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UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

A Handbook for Choosing the Right Gear for Physiological Monitoring

Warfighter Performance Group

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14. ABSTRACT
This document is an abbreviated handbook to be used as a reference for individuals who do not have experience in physiological monitoring. This handbook provides basic overviews of different types of physiological monitoring available and some of the limitations of various products. The purpose is to help individuals make informed decisions regarding some of the products available on the market.

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Summary

The advancements in technologies to monitor physiological changes of the brain (electroencephalography [EEG], functional near-infrared spectroscopy [fNIRS]), eye activity (eye tracking), sweat response (electrodermal activity [EDA]), heart activity (electrocardiogram [ECG], photoplethysmography [PPG]), and breathing (respiration monitoring) are reshaping our understanding of and ability to optimize human performance across a multitude of sectors. These technologies provide a deep dive into the physiological and cognitive states of individuals, offering profound implications for enhancing performance, safety, and well-being in varied settings. Here's a summary of how these technologies are making strides across different fields and their potential future implications.

EEG's strategic advantage in various sectors

EEG technology stands out for its ability to assess cognitive workload and fatigue, offering a strategic advantage in optimizing system designs and enhancing Soldier and workplace performance. In healthcare, EEG's precision in diagnosis and monitoring enriches patient care significantly. Fitness professionals and sports coaches are using EEG data to tailor training programs that not only maximize performance but also mitigate injury risks. Educational strategies are being refined based on EEG findings related to attention and learning progression, aiming for more effective teaching methods. For product developers, understanding the applications and limitations of EEG guides the creation of innovative health devices, while regulatory bodies are provided a scientific basis for crafting policies for the use of physiological measurement tools. Emergency teams and military personnel benefit from EEG's ability to monitor stress and cognitive states, which is crucial for operational effectiveness and safety.

Eye tracking for cognitive workload assessment

Eye tracking technology offers precise, real-time evaluation of human attention and processing capacities, enhancing military training, healthcare outcomes, and workplace productivity. Overcoming challenges related to data quality and system integration can further leverage eye tracking's potential in understanding and optimizing cognitive performance.

EDA's role in understanding psychological state

EDA emerges as a pivotal tool for quantifying stress, emotional intensity, and attentional shifts. Its adaptability, and the evolution of wearable technologies, highlight its potential to revolutionize our approach to human performance and well-being.

fNIRS: Monitoring brain activity and oxygenation

fNIRS's versatility in assessing cognitive workload, fatigue, and attention in real-time makes it valuable across various disciplines. Its successful application hinges on addressing the device's footprint, compatibility, and user skill level, with evolving technology broadening its operational use.

The expanding market for ECG and PPG technologies

ECG and PPG technologies offer a non-invasive, real-time glimpse into heart functioning, with vast applications in operational settings, healthcare, fitness, and research. Their integration into diverse fields promises enhanced monitoring, assessment, and improvement of human performance.

Advancements in respiration monitoring

Sophisticated wearable technologies for respiration monitoring provide unique observations of cognitive workload, stress, and health, despite challenges like speech and movement artifacts. Ongoing advancements continue to improve their utility and accuracy.

As these various technologies evolve, they offer a promising avenue for continually expanding the boundaries of human performance and cognitive enhancement. Stakeholders across healthcare, fitness, military, and workplace wellness must stay informed of these advancements to fully leverage their potential, ensuring interventions' safety and effectiveness, and addressing ethical considerations. The future of human performance optimization is poised for significant growth, driven by technological advancements that bridge advanced neuroscience with practical applications, promising substantial benefits for individual and collective well-being.

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Introduction

The purpose of this abbreviated handbook is to provide a reference for individuals who do not have experience in physiological measurement. This reference will help them understand the uses and limitations of products presented to them, and most importantly, will help them make informed decisions regarding the operational use of different products. Table 1 below indicates potential users and how they may use this handbook.

Table 1. Overview of Potential Users of Handbook

Person	Description	Uses
Program manager	Persons running programs such as those developing new systems for the aircraft	To determine whether inclusion of physiological devices to measure workload, etc., is beneficial To aid in understanding the utility of various sensor products presented to them
Special Operations Command (SOCOM) leadership	Persons in a position to make decisions regarding acquiring various products to promote performance of Soldiers	To aid in understanding the utility of various sensor products presented to them
Healthcare providers and clinicians	Flight surgeons, doctors, nurses, and other healthcare professionals	To assist in understanding the options and limitations of integrating physiological measurement devices into patient care
Fitness professionals	Personal trainers, physiotherapists, and wellness coaches	To enhance their clients' fitness and wellness plans
Educators and researchers	Academics and students in fields such as kinesiology and sports and health sciences	To understand the practical aspects of using physiological measurement devices in their research or studies
Sports coaches and athletic trainers	Individuals responsible for training athletes	To integrate physiological measurements into training programs to optimize performance and monitor athletes' health
Corporate wellness managers	Individuals responsible for corporate health and well-being downrange	To incorporate health monitoring tools in corporate wellness programs
Product developers and engineers	Those in the process of developing health, fitness, or medical devices	To understand the user perspective and the practical

		limitations of existing measurement technologies
Regulatory and policy makers	Individuals involved in creating policies or regulations	To mandate proper and safe use of physiological measurement devices in various contexts, such as workplace wellness, public health initiatives, or sports
Health and fitness enthusiasts	Non-professionals	To make informed decisions about using physiological measurement devices for personal use
Human resources (HR) professionals	HR personnel	To understand health and wellness tools that could be offered as part of employee benefits packages
Emergency response teams and military personnel	Those in roles where physiological monitoring is utilized	Critical for ensuring the safety and effectiveness of team members in high stress or physically demanding situations

Electroencephalography (EEG)

What EEG can measure: Brain activity through sensors placed on the head or in the ear to assess cognitive states such as workload, fatigue, attention, and learning progress.

This can tell us:

- **How busy/overloaded someone is:** Useful for program managers and SOCOM leadership to assess operator workload and cognitive state during critical missions or system development phases.
- **How fatigued someone is:** Essential for healthcare providers, clinicians, and fitness professionals to monitor patient or client fatigue levels, aiding in tailored treatment or training plans.
- **Whether someone is distracted or paying attention:** Beneficial for educators, researchers, sports coaches, and corporate wellness managers to evaluate engagement and attention, optimizing learning environments or wellness programs.

Demonstrated usefulness:

- **Workload evaluation:** Provides an additional level of understanding of cognitive workload, supporting program managers and SOCOM leadership in decision-making processes regarding system enhancements or operator training.
- **Learning assessment:** Indicates when a skill has been acquired, assisting educators and trainers in assessing the effectiveness of training programs. However, it should complement other assessment methods rather than serve as the sole measurement tool.

What to consider when thinking about using EEG

Footprint:

- **Varies based on brand chosen and the amount of data required.**
- **Wired vs. wireless:** Wireless systems offer more mobility, critical for applications in field environments or when movement is necessary.
- **Needs a computer or smartphone to which data can be transmitted:** Important consideration for operational environments where equipment must be portable and easily integrable.

Skills needed to apply:

- **Varies based on the chosen system:** Some systems are designed for easy self-application, while others may require technical knowledge or assistance.

Time required to apply:

- **Depends on the chosen system:** Dry electrode devices are quicker to set up but may offer lower data quality, whereas wet electrode devices provide higher quality data but require more setup time.
- **More electrodes = more time to apply:** Important for planning in operational contexts where time is critical.

Helmet and personal protective equipment compatibility:

- **Some systems may fit beneath a helmet but could cause discomfort:** A key consideration for military and emergency response teams.
- **Several systems have been successfully worn with communication headsets:** Relevant for corporate wellness programs or sports coaching where communication devices are commonly used.

Operational use of EEGs

When considering EEG devices for operational use, it's crucial to evaluate:

- **Whether the system is wired or wireless:** Wireless systems may be more suited for dynamic or field environments.
- **How many electrodes it uses:** More electrodes can provide more detailed data but require more setup time.
- **Whether it has signal processing software, or if that must be done separately:** Integrated software can simplify data analysis, crucial for fast-paced operational settings.

Use case summary:

Program manager
EEG can help program managers in the development of new aircraft systems by providing a method of evaluating the cognitive workload of operators. By measuring brain waves while an aviator uses new aircraft systems, EEG can reveal whether cognitive workload is decreased, thereby increasing operator performance and safety.

SOCOM leadership
For SOCOM Leadership, EEG offers a valuable tool to assess the utility of various sensor products aimed at promoting Soldier performance. It can measure cognitive states like workload and fatigue, essential for making informed decisions about acquiring new technologies.

Healthcare providers and clinicians
EEG is indispensable for healthcare providers looking to incorporate physiological measurement devices into patient care. It aids in diagnosing and monitoring neurological disorders, evaluating patient responses to treatments, and understanding the effects of various conditions on brain activity.

Fitness professionals
For fitness professionals, EEG provides a way to enhance clients' fitness and wellness plans by monitoring brain activity related to stress, relaxation, and cognitive engagement during physical activities. This can help tailor more effective training programs.

Educators and researchers
EEG is a vital tool for educators and researchers in kinesiology, sports science, and health sciences, offering a method to gauge the brain's response to cognitive and physical tasks. It helps in understanding how different teaching methods or training regimens impact cognitive load and learning outcomes.

Sports coaches and athletic trainers
EEG allows sports coaches and athletic trainers to integrate physiological measurements into training programs. By monitoring brain activity, they can optimize performance, reduce the risk of overtraining, and better understand athletes' mental states.

Corporate wellness managers
For corporate wellness managers, EEG can support the design and implementation of wellness programs that incorporate health monitoring tools. It enables the assessment of stress, workload, and overall well-being in employees, contributing to more effective wellness strategies.

Product developers and engineers
EEG provides product developers and engineers with a method to evaluate user perspectives and practical limitations of existing measurement technologies. This knowledge is crucial for developing health, fitness, or medical devices that meet real-world needs.

Regulatory bodies and policy makers
EEG can inform regulatory bodies and policy makers about the safe and effective use of physiological measurement devices in various contexts. Understanding EEG applications and limitations aids in creating policies that ensure the well-being of users across different settings.

Health and fitness enthusiasts
For health and fitness enthusiasts, EEG offers a way to make informed decisions about using physiological measurement devices for personal health monitoring, including stress management, cognitive function improvement, and overall wellness.

Human resources professionals
HR professionals can use EEG insights to understand health and wellness tools that could be offered as part of employee benefits packages. It helps in selecting interventions that can improve workplace productivity and employee satisfaction.

Emergency response teams and military personnel
EEG is critical for emergency response teams and military personnel, where physiological monitoring can ensure the safety and effectiveness of team members in high-stress or physically demanding situations. It can detect states of fatigue, stress, and cognitive overload, which are crucial for mission success and personnel well-being.

Table 2. Summary of the Key Aspects and Findings of EEG Use

Category	Description	Implications
Brain waves	- Delta (0.5 to 4 Hertz [Hz]) - Theta (4 to 7 Hz) - Alpha (8 to 12 Hz) - Beta (13 to 25 Hz) - Gamma (25+ Hz)	Associated with varying degrees of cognition and functioning, allowing for the assessment of psychological and physiological phenomena
Historical development	First discovered by Hans Berger in 1929	Paved the way for the use of EEG in diagnosing and monitoring a range of disorders
Measuring EEG	Methods range from wireless systems with few electrodes to wired systems with many electrodes	Choice between mobility (wireless) and data quality (wired), depending on operational needs
Applications	- Monitoring cognitive engagement and performance - Diagnosing neurological disorders - Researching psychopathology and brain function	Enables real-time detection of cognitive states such as workload, fatigue, and attention
Operational use	Considerations include system footprint, skill level required, time to apply, and compatibility with personal protective equipment	Highlights the need for technology that balances ease of use with comprehensive data capture in various settings

Conclusion

The implications of EEG findings are profound across varied sectors, demonstrating its versatility as a tool for enhancing performance, safety, and well-being. For program managers and SOCOM leadership, EEG's ability to assess cognitive workload and fatigue offers a strategic advantage in optimizing system designs and Soldier performance, respectively. Healthcare providers can leverage EEG for precise diagnosis and monitoring, enriching patient care. Fitness professionals and sports coaches can tailor training programs based on EEG data to maximize performance while mitigating injury risks. In educational settings, EEG findings on attention and learning progression provide an additional tool for developing more effective teaching strategies. For product developers, understanding the applications and limitations of EEG guides the creation of innovative health devices. Regulatory bodies gain a scientific basis for crafting policies on the use of physiological measurement tools. Lastly, for emergency teams and military personnel, EEG’s role in monitoring stress and cognitive states is crucial for ensuring operational effectiveness and safety. Across all these applications, EEG stands as a cornerstone technology, bridging the gap between advanced neuroscience and practical, everyday applications.

Figure 1. Depictions of EEG systems (left, StarStim; right, Advanced Brain Monitoring B-Alert) that include pre-defined electrode placeholders.

Eye Tracking

What eye tracking can measure: Eye tracking measures cognitive workload, attention, fatigue, and task engagement through changes in eye movement dynamics, pupil size, and gaze patterns, providing insight into human cognitive processes and visual attention.

This can tell us:

- **How busy/overloaded someone is:** Eye tracking reveals increased fixations under heavy cognitive load, indicating higher processing demands.
- **How fatigued or impaired someone is:** Changes in pupil diameter signal shifts in cognitive effort, correlating with fatigue levels.
- **Whether someone is distracted or paying attention:** Analysis of gaze direction and fixation duration provides a method for evaluating focus and engagement levels.

Demonstrated usefulness:

- **Workload evaluation:** Eye tracking offers objective measurement of cognitive workload, enhancing understanding of human-machine interaction in computer-based tasks.
- **Learning assessment:** Identifies attentional allocation, aiding in the optimization of educational content delivery.

What to consider when thinking about using eye tracking

Footprint:

- **Varies by system:** Single-camera setups offer simplicity, but the scope of their view is limited, while multi-camera and head-mounted systems provide comprehensive tracking at the cost of increased complexity. Electrooculography (EOG) can also be used to measure where the eyes are looking using electrodes placed on the face.
- **Head-mounted vs. stationary:** This decision impacts mobility and data precision, with head-mounted devices offering detailed evaluations within dynamic environments.

Skills needed to apply:

- **Expertise in calibration and analysis:** Ensuring accuracy of eye tracking data requires technical skill, particularly in complex setups. The use of EOG is typically simpler to apply and use.

Time required to apply:

- **2-5 minutes for EOG systems:** Quick setup for straightforward applications.
- **5-10 minutes for simple camera systems:** Quick setup for straightforward applications.
- **10-30 minutes for advanced camera systems:** Preparation time increases with system complexity and environmental factors.

Helmet and personal protective equipment compatibility:

- **Varies with device design:** Head-mounted camera systems may need customization to fit under helmets without sacrificing comfort or data quality. EOG systems may be uncomfortable beneath helmets.
- **Some devices integrate with protective gear:** Tailored solutions can embed eye tracking into existing equipment.

Operational use of eye tracking devices

When considering eye tracking devices for operational use, it's crucial to evaluate:

- **Device adaptability:** Ensuring the system functions effectively in varied operational settings.
- **Data analysis depth:** Advanced software is necessary for translating raw data into actionable outcomes.
- **Impact of environmental factors:** Operational environments can influence data quality; robust systems mitigate these effects.

Use case summary:

Program manager
Eye measures can be used to validate the cognitive load implications of new systems, ensuring designs support optimal operator performance. By collecting eye measure data while new systems are used and tested, measures such as pupil diameter can help tell how the new systems impact cognitive load, and eye tracking can inform where individuals are fixating their attention.

SOCOM leadership
For SOCOM leadership, the use of eye measures can provide an evaluation of cognitive workload and attention to inform strategic decisions about equipment and training enhancements. This can be used to improve training efforts.

Healthcare providers and clinicians
Healthcare providers and clinicians may consider applying eye tracking in diagnostics and rehabilitation, monitoring cognitive states and recovery progress. Information regarding where individuals are looking and fixating attention during recovery could assist in providing an individualized care plan.

Fitness professionals
Eye tracking and other eye measures can be integrated into assessments, tailoring fitness programs to individual cognitive and physical capacities. This information can be used to improve coordination.

Educators and researchers
Eye measures can be employed to dissect learning processes, refining educational strategies for diverse cognitive styles. This can help inform ways of presenting information to ensure the information is displayed in an easy-to-consume way, ultimately improving learning outcomes.

Sports coaches and athletic trainers
Adopting eye tracking for athlete monitoring can assist in optimizing training regimens based on cognitive and visual attention. It can be used to improve hand-eye coordination and refine target identification and tracking.

Corporate wellness managers
Corporate wellness managers can implement eye tracking in wellness initiatives, tracking employee engagement and cognitive health. This can be used to refine health-promoting strategies and promote overall wellness and stress reduction.

Product developers and engineers
Developers and engineers can optimize designs with user-focused eye tracking research, enhancing usability and effectiveness. By integrating eye measures into the development process, the usability of a product in development can be evaluated at every stage of the process. This will ultimately lead to a product that is best suited for the end users.

Regulatory bodies and policy makers
Regulatory bodies and policy makers can shape policies around the safe and ethical use of eye tracking and eye measure technology in public and private sectors. The ethical use of eye measures is of the utmost importance given the ability to identify individuals with recordings of the eyes.

Health and fitness enthusiasts
Personal use of eye tracking can aid in health optimization by understanding cognitive responses to various activities. Eye measures could be used to improve hand-eye coordination and object identification, which can carry over into a variety of life settings, such as driving or sports.

Human resources professionals
Eye tracking technology may be used for evaluating different services for potential inclusion in comprehensive wellness packages. For example, eye tracking could be used to evaluate relaxation techniques that may be considered for improving employee health and well-being.

Emergency response teams and military personnel
The use of eye measures can enhance situational awareness and decision-making training through cognitive workload assessment. Eye tracking can be used to make improvements to techniques used by emergency response teams and military personnel, as well as in determining when additional training may be needed.

Table 3. Summary of Key Aspects and Findings in Eye Tracking Research

Category	Description	Observations
Eye movement metrics	Fixations, saccades, and pupil dynamics	Indicators of cognitive workload, attention, and engagement
Historical development	From early 1800s studies to modern infrared technology	Evolution of eye tracking for deeper cognitive and visual process understanding
Biological mechanisms	Controlled by oculomotor nuclei and cerebellum	Link visual attention to cognitive processes through eye movement
Device types	Single-camera, multi-camera, and head-mounted	Vary in complexity, field of view, and sensitivity to user movement
Operational use	Applications in military, healthcare, education, and usability testing	Provides objective data on user interaction and cognitive workload
Measuring eye metrics	Number of fixations, fixation duration, saccade amplitude, and pupil diameter	Metrics reflect cognitive effort, attention allocation, and mental state
Evaluating operator states	Used to assess cognitive workload, fatigue, and distraction	As a tool for real-time, objective measurement of operator performance and mental workload in various tasks

Conclusion

Eye tracking technology stands out as a powerful tool for assessing cognitive workload, providing precise, real-time insight into human attention and processing capacities. Its application spans from enhancing military training and operational readiness to improving healthcare outcomes and workplace productivity. By addressing the challenges of data quality and system integration, eye tracking can significantly contribute to the understanding and optimization of cognitive performance across various fields.

Figure 2. Pupil Core Binocular head-mounted headset (Pupil Labs, Berlin, Germany).

Electrodermal Activity (EDA)

What EDA can measure: EDA provides continuous, objective measures of psychological stress, emotional intensity, and attentional awareness by detecting changes in skin conductance related to autonomic nervous system activity.

This can tell us:

- **How busy/overloaded someone is:** EDA is a direct indicator of sympathetic nervous system activation, offering a view of cognitive load and stress levels without subjective bias.
- **How fatigued someone is:** Variations in skin conductance levels signal physiological arousal states, helping to identify fatigue through decreased responsiveness.
- **Whether someone is distracted or paying attention:** EDA fluctuations provide a window into momentary shifts in attention and cognitive engagement, capturing both conscious and subconscious awareness.

Demonstrated usefulness:

- **Workload evaluation:** By measuring sweat gland activity, EDA offers a quantifiable, continuous metric for assessing cognitive workload in dynamic tasks, enhancing operational performance analysis.
- **Learning assessment:** Utilized to gauge learner engagement and emotional response, EDA metrics support the optimization of educational methodologies and content delivery to improve learning outcomes.

What to consider when thinking about using EDA

Footprint:

- **Compact and adaptable to various settings:** EDA devices, especially wearables, offer unobtrusive monitoring, suitable for both laboratory and field applications.
- **Choice between wired and wireless systems:** Selection depends on the context of use, balancing data accuracy with participant mobility and comfort.
- **Minimal equipment requirement:** Modern EDA devices can interface with mobile technologies for data collection and analysis, promoting ease of use and accessibility.

Skills needed to apply:

- **Operational proficiency with EDA devices:** Understanding device setup, electrode placement, and basic troubleshooting to ensure high-quality data capture.

Time required to apply:

- **Rapid deployment:** Setup times vary from under 5 minutes for wearables to 10-15 minutes for more complex electrode placements, facilitating ease of integration into various research and operational contexts.

Helmet and personal protective equipment compatibility:

- **Versatility in electrode placement:** While optimal signal quality is obtained from hand placements, alternative sites can accommodate equipment constraints without significantly compromising data integrity.
- **Integration with existing safety gear:** Wearable EDA devices are designed to complement standard operational gear, minimizing interference with task performance.

Operational use of EDA devices

Key considerations for EDA measurement in operational settings:

- **System connectivity:** Assessing the practicality of wired versus wireless configurations to support user mobility.
- **Electrode configuration:** Determining the optimal number and placement of electrodes to balance data quality with operational feasibility.
- **Data processing capabilities:** Evaluating the need for onboard versus external signal processing to streamline data analysis workflow.

Use case summary:

Program manager
Program managers can consider employing EDA to determine the effect that new systems have on the end-users' stress and cognitive workload. This information can ultimately lead to the ability to provide objective physiological feedback to system developers, which would in turn enhance the system, and thereby the user's experience.

SOCOM leadership
SOCOM leadership can leverage EDA data for objective assessment of Soldier stress and readiness, informing training and operational decision-making. This can further be used to determine stress-reducing techniques and provide an objective method of determining their effectiveness.

Healthcare providers and clinicians
Providers and clinicians can integrate EDA into patient care protocols for monitoring stress and emotional states, supporting diagnostic and therapeutic interventions. The ability to monitor emotional states may improve the course of treatment and lead to more successful patient outcomes.

Fitness professionals
Fitness professionals could apply EDA in client's personal training programs to tailor stress management and cognitive engagement strategies, promoting overall wellness and potentially reducing recovery time.

Educators and researchers
EDA could be used to explore cognitive and emotional dynamics in educational settings, facilitating research into effective teaching practices. The use of EDA in these settings could also

assist in mitigating stress which may aid in reducing learning time.

Sports coaches and athletic trainers
By adopting EDA for athlete monitoring, coaches and trainers can evaluate stress levels and use EDA data to reduce and mitigate stress. The use of EDA to manage stress could ultimately lead to optimization of performance and recovery.

Corporate wellness managers
Wellness managers could implement EDA in wellness initiatives, offering data-driven approaches to stress reduction and emotional well-being in the workplace. EDA can be used to monitor stress levels and evaluate the impact of different interventions on reducing stress.

Product developers and engineers
Developers and engineers may use EDA to evaluate the cognitive load and stress that newly developed systems and products have on end-users. This can assist in the design of systems and products that minimally induce cognitive load or stress on the end-user.

Regulatory bodies and policy makers
Regulatory bodies and policy makers can determine the guidelines for the ethical use of physiological monitoring tools like EDA in public health, workplace wellness, and consumer products.

Health and fitness enthusiasts
The use of EDA for personal health monitoring can help to gain insight into stress management and emotional awareness for improved well-being. This would allow individuals to try different methods of stress management and evaluate their effectiveness by monitoring their EDA measurements.

Human resources professionals
HR professionals may consider EDA-based tools for employee wellness programs, aiming to enhance workplace productivity and employee satisfaction. EDA-based tools can also be used to assess the effectiveness of wellness programs in reducing employee stress.

Emergency response teams and military personnel
Emergency responses teams and military personnel may utilize EDA to enhance situational training and readiness assessment through real-time monitoring of stress and cognitive workload. By evaluating the feedback from EDA measures, it can be determined whether individuals are ready to perform.

Table 4. Summary of Key Aspects and Findings of EDA Research

Category	Description	Implications
Biological mechanisms	Reflects sympathetic nervous system activity through skin conductance	Provides a direct measure of psychological and cognitive state
Historical development	Used since the 1880s for psychophysiological research	Demonstrates long-standing reliability and applicability
Measuring EDA	Captures tonic and phasic changes in skin conductance	Accurately interprets autonomic nervous system response to stimuli
Applications	Applied in military, healthcare, education, and consumer research	Offers versatile utility across diverse fields for monitoring stress and engagement
Operational use	Suitable for real-time monitoring with minimal operational footprint	Enhances operational efficiency and safety by monitoring stress and workload

Conclusion

EDA is a pivotal tool in the quantification of psychological and cognitive states, offering nuanced understanding of stress, emotional intensity, and attentional shifts. Its adaptability across diverse operational environments combined with the evolution of wearable technologies underscores its potential to revolutionize the understanding and optimization of human performance and well-being. Through careful consideration of its application, EDA provides an invaluable resource for researchers, clinicians, and operational leaders seeking to harness the power of psychophysiological data in their work.

Figure 3. Examples of typical EDA recording setups.

Functional Near-Infrared Spectroscopy (fNIRS)

What fNIRS can measure: fNIRS is a non-invasive method of measuring brain activity through changes in blood oxygenation. It evaluates cognitive workload by tracking hemodynamic responses, identifying mental fatigue through oxygenation patterns, and determining attention levels by monitoring prefrontal cortex activity. fNIRS is also useful in assessing engagement in educational contexts and operational performance in scenarios like aviation and driving simulations. Its capability for real-time brain activity monitoring across various tasks makes fNIRS a valuable tool for research and applications in neuroscience, education, and human factors engineering, offering a method of evaluating cognitive states.

This can tell us:

- **How busy/overloaded someone is:** fNIRS measures brain activity to determine cognitive workload and mental engagement by monitoring changes in blood oxygenation levels, offering insight into how busy or overloaded someone is during various tasks.
- **How fatigued someone is:** fNIRS detects changes in oxygenated and deoxygenated blood related to brain fatigue levels. By observing shifts in oxy- and deoxyhemoglobin levels, fNIRS provides an indirect measure of brain fatigue, aiding in understanding mental endurance and the need for rest.
- **Whether someone is distracted or paying attention:** fNIRS identifies shifts in brain oxygenation indicating focus or inattention. fNIRS detects changes in the prefrontal cortex region to determine if an individual is distracted or fully engaged in the task at hand.

Demonstrated usefulness:

- **Workload evaluation in aviation and driving simulations:** fNIRS has been extensively used to monitor pilot and driver workload, showing increased oxygenation in the prefrontal cortex under high cognitive demands.
- **Learning assessment in educational settings:** This technology can measure student engagement and cognitive activity during learning tasks, offering potential for personalized education strategies.

What to consider when thinking about using fNIRS

Footprint:

- **Device size and setup vary by manufacturer:** The footprint of fNIRS systems can range from portable designs that require minimal equipment to more extensive setups that require a network of sensors and wires.
- **Wired systems offer stability, wireless systems ensure mobility:** While wired configurations provide stable data transmission, wireless systems are crucial for applications that require movement or operation in diverse environments.
- **Computer or smartphone integration is necessary for data analysis:** Real-time data processing and long-term data storage require integration with computing devices, affecting the choice of system based on available infrastructure.

Skills needed to apply:

- Basic anatomical knowledge and familiarity with the device are essential for correct sensor placement and optimal data collection, mirroring the skills required for EEG application but with a focus on the specificities of fNIRS technology.

Time required to apply:

- **Setup time depends on the complexity of the system:** Time can vary significantly, with simpler devices requiring minutes to apply, while more complex setups might take longer to ensure accurate sensor placement.
- **Preparation varies with device type:** Devices with predefined sensor caps offer quicker setup times compared to those requiring manual sensor placement.

Helmet and personal protective equipment compatibility:

- **Compatibility varies with device design:** Some fNIRS systems are designed to be worn under helmets, making them suitable for use in operational environments, though comfort and fit can vary.
- **Successful integration with communication headsets:** Certain fNIRS models have been effectively used alongside communication devices, suggesting potential for wide-ranging applications in field and professional settings.

Operational use of fNIRS

When considering fNIRS devices for operational use, it's crucial to evaluate:

- **The flexibility of wired vs. wireless systems:** This choice impacts the potential applications of fNIRS and the environments where the device can effectively be used.
- **The number of electrodes impacts data quality and comprehensiveness:** More electrodes provide more detailed brain activity maps but may require more setup time and increase the system's complexity.
- **The necessity and availability of signal processing software:** Devices that come with integrated software for real-time data analysis offer advantages in operational settings where immediate feedback is valuable.

Use case summary:

Program manager
Program managers could utilize fNIRS to enhance understanding and evaluation of cognitive workload in system development. This would aid in determining the utility of newly developed systems and how the system impacts the end-users' cognitive workload.

SOCOM leadership
SOCOM leadership can leverage fNIRS for evaluating sensor products aimed at enhancing Soldier performance. By understanding cognitive states under various conditions, leadership can make informed decisions on acquiring products that best support Soldiers in operational

environments. Evaluating data produced from fNIRS can help determine how the different products impact Soldier performance after being implemented.

Healthcare providers and clinicians
Integration of fNIRS into patient care to monitor brain oxygenation and activity can offer providers and clinicians a non-invasive method to assess brain health. This is particularly valuable in settings such as intensive care units, operating rooms, and patient monitoring systems.

Fitness professionals
Fitness professionals can employ fNIRS in fitness and wellness plans to understand the neurological impacts of physical exercise on cognitive functions. This allows for the optimization of training programs that not only target physical health, but also cognitive well-being.

Educators and researchers
Educators and researchers can apply fNIRS in research to investigate the neural basis of learning and cognitive engagement. This technology provides an evaluation of student engagement and learning efficiency, paving the way for tailored educational strategies.

Sports coaches and athletic trainers
fNIRS can be utilized by sports coaches and athletic trainers to monitor athletes' cognitive load and stress levels during training and competition. This information helps in customizing training regimens that maximize performance while monitoring mental fatigue.

Corporate wellness managers
For corporate wellness managers, integrating fNIRS into wellness programs can help to assess and improve employee cognitive function and stress management. This technology can provide a data-driven understanding for developing programs that enhance productivity and well-being.

Product developers and engineers
Product developers and engineers can use fNIRS data to inform the design and development of health, fitness, and medical devices. Data derived from fNIRS can provide a unique understanding of user needs and help to identify the practical limitations of human cognition to aid in creating effective products.

Regulatory bodies and policy makers
fNIRS studies can be leveraged to guide the development of policies and regulations regarding the use of physiological measurement devices in various contexts, ensuring safety, efficacy, and ethical use.

Health and fitness enthusiasts
Individuals who are health and fitness enthusiasts can benefit from personal fNIRS devices to monitor cognitive state during physical activity, aiming to optimize personal health and performance through informed decisions.

Human resources professionals
HR professionals can explore fNIRS tools for health and wellness benefits packages, offering employees access to cutting-edge technology for monitoring their cognitive health and workload. These tools have the potential to be used in reducing stress and promoting healthy techniques for managing high workloads.

Emergency response teams and military personnel
Emergency response teams and military personnel can implement fNIRS in training and operational contexts to monitor cognitive workload, fatigue, and stress in high-stress environments, enhancing team effectiveness and decision-making under pressure.

Table 5. Summary of Key Aspects and Findings of fNIRS Research

Category	Description	Implications
Cognitive workload	Measures the hemodynamic response to cognitive tasks	Enables assessment of mental workload and identification of cognitive overload, facilitating optimization of task design
Fatigue	Observes fluctuations in blood oxygenation to indicate mental fatigue	Aids in determining the need for rest and adjusting work schedules to prevent cognitive decline
Attention and focus	Monitors activity in the prefrontal cortex related to focus	Provides an evaluation of engagement levels, helping tailor interventions to improve concentration
Engagement and learning efficiency	Evaluates cognitive activity in educational settings	Offers potential for personalized learning approaches by assessing student engagement
Operational performance	Used in high-demand environments to evaluate cognitive states	Enhances understanding of performance under stress, informing training and operational strategies
Historical development	Originated from the development of optical methods for tissue oxygen monitoring	Paved the way for non-invasive brain activity monitoring, highlighting the evolution of neuroimaging techniques
Measuring fNIRS	Utilizes light absorption properties of hemoglobin to measure brain activity	Allows for the indirect measurement of neural activity through hemodynamic responses
Applications	Extends across neuroscience, psychology, education, and more	Demonstrates the versatility of fNIRS in providing valuable insight into human

		cognition and behavior
Operational use	Considerations include device footprint, helmet compatibility, and skill required for application	Impacts the feasibility and effectiveness of fNIRS in real-world settings, from clinical to field applications

Conclusion

fNIRS is a versatile tool for monitoring brain activity and oxygenation in various settings, from medical to operational environments. Its capability to assess cognitive workload, fatigue, and attention in real-time makes it valuable across multiple disciplines. However, successful application depends on careful consideration of the device's footprint, compatibility with protective equipment, and the user's skill level. As fNIRS technology continues to evolve, its integration into operational use expands, offering new possibilities for enhancing performance, safety, and wellness.

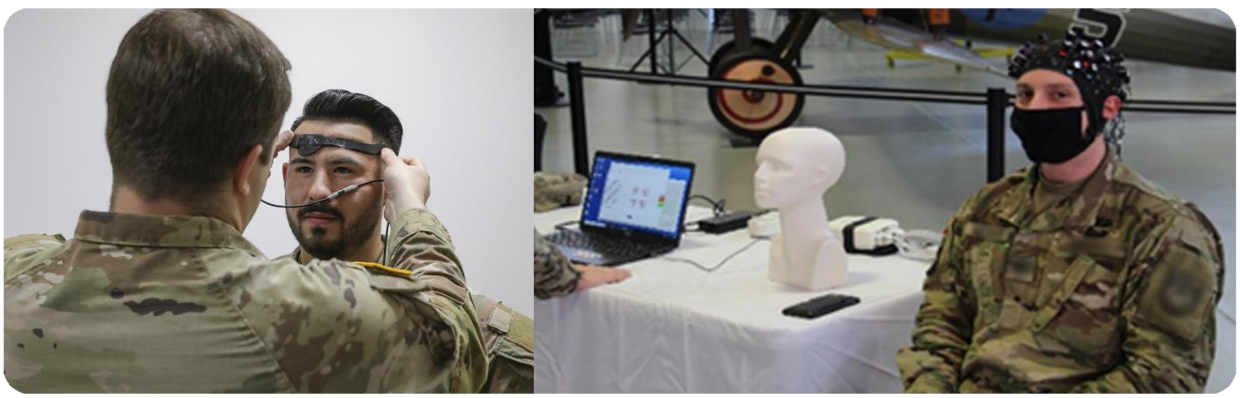

Figure 4. fNIRS systems. (left, example of a headband fNIRS system [NIRSense]; right, example of a full head fNIRS system [NIRx]).

Electrocardiography (ECG) and Photoplethysmography (PPG)

What ECG and PPG can measure: ECG and PPG are technologies used to measure the electrical and volumetric changes associated with the cardiac cycle. ECG captures heart rate (HR), heart rate variability (HRV), and electrical activity related to heart muscle function, offering an understanding of cardiac health and stress levels. PPG, through light-based sensors, measures blood volume changes in the microvascular bed of tissue, providing data on HR, HRV, and circulatory health. Together, they can assess physiological states like cognitive workload, fatigue, stress, and overall cardiovascular health, making them invaluable in healthcare, fitness, and research settings.

This can tell us:

- **How busy/overloaded someone is:** HR and HRV analysis can indicate cognitive or physical workload.
- **How fatigued someone is:** Examination of HR and HRV values can indicate fatigue, with lower HR averages indicating fatigued states; HRV changes can indicate sleep deprivation effects.
- **Whether someone is distracted or paying attention:** Variations in HR and HRV can suggest shifts in cognitive states such as attention.

Demonstrated usefulness:

- **Workload evaluation:** ECG and PPG technologies play a crucial role in assessing workload impacts on individuals by tracking HR and HRV. An increase in HR alongside a decrease in HRV is indicative of heightened cognitive effort or physical stress, serving as objective measures to evaluate workload in both operational and research settings. This data can help tailor tasks to prevent cognitive overload and optimize performance, especially in high-stress professions such as military or emergency response roles.
- **Learning assessment:** The variability in heart rate metrics, captured by ECG and PPG, offers a window into the learner's cognitive process and engagement levels. Fluctuations in HR and HRV can signal changes in attention, stress, and mental workload during learning tasks, providing educators and trainers with feedback to adjust instructional strategies. This ensures that educational content is delivered at an optimal pace and complexity level, fostering a conducive learning environment that adapts to the learner's physiological state.

What to consider when thinking about using ECG and PPG

Footprint:

- **Ranges from wrist-worn devices to chest bands:** The small size and flexibility of these devices minimize interference with daily activities, making continuous monitoring feasible and non-intrusive. This versatility supports a broad range of applications, from fitness tracking to clinical monitoring, without compromising user comfort or activity.

- **Wired vs. wireless:** The shift toward wireless technology enhances user mobility and facilitates the integration of heart rate monitoring into various aspects of life, including high-mobility operational scenarios where freedom of movement is crucial.
- **Requires a smartphone or computer for data transmission:** The necessity for an external device for data analysis and storage underscores the importance of accessible technology in maximizing the utility of ECG and PPG data, enabling users to make informed decisions based on their physiological data.

Skills needed to apply:

- **Basic training for electrode placement:** Proper training ensures the reliability of data collected, highlighting the importance of accuracy in electrode placement for effective heart rate monitoring. This foundational skill is essential for both healthcare professionals and individuals using personal devices, ensuring that the data collected is both accurate and meaningful.

Time required to apply:

- **Quick setup for wearable devices:** The ease of setup for wrist-worn devices and chest bands facilitates use in a wide range of scenarios, from everyday fitness tracking to acute clinical monitoring, streamlining the process of capturing valuable heart rate data.
- **Slightly longer for multi-lead ECG setups:** The complexity of applying multi-lead ECG systems is balanced by the depth of data they provide, making them invaluable tools in detailed cardiac monitoring, especially in clinical settings where precise data is critical for diagnosis and treatment planning.

Helmet and personal protective equipment compatibility:

- **High compatibility with most personal protective equipment:** The design of modern ECG and PPG devices prioritizes compatibility with personal protective equipment, ensuring that individuals in hazardous occupations can benefit from continuous physiological monitoring without compromise.
- **Consider potential discomfort:** It's important to balance the benefits of continuous monitoring with the potential discomfort of long-term wear, especially in environments where equipment is worn tightly against the body. Device selection and placement should consider the user's comfort and the potential impact on data accuracy.

Operational use of ECG and PPG

When considering these devices for operational use, it's crucial to evaluate:

- **Wireless connectivity:** This feature is paramount for real-time monitoring in dynamic environments, allowing data to be transmitted and analyzed instantaneously, which is crucial for rapid decision-making in critical situations.
- **Number of sensors:** The choice between simplicity and detail in data collection must be balanced according to the specific needs of the operation. More sensors may provide comprehensive data but can also introduce complexity in setup and analysis.

- **Built-in signal processing:** Devices equipped with advanced signal processing can reduce the need for expert analysis, making heart rate data more accessible and actionable for users across a wide range of applications, from health monitoring to enhancing operational performance.

Use case summary:

Program manager
Program managers can leverage ECG and PPG data to assess the physiological impact of new systems on operators, ensuring that these systems do not exacerbate cognitive or physical stress. The historical progression from the original discovery to modern wearable technology underscores the potential for integrating these sensors into next-generation equipment, improving real-time decision-making and operator health monitoring.

SOCOM leadership
SOCOM leadership can utilize information from ECG and PPG technologies to evaluate Soldier readiness and stress levels in various operational environments. Understanding the nuances of HRV and its correlation with cognitive and physiological states such as workload, fatigue, and stress can guide leadership in tailoring training programs and missions to optimize performance and mitigate risks.

Healthcare providers and clinicians
For healthcare professionals working in high-stress environments like military healthcare settings, ECG and PPG technologies provide non-invasive methods to continuously monitor cardiovascular health. The ability to detect early signs of fatigue, stress, or hypoxia can transform patient care, allowing for timely interventions and personalized health monitoring.

Fitness professionals
Personal trainers and wellness coaches can use ECG and PPG measurements to design personalized fitness programs that accurately reflect an individual's cardiovascular response to exercise. Understanding the biological mechanisms of the cardiac cycle and its representation in ECG and PPG tracings enables professionals to optimize workout intensity and recovery for maximum health benefits.

Educators and researchers
Academics can explore the vast historical development and application of ECG and PPG in understanding human physiology. By integrating these technologies into studies, researchers can investigate the effects of cognitive load, stress, and physical activity on heart rate metrics, contributing to a deeper understanding of human health and performance.

Sports coaches and athletic trainers
Coaches can utilize ECG and PPG data to monitor athletes' cardiovascular responses to training, identifying optimal stress levels for peak performance and recovery. The distinction between ECG's electrical measurement and PPG's volumetric blood flow measurement offers a comprehensive view of an athlete's heart health and conditioning.

Corporate wellness managers
In corporate wellness programs, ECG and PPG devices can monitor employee stress and overall well-being. By analyzing HR and HRV, wellness managers can develop initiatives that promote health, reduce stress, and improve productivity, leveraging technology for healthier work environments.

Product developers and engineers
The detailed history and evolution of heart rate monitoring technologies provide a foundation for developing innovative ECG and PPG devices. Engineers can focus on creating more accurate, user-friendly, and secure wearable devices that cater to the needs of diverse user groups, from athletes to military personnel.

Regulatory and policy makers
Understanding the scientific basis and applications of ECG and PPG is crucial for developing policies that ensure the safe and effective use of these technologies. Policy makers can set standards for device accuracy, data privacy, and ethical use, especially in sensitive operational settings.

Health and fitness enthusiasts
Individuals interested in personal health and fitness can use ECG and PPG wearables to monitor their heart rate dynamics during various activities. Monitoring this allows for more informed decisions about exercise intensity, recovery needs, and overall health management.

Human resources professionals
HR professionals can consider ECG and PPG devices as part of comprehensive wellness benefits, offering employees tools to monitor and manage their stress and fitness levels. This approach supports a culture of health and well-being within an organization.

Emergency response teams and military personnel
For teams operating in high-stress environments, continuous monitoring of HR and HRV can be critical. ECG and PPG technologies offer practical solutions for assessing physiological stress, fatigue, and readiness in real-time, enhancing operational effectiveness and safety.

Table 6. Summary of Key Aspects and Findings of ECG and PPG

Category	Description	Implications
Historical development	Evolution from Galvani's experiments to modern wearable technologies	Highlights the robust scientific foundation and continuous innovation in heart rate monitoring
Measuring ECG and PPG	Techniques for capturing heart rate and variability using wearable devices	Demonstrates the practicality and versatility of current technologies in various settings
Applications	Use in healthcare, fitness, research, and operational settings	Shows the wide applicability and relevance across sectors
Operational use	Integration into military, emergency response, and high-stress environments	Underscores the reliability and necessity of heart rate monitoring in critical situations

Conclusion

As the market for wearable health monitoring devices continues to expand, the potential applications of ECG and PPG in operational settings, healthcare, fitness, and research are vast. These technologies offer a non-invasive, real-time window into the human heart's functioning, providing invaluable understanding of physiological and cognitive states that influence performance, health, and well-being. As we continue to explore and understand these complex measurements, the integration of ECG and PPG into diverse fields promises to enhance our ability to monitor, assess, and improve human performance across a spectrum of activities.

Figure 5. Examples of ECG recording setups (left, four-lead Shimmer device; right, band-only Polar H10).

Respiration

Respiration monitoring can measure breathing rate, depth, and patterns, providing insight into cognitive workload, stress levels, fatigue, and engagement. Respiration rate can provide information about physiological and cognitive state, aiding in health assessment, fitness optimization, learning effectiveness, and operational readiness by tracking changes in respiratory patterns in response to various physical and mental activities.

This can tell us:

- **How busy/overloaded someone is:** Advanced respiration monitoring has demonstrated that as cognitive or physical demands increase, so does respiration rate. This increase is not merely a reflection of physical exertion, but aligns with heightened mental workload, offering a direct window into the body's stress response mechanisms.
- **How fatigued someone is:** Fatigue alters respiration patterns, typically leading to deeper, more pronounced breaths as the body attempts to increase oxygen intake. Monitoring these subtle changes provides clues to an individual's state of fatigue, crucial for managing work-rest cycles effectively.
- **Whether someone is distracted or paying attention:** Fluctuations in breathing rate and depth can indicate shifts in attention levels. Irregular respiration patterns may suggest distraction, while steady, consistent patterns could imply focused attention, making respiration monitoring a valuable tool in assessing engagement.

Demonstrated usefulness:

- **Workload evaluation:** Studies have found a correlation between increased respiration rates and higher cognitive loads. This relationship underscores the utility of respiration monitoring in evaluating mental workload, offering a non-intrusive means to optimize task allocation and design in both workplace and military settings.
- **Learning assessment:** The link between respiration patterns and cognitive processing depth provides educators and trainers with a physiological marker of student engagement and learning efficiency. This information can guide the development of educational strategies that are tailored to maintain optimal cognitive load for enhanced learning outcomes.

What to consider when thinking about using respiration monitoring

Footprint:

- **Compact sensors with minimal interference:** Modern respiration monitoring devices, such as wearable bands or stick-on sensors, are designed to be unobtrusive, allowing for continuous monitoring without disrupting normal activities.
- **Preference for wireless connectivity:** The shift toward wireless technology facilitates data collection in real-time, which is crucial for applications requiring mobility and flexibility, including field operations and sports training.
- **Reliance on external devices for data analysis:** The need for a smartphone or computer to process the collected data underscores the importance of integrating respiration

monitoring with existing digital infrastructure for efficient data management and analysis.

Skills needed to apply:

- **Range from basic observation to technical setup:** The simplicity of basic respiration rate monitoring contrasts with the more complex requirements of setting up and interpreting data from advanced sensors. Varying levels of training may be needed, depending on the application complexity.

Time required to apply:

- **Immediate to extended setup times:** While counting breaths can be performed almost instantly, deploying sophisticated sensor systems necessitates additional preparation, influenced by factors like body composition and sensor type.

Helmet and personal protective equipment compatibility:

- **Designed for compatibility with personal protective equipment:** The integration of respiration sensors into personal protective equipment, including helmets, ensures safety without compromising monitoring capabilities. However, user comfort and sensor stability under extreme conditions remain areas for consideration.

Operational use of respiration monitoring

Critical evaluation criteria:

- **Wireless vs. wired configurations:** The operational context dictates whether wireless or wired configurations are suitable, with wireless options offering essential mobility for field applications.
- **Sensor quantity and sophistication:** A higher number of sensors can provide more comprehensive data but may require more intricate setup and calibration.
- **Necessity for embedded signal processing:** Devices with onboard processing capabilities streamline data usage, making real-time decisions based on physiological status more feasible.

Use case summary:

Program manager
Utilizing respiration monitoring technologies enables program managers to quantitatively assess the impact of system designs on operator workload, facilitating the development of systems that enhance performance without increasing cognitive strain.

SOCOM leadership
In military contexts, respiration monitoring provides an actionable evaluation of Soldier readiness and stress levels and is essential for mission planning and personnel management, especially in high-stakes environments.

Healthcare providers and clinicians
For healthcare professionals, respiration monitoring offers a window into patient respiratory health, aiding in the diagnosis and management of conditions that affect breathing patterns, as well as monitoring stress and recovery in clinical settings.

Fitness professionals
By integrating respiration data, fitness professionals can more accurately gauge exercise intensity and recovery, tailoring programs to optimize physiological benefits and avoid overtraining.

Educators and researchers
The correlation between respiration patterns and cognitive load presents a unique opportunity for educators and researchers to explore the physiological underpinnings of learning processes and cognitive engagement.

Sports coaches and athletic trainers
Respiration monitoring equips coaches and trainers with critical data to optimize athlete performance, focusing on efficient breathing techniques and stress management to enhance endurance and recovery.

Corporate wellness managers
In the corporate realm, respiration monitoring can be a cornerstone of wellness programs aimed at reducing workplace stress, promoting mindfulness, and improving overall employee health.

Product developers and engineers
The advancement in respiration monitoring technologies challenges product developers and engineers to innovate, creating more accurate, comfortable, and user-friendly devices for a wide range of applications.

Regulatory bodies and policy makers
As respiration monitoring technologies proliferate, regulatory bodies and policy frameworks must evolve to ensure the safe, ethical, and effective use of these devices, safeguarding user data.

Health and fitness enthusiasts
Individuals interested in personal health optimization can leverage respiration monitoring to inform their wellness practices, from stress management to exercise programming.

Human resources professionals
HR departments can introduce respiration monitoring as part of comprehensive wellness initiatives, offering employees tools to manage stress and improve well-being.

Emergency response teams and military personnel
For those in high-stress operational roles, continuous respiration monitoring can be a critical tool for maintaining operational readiness and managing physiological stress.

Table 7. Summary of Key Aspects and Findings of Respiration Monitoring Use

Category	Description	Implications
Historical development	Respiration mechanics were first explored during the classical Greek period, evolving significantly with innovations like the pulse oximeter in 1974	Highlights the long history of innovation in respiratory monitoring, underscoring its importance in health and cognitive state assessment
Measuring respiration	Techniques range from simple breath counting to advanced wearable sensors measuring breathing rate, tidal volume, and oxygen saturation	Diverse methods enable tailored applications from basic health checks to comprehensive physiological monitoring
Applications	Used in healthcare for diagnosing respiratory conditions, in fitness to optimize training, in education for learning assessment, and in military for operational readiness	Demonstrates respiration monitoring's versatility in assessing and enhancing human performance and health across various domains
Operational use	Considerations include sensor footprint, skill level required for application, time to apply, personal protective equipment compatibility, device robustness, and data privacy	Operational effectiveness depends on ease of use, reliability under different conditions, and secure data management, impacting wide-ranging deployment in real-world settings

Conclusion

The evolution of respiration monitoring from basic observational techniques to sophisticated wearable technologies has opened new avenues for understanding human physiology in-depth. By providing real-time evaluation of respiratory patterns, these technologies offer a unique perspective on cognitive workload, stress, engagement, and overall health. Despite the challenges posed by speech and movement artifacts, ongoing advancements in sensor design and data processing continue to enhance the utility and accuracy of respiration monitoring across diverse applications. As we harness these technologies for health, performance, and well-being, the potential to optimize cognitive and physical capacities through targeted interventions becomes increasingly tangible.

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