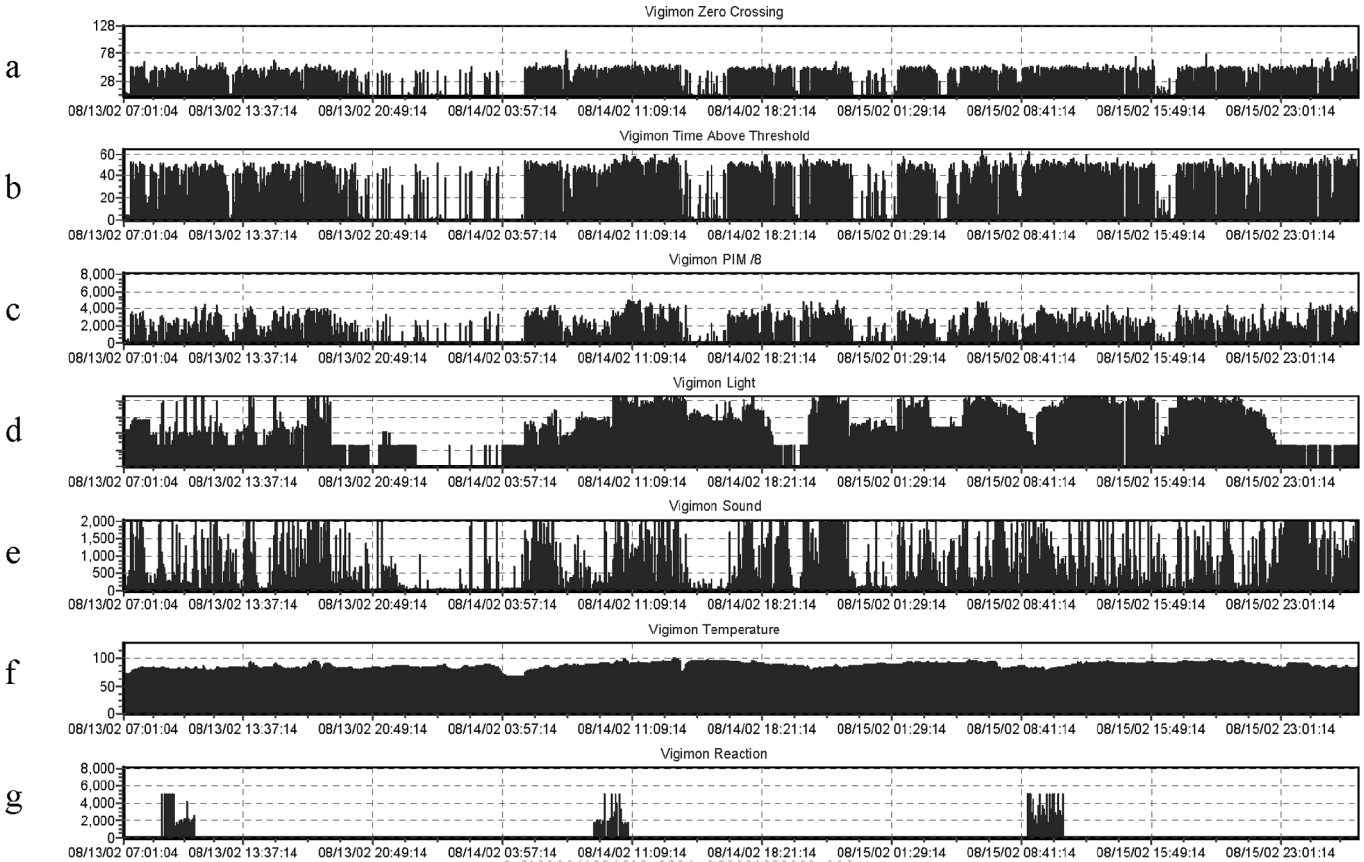

Fig. 5. Vigilance monitor data collected during part of an 8-d U.S. Marine Infantry Officer Training exercise. On Aug. 14 the unit engaged in simulated night attack; on Aug. 15 another night attack scenario was the activity.

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more variable than ambient illumination and rose earlier in the morning and fell asleep later at night, perhaps an indication of exposure to artificial sources of light in the morning and evening. Ability to monitor illumination levels, particularly in studies of circadian rhythms, performance, and sleep, will provide information on a potentially confounding factor, as well as describing the milieu in which an individual is operating.

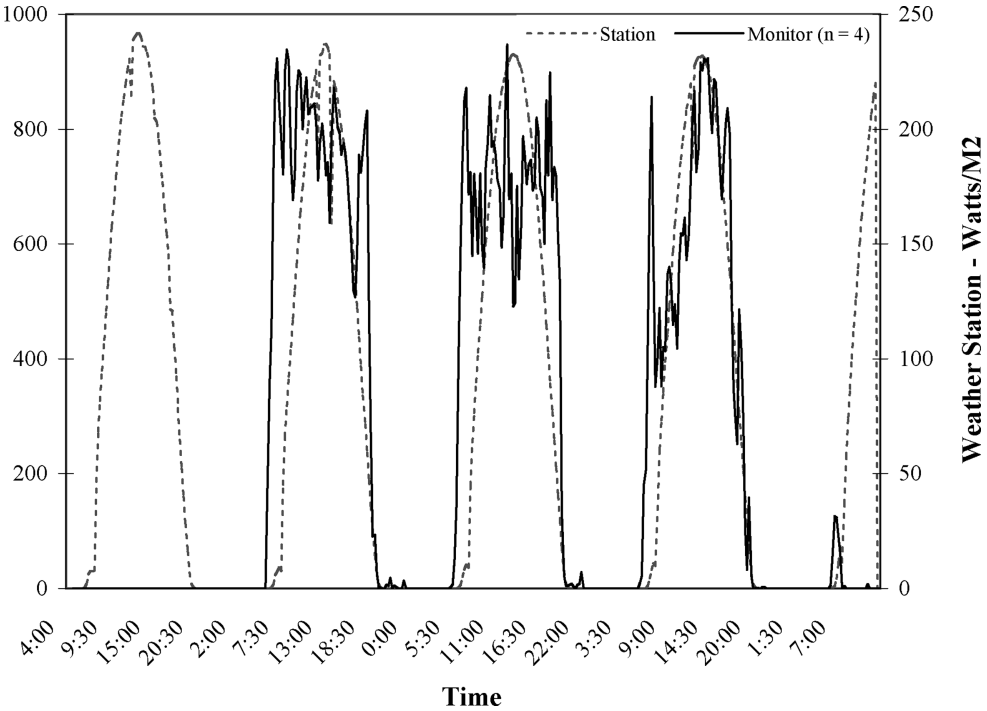

Fig. 6. Ambient light levels during the Camp Parks field study. Ambient light levels were recorded on the wrists of four subjects and the mean value derived. Weather station data were concurrently recorded at the site by a stationary device.

Although the importance of ambient temperature in regulating behavior is documented, the pattern of ambient temperature an individual is exposed to is difficult to obtain. Extreme heat or cold will have effects on a wide range of behaviors, including activity, sleep, and physical and mental performance. Subtle variations in climate are difficult to measure, but humans go to great lengths to regulate the ambient temperature they experience. Therefore, the monitor includes a solid-state thermistor which continuously assesses ambient temperature (Fig. 2F). Although ambient temperature is not the only environmental factor modulating thermal state, it is important. In field studies it is difficult to obtain information on ambient temperature conditions to which soldiers are exposed. Furthermore, even when climatic data are available, they do not describe the conditions an individual experiences, but rather the conditions at a stationary weather station (22). In the study conducted at Camp Parks discussed above, large variations in individual ambient temperatures were observed (**Fig. 7A**). The differences in individual temperature exposures at identical times in the geographically constrained environment of Camp Parks, where test subjects were rarely more than several hundred meters apart, were greater than 25°C. In this study, the stationary weather station recorded air and ground temperature. **Fig. 7B** presents both weather station data and mean temperature exposures in four subjects. The individual patterns of thermal exposure recorded by the vigilance monitors track the daily fluctuations in air temperature each day, but appear to be significantly damped, particularly with regard to the higher daytime temperatures recorded; presumably reflecting the behavioral responses of the wearer, who may have been avoiding the heat by moving to shaded locations. The pattern of light exposure on most days (Fig. 6) is consistent with this interpretation. Interestingly, it also appears that the lowest temperature individuals experienced occurred at dawn and dusk (Fig. 7B), not in the early morning hours.

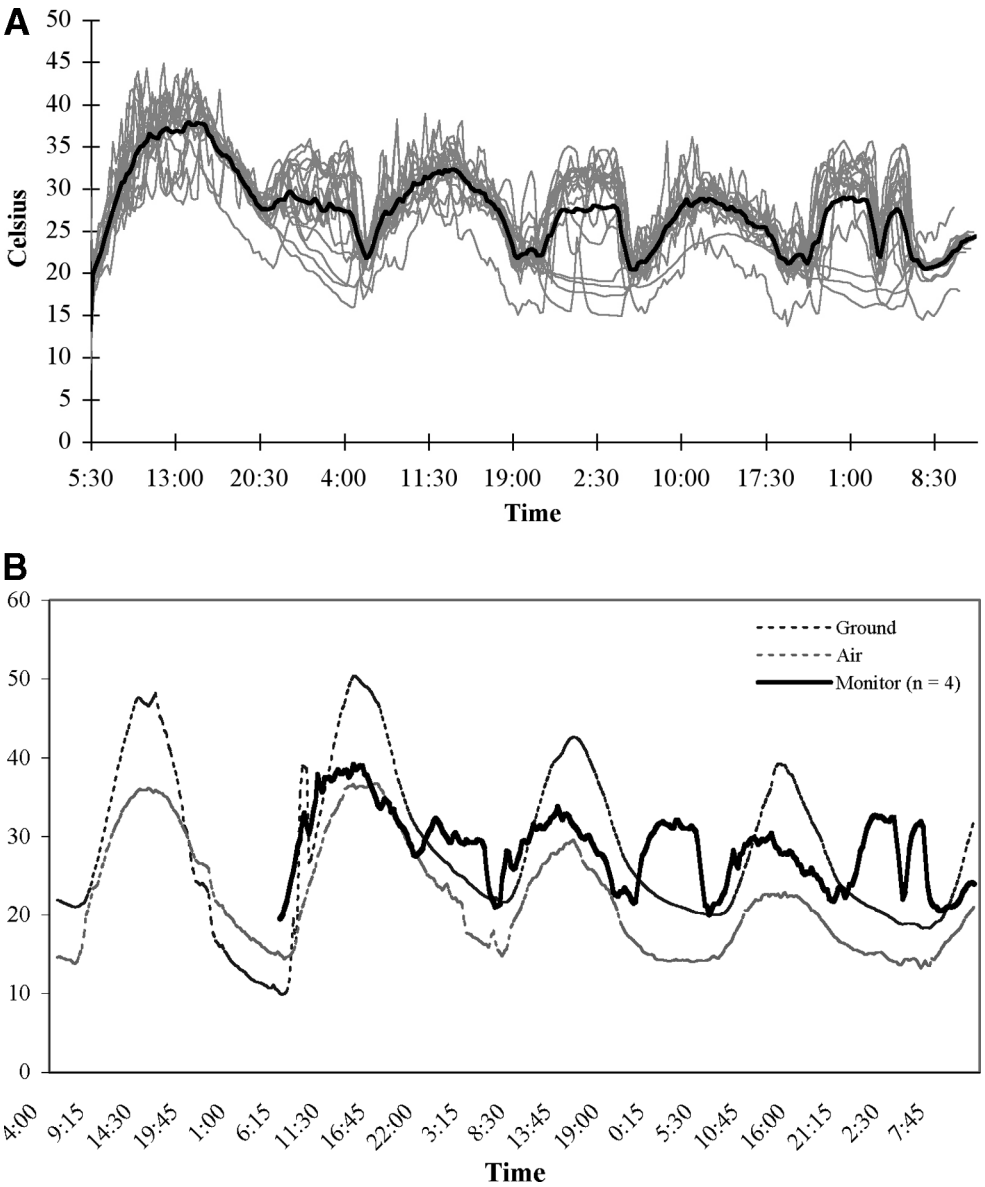

Fig. 7. A (Upper). Mean and individual temperature exposures during the Camp Parks field study. Data from individual monitors are plotted in gray. Mean temperature levels are plotted in black (n = 18). B(Lower). Mean temperature data from four subjects in the Camp Parks field study plotted with ground and air temperature simultaneously recorded by the weather station.

Discussion

Currently, the second and third generation devices are being used in a series of studies. In several studies, we are examining the ability of multifrequency actigraphy to improve estimates of energy expenditure compared with the standard actigraph (14). Another is using the devices to assess shivering. We have previously demonstrated that the devices can be programmed to acquire data at 50 Hz, sufficient to observe shivering, which occurs in humans in the 10-Hz frequency range (14). In a study conducted in a cold chamber (25), the monitors successfully documented the presence of shivering in a number of volunteers (14). In a recently completed study, the monitors were used to assess vigilance as volunteers navigated through complex environments (15). In one laboratory study, the monitors are being used to examine effects of different diets on cognitive performance and activity. The versatility of these devices, given their onboard computational power and programmability, memory capacity, environmental monitoring, and advanced actigraphic functions in combination with their behavioral assessment capabilities, has only begun to be explored. We believe they are well suited for examining and, if desired, modifying, cognitive performance as humans go about their daily lives, particularly in the environments in which warfighters must operate. This is what they were designed to accomplish. Clinical applications in situations where disease states adversely affect cognitive function are also possible.

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ACKNOWLEDGMENTS

This paper is dedicated to the memory of Mr. Mark Godwin; without his key contributions the second and third generation vigilance monitors could not have been designed or produced. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Department of the Army, Department of the Navy, the Department of Defense, or the U.S. Government. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provisions of 45 CFR, Part 46. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70–25 and USAMRMC Regulation 70–25 on the use of volunteers in research. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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