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Light and the Brain: Exploring Neurons and Light Sensitivity

BIOS4YOU AR 2.0

BIO-INSPIRED STEM TOPICS FOR ENGAGING YOUNG GENERATIONS THANKS TO THE USE OF AUGMENTED REALITY

Project Number: KA220-BW-23-30-126516

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General topic of the learning path	Neuroscience and Light: Understanding Brain Responses to Light
Specific name of the learning unit	Light and the Brain: Exploring Neurons and Light Sensitivity
Target user age	14-18 years
Learner prerequisites	Basic knowledge of Biology, Physics
Description of the learning unit	This unit will guide teachers and students on how light affects the brain and how neurons respond to external stimuli like light. AR tools will enhance visualization, allowing students to interact with 3D models of neurons and brain structures. Students will explore real-world applications such as circadian rhythms, optogenetics, and light therapy.
Subjects involved	Physics, Biology, Neuroscience, Cognitive Science
Keywords	Light, Neuroscience, Neurons, Brain, Circadian Rhythms, Optogenetics, AR, Visualization, Interactive Learning
Key-skills, abilities, knowledge that can be acquired	- Understanding how neurons communicate and respond to stimuli - Exploring light's impact on brain functions like sleep, alertness, and emotions - Problem-solving skills through real-world applications (e.g., light therapy, optogenetics) - AR-based visualization and interactive learning with brain models
Resources and didactic tools used	Research papers, books, scientific databases, online resources, AR tools (e.g., Merge Cube, JigSpace, BrainVR, Google Expeditions).
Evaluation criteria and assessment	Based on the knowledge, abilities, and skills gained during the course, including AR-based assessments, interactive simulations, problem-solving tasks, and student reflections on light and the brain.

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Introduction:

Light significantly influences human physiological and cognitive processes, extending beyond vision to affect neural activity, emotions, and biological rhythms. Light is a significant environmental factor that affects various brain functions. Clinical studies have demonstrated the therapeutic potential of light therapy in treating conditions such as depression, cognitive impairment, chronic pain, and sleep disorders. However, the exact biological mechanisms through which light therapy exerts its effects remain incompletely understood (Huang et al., 2024).

The brain processes light through visual and non-visual pathways, regulating essential functions such as circadian rhythms, pupil reflexes, and cognitive performance. Recent research has demonstrated that bright light enhances cognitive performance by influencing hypothalamic activity, suggesting a direct link between light exposure and mental sharpness (https://neurosciencenews.com/cognition-bright-light-25973/?utm). Furthermore, studies have shown that light exposure behaviors predict mood, memory, and sleep quality, emphasizing the critical role of light in neurophysiological regulation (*Siraji et al., 2023*).

In neuroscience, optogenetics has emerged as a revolutionary technique that combines optics and genetics to control and monitor the activity of individual neurons in living tissue. Advances in optogenetics have expanded its applications beyond basic research, enabling the regulation of cellular activities for biomedical treatments such as photomedicine and immunotherapy (*Chen et al., 2022*).

These developments highlight the therapeutic potential of light-based interventions in treating central nervous system disorders, offering new possibilities in Nseurotherapy (*Geng et al., 2023*).

Additionally, light intervention has been shown to significantly impact alertness and mental performance, particularly in counteracting cognitive fatigue during the post-lunch dip, demonstrating how controlled light exposure can optimize human efficiency (*Askarpoor et al., 2019*).

This training unit introduces students to the interdisciplinary connections between neuroscience, physics, and biomedical applications, focusing on how light influences brain activity and cognitive performance. Students will use the Brainapse augmented reality app to engage in interactive and visually enriched learning experiences. Through dynamic 3D brain models and animated neural pathways, they will explore how neurons respond to stimuli such as light and how these responses relate to cognitive and sensory functions. By immersing students in realistic visualizations of brain structures and processes, Brainapse supports a deeper understanding of neural function and encourages critical thinking about the role of light in neuroscience research and light-based therapeutic technologies.

Dual Systems of Light Detection: Photoreceptors and Neural Pathways

In animals, including humans, photoreceptors (light-sensing cells) called rods and cones are located in the retina, a tissue layer at the back of the eye that responds to light. The rods and cones analyze visual signals transmitted via electrical signals to the brain, which interprets what is "seen." Another type of photoreceptors in the retina, called intrinsically photosensitive retinal

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ganglion cells (ipRGCs), use long protrusions (axons) that form the optic nerve to convey visual signals from rods and cones. The ipRGCs also perform other functions, such as setting the body's light-driven circadian rhythms and distinguishing contrast and color. It has been known that photoreceptors in animals detect light by using a signaling pathway named for the cell's origin (https://www.hopkinsmedicine.org/news/newsroom/news-releases/2024/01/retinal-photoreceptors-use-dual-pathways-to-tell-brain-ive-seen-the-light).

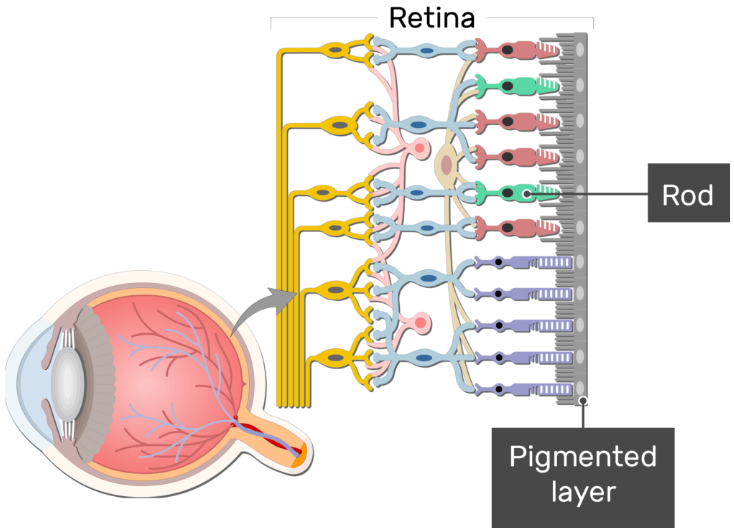

Figure 1. https://www.getbodysmart.com/sensory-system/retina/

People spend a significant portion of their lives indoors, estimated at around 80% to 90% (Thach et al., 2020). As such, the impact of indoor environments on occupant comfort has become a central focus in research and practice (Lamb et al., 2016). In recent years, growing attention has been given to the crucial role of thermal and lighting conditions in shaping office environments (Konstantzos et al., 2020). These environmental factors have been shown to strongly influence employees' stress levels and task performance, ultimately affecting overall individual and team satisfaction (Witterseh et al., 2004). Among these, correlated color temperature (CCT) and thermal sensation are critical, as they directly impact comfort, stress, and performance in indoor spaces.

How Light Affects Biological Systems

Changes in lighting conditions have broad effects on diverse physiological and behavioral functions, including circadian rhythm, mood, and cognition (LeGates et al., 2014).

The stability of the solar cycle serves as a crucial cue for regulating mammalian behavior, mainly through its significant impact on mood and cognitive function. These influences have been extensively studied in laboratory animals (Bedrosian et al., 2011; LeGates et al., 2012) and humans (Vandewalle et al., 2010). Disruptions in light exposure, whether due to natural

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environmental factors or human activities such as crossing time zones and experiencing jet lag, as well as engaging in shift work, have been associated with depressive symptoms and cognitive impairments (Roh et al., 2016).

- Circadian Rhythmus

Circadian health is essential for aligning human internal biological clocks with natural light-dark cycles. It is crucial for overall well-being and impacts sleep, mood, and metabolism.
This internal clock is located in a tiny cluster of cells known as the suprachiasmatic nucleus (SCN). The SCN is in a part of your brain called the hypothalamus. Throughout the day, internal clock genes in the SCN send signals to control the activity throughout your body.

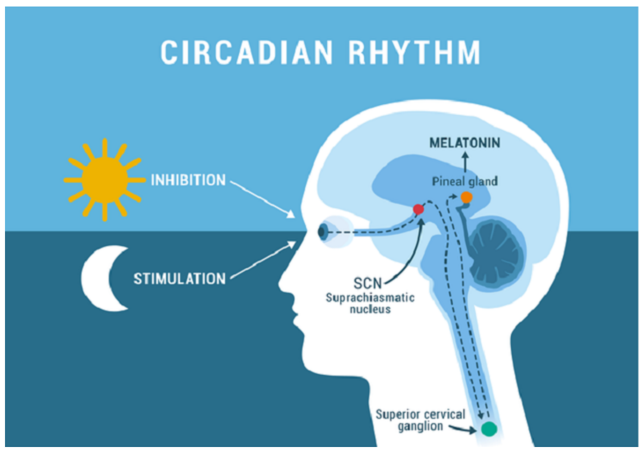

Figure 2. Circadian rhythm, source: https://www.okoa.org/articles/circadian-rhythm-see-what-is-it

Circadian lighting conditions formed by transmitted daylight present opportunities to enhance both energy efficiency and indoor health. These influential factors on circadian daylight can be categorized into four dimensions. These dimensions are: a) variation of the daylight source, which relies on solar and sky conditions; b) optical and morphological properties of the window glazing that effectively alter the transmitted light spectral power distribution and intensity; c) interior space design and surface spectral feature influence the transmitted light distribution within the space; and the last one is d) human factors that affect the amount of exposure to circadian daylight by varying the direction of the human gaze and their corneal height. Engineers and architects can focus on dimensions in the context of these four factors. Window properties and indoor spatial conditions promote a healthy indoor environment influenced by circadian light, as dimensions of daylight source and Human factors are unpredictable and uncontrollable (Ardabili et al., 2025).

- The Pupil Reflex: How do our eyes respond to light?

Our pupil's ability to change size is an essential physiological response that adjusts the amount of light hitting the retina to optimize vision and protect the retina. Pupils constrict in response to brightness, whereas they dilate in response to dark conditions (known as the pupillary light response or reflex). In contrast, these responses are related; they are considered to be driven by different neural pathways (Mathôt, 2018).

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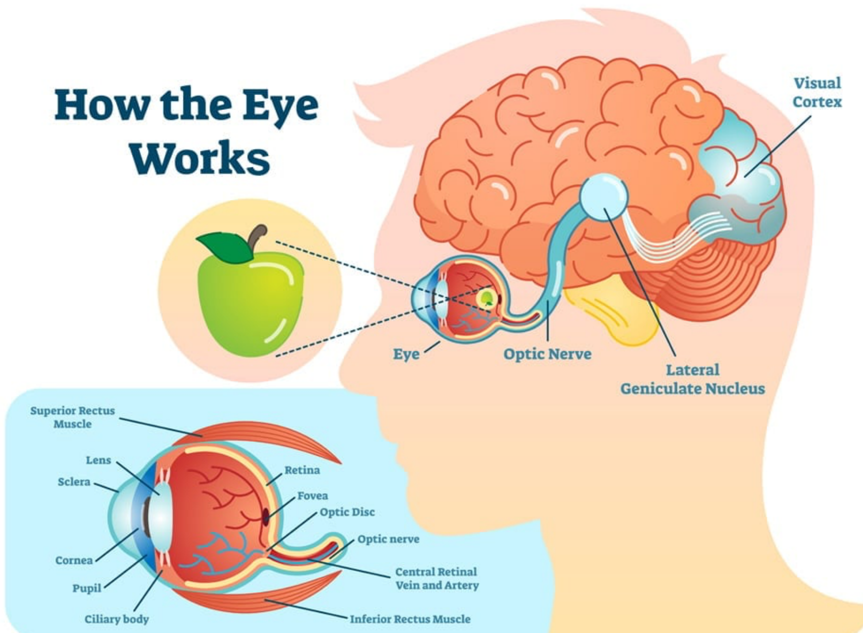

Figure 3. The Eye and the Brain, source: VectorMine/Shutterstock

- Human perception and behavior:

Correlated color temperature (CCT) and thermal sensation are essential factors influencing indoor environments and significantly affecting occupant comfort, stress, and task performance. Effects of lighting on task performance, stress, and thermal sensation in the working environment (Erkan et al., 2025). Correlated Color Temperature (CCT) describes the appearance of light from a source in terms of its color tone. It is commonly categorized by warmth or coolness: lower CCT values correspond to warmer, yellowish light, while higher values indicate more extraordinary, bluish light (Liu et al., 2022).

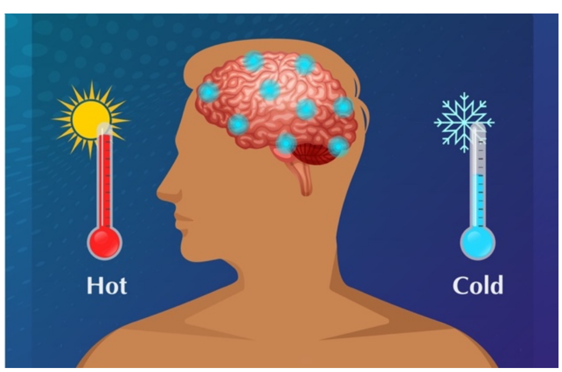

Figure 4. Brain and thermal sensation, source: https://www.waseda.jp/top/en/news/83173

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Individuals' subjective perception of the thermal environment is critical in determining occupant comfort and is closely linked to work performance in indoor settings (Soto et al., 2022). Considering individuals' thermal sensation preferences is vital for promoting comfort and productivity, particularly in work environments. Research has shown that when people adapt to their thermal conditions, they experience greater comfort, higher job satisfaction, and improved cognitive performance (Yeganeh et al., 2018).

Stress is the body's response to uncertainty or specific demands. It typically unfolds in alarm reaction, resistance, and exhaustion. These stages reflect the body's physiological efforts to cope with stress and are marked by the release of cortisol, increased heart rate, and adrenaline secretion. If the stressor remains unresolved, the body may enter the final exhaustion stage (Seley,1956).

In workplace settings, stress refers to the physiological and psychological reactions individuals experience when they perceive demands or pressures that exceed their ability to cope (Awada et al., 2023). This stress can manifest in various physical symptoms, including elevated heart rate, high blood pressure, muscle tension, irritability, difficulty concentrating, and reduced cognitive performance (Askaripoor et al., 2018). High-stress levels in the workplace can significantly impact job satisfaction, productivity, and performance. Excessive stress may also result in adverse outcomes such as decreased motivation, impaired decision-making, lower creativity, and increased absenteeism (Altindag, 2020).

Electroencephalogram (EEG) and Heart Rate Variability (HRV) are frequently used to assess stress (Di az et al., 2019). EEG measures electrical brain activity, offering insights into stress-related cognitive and emotional processes (Choi et al., 2015). HRV, on the other hand, tracks the time intervals between heartbeats, indicating how the autonomic nervous system regulates stress (Kaklauskas et al., 2011). By utilizing EEG and HRV as objective indicators, researchers in neuro-architecture aim to better understand the physiological responses to varying lighting and thermal conditions in indoor environments (Li et al., 2023).

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EEG activity:

Electroencephalography (EEG) measures the brain's electrical activity by detecting signals from electrodes placed on the scalp (Teplan, 2002). Depending on the EEG device, various electrode placement systems are used. Raw EEG data are typically collected and then processed to extract specific frequency bands relevant to stress detection, mainly the alpha and theta waves.

Processing EEG data involves several steps. First, the continuous EEG signal is divided into shorter segments, or epochs, usually lasting a few seconds each, to simplify analysis. These epochs are then subjected to spectral analysis, which calculates the power spectral density and enables the extraction of features in the frequency domain (Yang et al., 2018). The focus is primarily on the alpha (8–13 Hz) and theta (4–7 Hz) frequency bands, which are known to reflect stress-related brain activity.

Alpha waves are typically associated with states of relaxation and are commonly observed during restful or passive conditions (Prent & Smit, 2020). In contrast, theta waves are linked to cognitive load, attention, and emotional arousal, making them particularly relevant for assessing stress (Abdalhadi et al., 2024). Therefore, the power within these bands is computed and analyzed to determine stress levels during experimental sessions.

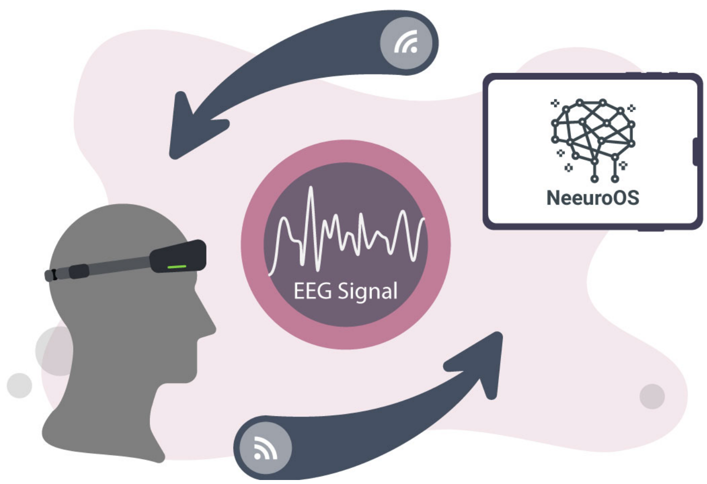

Figure 5. Electroencephalogram (EEG), source: https://www.neeuro.com/blog/understanding-electroencephalogram-eeg-for-better-brain-health

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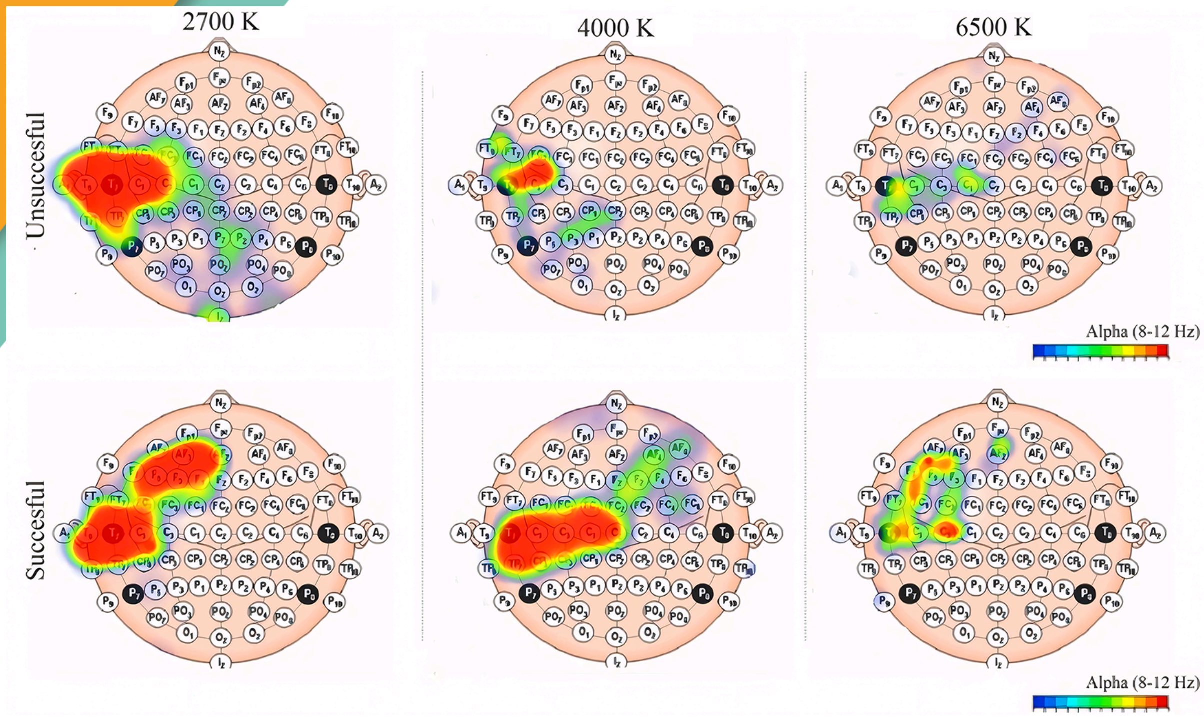

Figure 6. Brain maps change depending on the alpha power value of successful/unsuccessful participants at different CCT Levels, source: Erkan et al., 2025.

The brain's stress-related EEG signatures, such as reduced alpha power and elevated theta activity, are direct markers of how perception, emotion, and cognition are influenced by environmental conditions, remarkably light (Yang et al., 2018; Abdalhadi et al., 2024).

Light therapy is a targeted intervention that uses high-intensity, broad-spectrum artificial light to simulate natural daylight and reset the body's internal clock. Typically administered through a 10,000-lux light box, it is especially effective in the morning to realign circadian rhythms and improve neural regulation of stress and mood.

Figure 7. Light therapy, source: https://www.universiteitleiden.nl/en/research/research-projects/social-and-behavioural-sciences/psychology/bioclock-light-therapy-for-depression

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Benefits Linked to Brain Activity and Behavior:

- Boosts Alpha Waves (Relaxation): Bright light exposure increases alpha power in EEG, signaling improved calmness and cognitive readiness (Berger et al., 2022).
- Improves Sleep-Wake Cycles: A Stanford study found that combining light therapy with behavioral techniques gave adolescents 43 minutes of extra sleep per night, reducing sleep-related stress and improving daily functioning (Stanford Medicine, 2019).
- Reduces Depression Symptoms: Bright light therapy enhances brain arousal and mood regulation, which has been linked to increased prefrontal activity, which is key for emotional regulation in teens (Berger et al., 2022).
- Resets Cortisol and Melatonin Cycles: Early-morning exposure to bright light naturally suppresses melatonin (the sleep hormone) and boosts cortisol (the alertness hormone), helping the brain feel more awake and emotionally balanced during the day (Scheer & Buijs, 1999).

- Enhancing EEG Applications Through AR

Integrating EEG with Augmented Reality (AR) provides a promising direction for developing immersive, responsive environments that reflect real-time neurophysiological states. Viczko et al. (2021) explored this synergy by combining an AR meditation experience with frontal gamma asymmetry neurofeedback using a Muse EEG headband. Participants, all experiencing moderate anxiety or depression, took part in an AR experience designed to evoke positive emotional states. They explicitly used the Healium app to visualize butterflies emerging from a chrysalis as users engaged in loving-kindness meditation.

The study revealed that both the AR-only and AR-plus-neurofeedback (AR+NF) groups experienced significant improvements in mood, including reduced tension and increased calmness, but the AR+NF group reported higher engagement. EEG data showed increased alpha activity and trending changes in gamma activity, particularly in brain regions linked with emotional regulation, such as the anterior cingulate cortex and insula. These findings suggest that EEG-enhanced AR can serve as a real-time feedback loop, adjusting the environment based on brainwave activity to deepen meditative or therapeutic outcomes.

Crucially, the study illustrates how AR can enhance EEG-based research and interventions by:

- Visualizing neurofeedback in context, increasing user engagement.
- Allowing for interactive emotional regulation experiences, primarily through positive feedback mechanisms like visual rewards (e.g., butterflies hatching when EEG thresholds are met).
- Supporting real-time stress monitoring, with EEG acting as a dynamic biometric interface that influences AR content.

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Thus, integrating EEG with AR offers a novel educational and therapeutic approach and enhances user awareness of their internal states. It is a powerful tool for applications in stress management, emotional self-regulation, and mental health education.

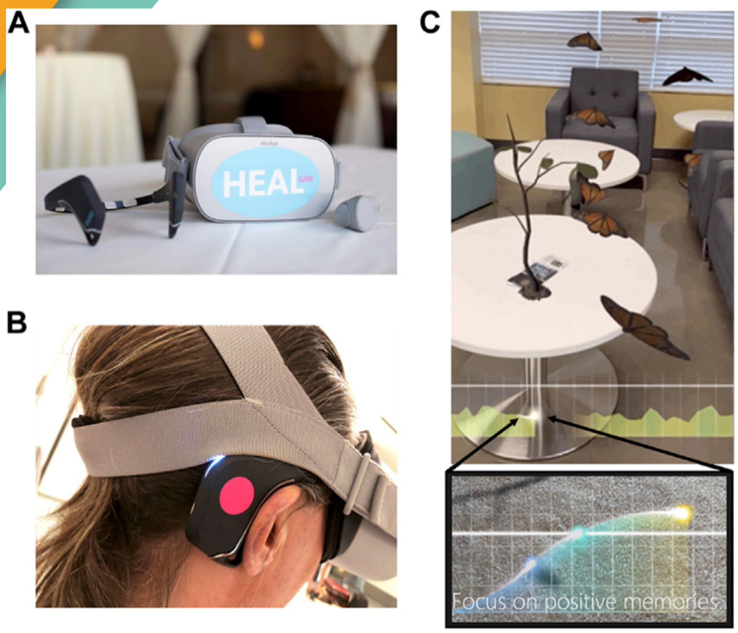

Figure 8. Examples of the equipment and AR visual experience: (A) Muse headband for neurofeedback and the Healium augmented reality headset. (B) The Healium neurofeedback setup is worn. (C) A screenshot of the AR-guided meditation with chrysalis hatching neurofeedback. Below is an enlarged image of the threshold line (solid) and "firefly" depicting gamma asymmetry ratios, with

Augmented Reality and Cognitive Response:

Physiological responses are affected by Indoor environment quality:

On average, people spend about 90 % of their time in buildings and consume an immense amount of energy to maintain a comfortable indoor environment.

Most of the energy consumed in buildings is spent maintaining indoor environmental quality (IEQ), and excessive reduction of energy consumption may degrade IEQ for a comfortable life (De Rosa et al., 2014). Therefore, in modern society, minimizing the energy consumption in buildings while maintaining satisfactory IEQ is no longer an option but an essential (˘Sujanov´a et al., 2019).

Meanwhile, technologies and methods for energy consumption monitoring continue to develop. Energy management systems help increase energy efficiency, and more efficient processes and innovative technologies are expected to emerge in the future (Aliero et al., 2022). Past research suggests that energy consumption can be reduced by visualizing energy consumption using augmented reality (AR) technology (Bekaro et al., 2018).

Augmented Reality (AR) is rapidly becoming a transformative tool in science education, especially for making complex biological systems like the brain more accessible to high school learners. A particularly compelling application is the use of AR to simulate cognitive and neurological responses to light, such as pupil dilation, reaction time, and simulated neural activity. These are

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key indicators of how the brain processes environmental light stimuli and adapts its behavior accordingly.

Light exposure triggers various physiological and neurological responses in the brain. For example, light entering the eye activates retinal photoreceptors, setting off a cascade that reaches brain regions responsible for alertness and circadian regulation. One well-documented response is the change in pupil size, which reflects both luminance and cognitive effort. As Mathôt (2018) explains, pupillometry, measuring pupil diameter, offers a window into cognitive load and sensory processing, making it a valuable tool for studying brain function under changing light conditions.

Although AR platforms cannot directly record brain activity, they can be programmed to simulate neurological outcomes based on established scientific data. Research by Chang et al. (2012) demonstrated that even brief exposures to bright light can significantly enhance cognitive alertness and alter subjective sleepiness, findings that can be embedded into interactive AR environments to model realistic cognitive effects.

Figure 9. AR tools, Source: https://delta2020.com/blog/142-how-augmented-and-virtual-reality-could-help-bring-the-classroom-to-life

In human-centered design, it is crucial to consider how the indoor environment affects both physiological and cognitive responses. Elements such as lighting, thermal comfort, air quality, and acoustics have significantly impacted occupants' comfort, productivity, and well-being (Al Horr et al., 2016; Frontczak & Wargocki, 2011). These environmental factors shape how individuals feel physically and influence cognitive function, attention, and emotional states. For instance, Mendell and Heath (2005) found that the quality of indoor environments in schools directly affects student performance and health, underscoring the need to prioritize user experience in building design.

Recent findings demonstrated that visualizing energy consumption through AR does not significantly affect subjective Indoor Environmental Quality (IEQ) satisfaction while reducing indoor energy consumption. An AR system monitors occupant reactions and behaviors to change energy consumption. Still, it is also essential to investigate the effects of these measures on

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occupant satisfaction because IEQ significantly impacts occupant satisfaction, health, and productivity (Mirzaei et al., 2020). These physiological responses include heart rate variability (HRV), electroencephalogram (EEG), electrodermal activity (EDA), and skin temperature (SKT), which are used in many studies related to IEQ to evaluate occupant subjective satisfaction quantitatively (Sun et al., 2020).

Exploring Brain Activity Through Augmented Reality

Technology is now ingrained in education, and the results show that it positively impacts learning and teaching methods (Dübel et al. 2014). AR/VR technology can provide simulated experiences that temporarily or permanently replace some components of hands-on instruction (Bakharia et al. 2016). AR provides an efficient way to represent a model that needs visualization so that a brain model can benefit the most from AR.

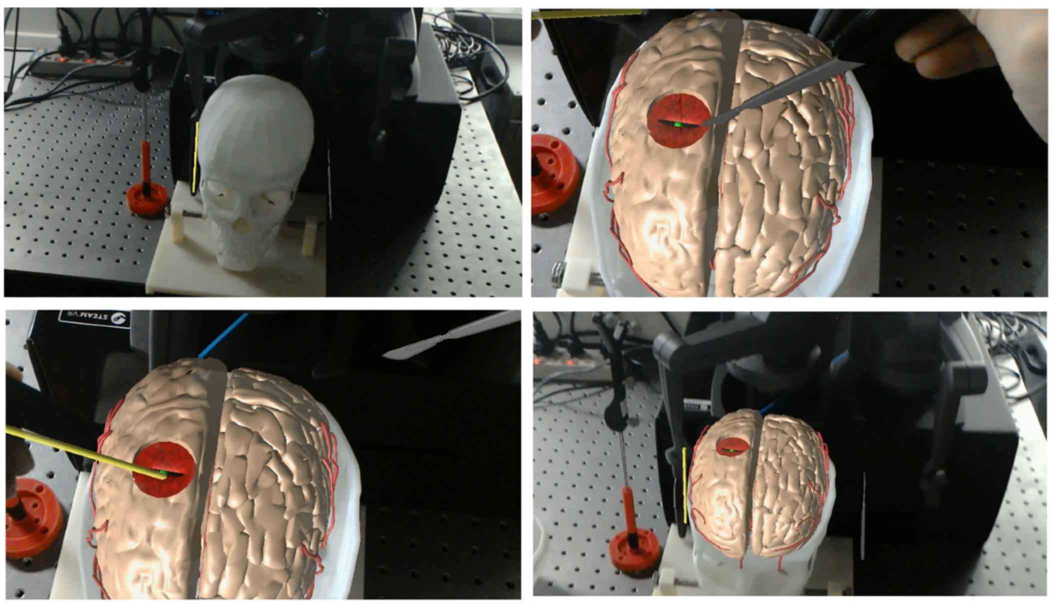

Figure 10. Augmented reality guidance for neurosurgery, source: Si et al., 2019.

In recent years, augmented reality (AR) has emerged as a transformative tool in education and neuroscience, offering new possibilities for visualizing and interacting with complex biological systems. One promising application lies in exploring brain activity, where AR can bridge the gap between abstract neural processes and tangible learning experiences. AR enables real-time, spatial visualization of anatomical structures and brain functions, enhancing learners' engagement and comprehension (Bacca et al., 2014; Radu, 2014). In the context of neuroscience education, especially among younger learners, AR applications such as *Brainapse* present an innovative approach to understanding neural mechanisms by overlaying digital brain models with animations of brain activity and cognitive functions.

This aligns with findings by Kucuk et al. (2016), who reported that AR-based learning environments significantly improve students' conceptual understanding and motivation in science

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subjects. Furthermore, research by Billinghurst et al. (2015) highlights AR's potential to support embodied learning, where users actively engage with spatial and temporal representations of brain functions. By integrating AR into neuroscience education, we aim to investigate how these technologies can enhance students' ability to grasp fundamental concepts in brain anatomy and cognitive processes and foster more profound interest in STEM-related fields.

Brainapse is an interactive educational app that uses augmented reality (AR) to bring the human brain to life. By merging 3D anatomical models with real-world environments, the app offers students an engaging way to explore brain structures, neural pathways, and cognitive functions. It transforms abstract biological concepts into tangible learning experiences, making it especially valuable for younger learners or those new to neuroscience. With its visual clarity and immersive design, Brainapse opens new opportunities for interactive, curiosity-driven learning both in and outside the classroom.

The image below demonstrates the use of augmented reality to visualize the human skull in three dimensions. Through Brainapse, students can explore the anatomical structure of the skull, which consists of the cranium and the mandible. This interactive visualization helps learners understand the skull's protective role and its importance in housing the brain, enhancing spatial awareness and memory retention through immersive technology.

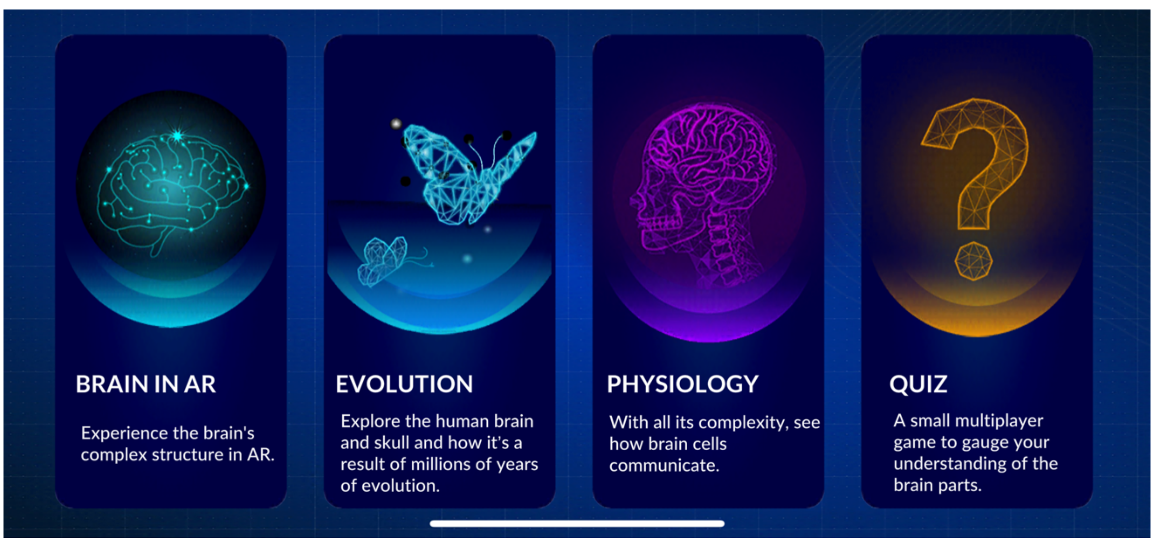

Figure 11. Brainapse App

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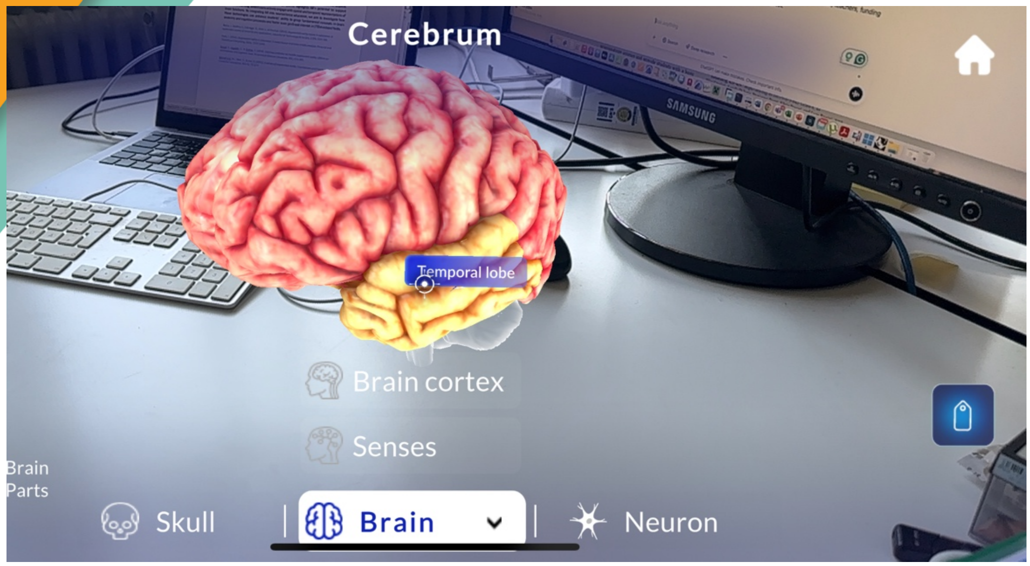
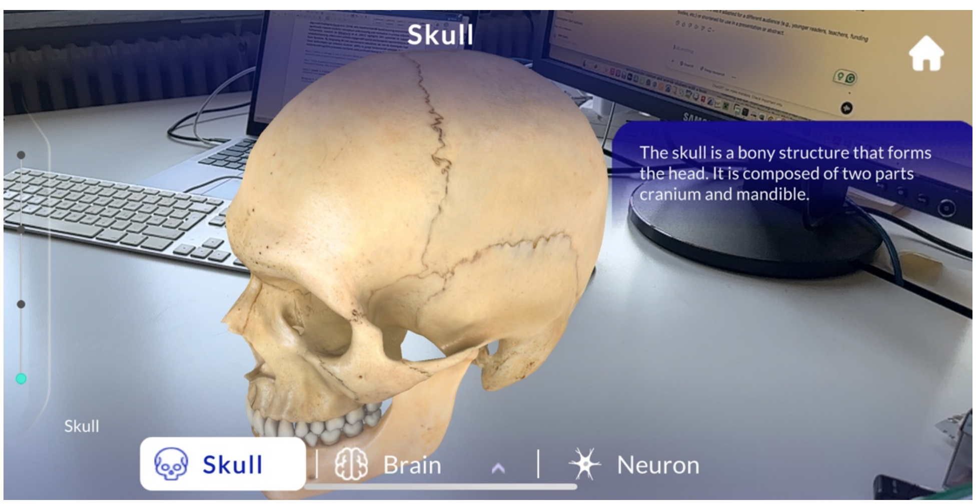


This view below displays the cerebrum focusing on the temporal lobe, a region essential for processing auditory information and memory formation. Using AR, students can directly interact with the labeled parts of the brain, fostering a deeper understanding of functional neuroanatomy. Such interactive elements have improved knowledge retention and learner motivation in science education (Kucuk et al., 2016).



The app highlights the somatosensory association cortex located in the parietal lobe. This region integrates and interprets sensory information from various modalities. Augmented reality makes this concept more concrete for students by presenting it in a real-world context, allowing for experiential learning that supports multisensory engagement (Bacca et al., 2014).

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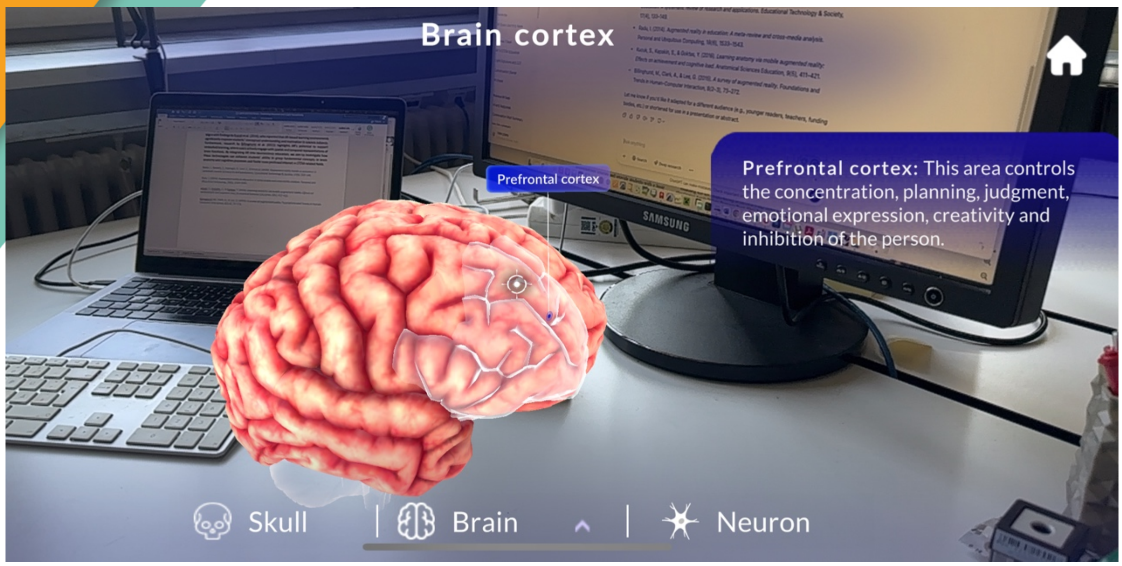
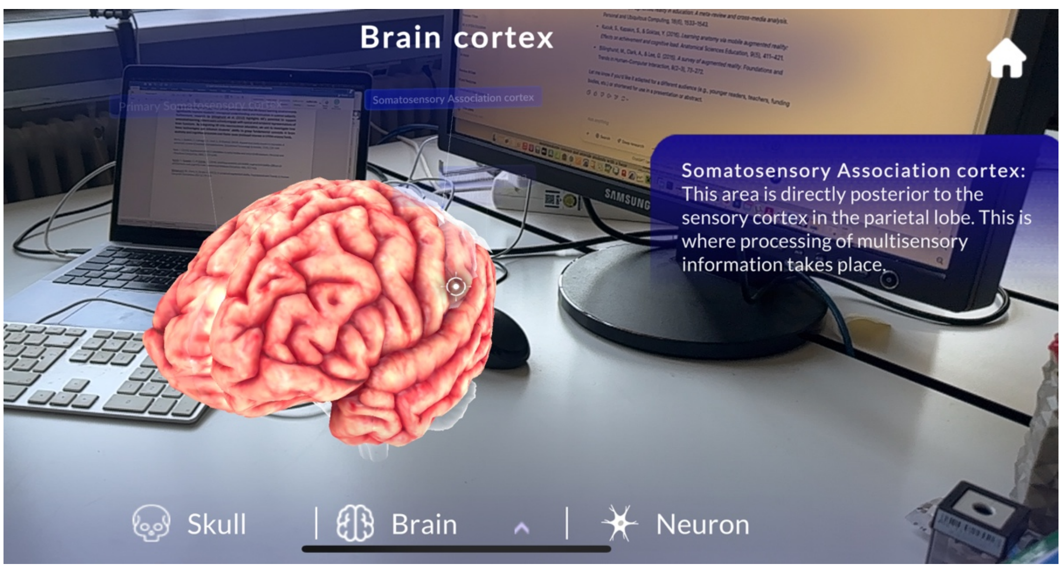


This visualization zooms in on the prefrontal cortex, known for its role in planning, decision-making, creativity, and emotional regulation. Brainapse enables learners to connect cognitive functions with their anatomical locations, creating a powerful learning experience that links biology with behavior, supported by studies in AR-enhanced science learning (Billinghurst et al., 2015).



This scene immerses students in a microscopic view of nervous tissue, illustrating neurons and glial cells in a dynamic, 3D environment. By virtually stepping into the brain's cellular landscape, learners appreciate the complexity of neural communication and tissue organization, an experience difficult to replicate through textbooks alone (Radu, 2014).

The Brainapse app offers a unique opportunity to support the learning objectives of this training unit, *Light and the Brain: Exploring Neurons and Light Sensitivity,* by visually guiding students

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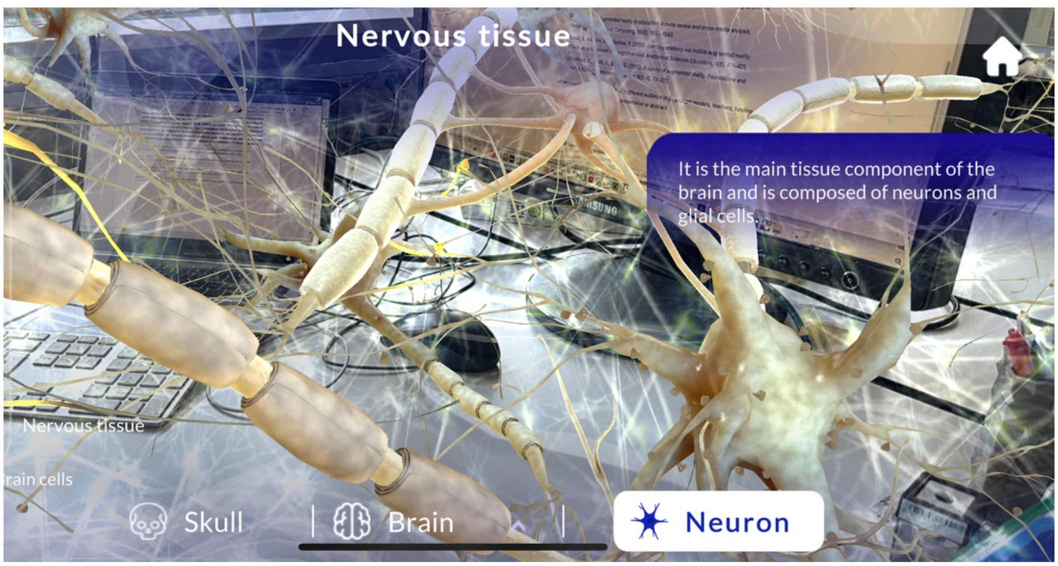
through the brain's structure, functions, and neural components. Although the app doesn't simulate light sensitivity directly, it provides a clear and interactive visualization of key brain areas involved in sensory processing, such as the occipital lobe (responsible for visual perception) and neuronal networks (responsible for transmitting signals, including those related to light stimuli).

By exploring these parts in 3D, students can better understand how neurons communicate sensory information, how light stimuli are processed, and how different brain regions are activated in response. This spatial and immersive learning aligns with evidence suggesting AR enhances conceptual understanding and memory (Bacca et al., 2014; Radu, 2014). Additionally, seeing neurons and nervous tissue in detail fosters a deeper appreciation for how the brain detects, processes, and responds to external stimuli like light, supporting the development of both scientific knowledge and curiosity.



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Phase	Description
Explore	- Investigate how light influences the brain, including visual/non-visual pathways, circadian rhythms, and stress responses.
	- Content Development: Develop learning materials integrating neuroscience, cognitive science, and light-based technologies.
	- Needs Analysis: Assess learners' prior knowledge of biology, light, and brain function to customize instruction.
Execute	- Curriculum Implementation: Deliver sessions on neuron-light interaction, light therapy, and EEG-brainwave relationships using AR tools.
	- Interactive Exercises: Utilize AR applications (e.g., Brainapse, Merge Cube) to explore neural pathways, circadian cycles, and light-related cognitive functions.
	- Feedback Collection: Collect reflections, performance data, and peer discussion outcomes regarding light's effect on brain function and emotions.
Enhance	- AR Integration: Use AR simulations to visualize neurons, light-sensitive brain regions, and EEG wave changes under different lighting.
	- Interactive Learning: Enable students to adjust light levels and observe effects on brain models (e.g., pupil reflex, circadian rhythm).
	Gamified Content: - **Points and Badges**: Reward correct identification of brain structures or simulation results. - **Leaderboards**: Rank students based on accuracy in completing light-neuron reaction scenarios. - **Quests and Levels**: Unlock advanced topics like optogenetics and light therapy as students progress. - **Rewards for Exploration**: Embed bonus AR content (e.g., hidden facts or EEG visualizations). - **Collaborative Gamified Tasks**: Groups analyze stress data or circadian alignment under virtual lighting scenarios.
	AR-Based Assessments: - Students demonstrate understanding by interacting with virtual brain simulations and completing analysis of light’s impact on neural function.

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