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ADAPTIVE BIOPHILIC SPACE BASED ON ARDUINO UNO FOR VISUAL COMFORT AND STRESS-RESPONSIVE VENTILATION

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Abstract: *This study presents a prototype of an adaptive biophilic room using an Arduino Uno platform, designed to respond to users' physiological stress conditions and ambient light intensity. The system employs a heartbeat sensor placed on the fingertip as a simplified indicator of stress level and a Light Dependent Resistor (LDR) to detect variations in room lighting. These inputs control actuators consisting of a servo motor that simulates window opening as a representation of ventilation and an LED operated using Pulse Width Modulation (PWM) to represent adaptive lighting. The research method includes electronic circuit design, development of adaptive control logic, and experimental simulations under various heart rate (BPM) and lighting conditions. The results indicate that when BPM exceeds a predefined threshold (>90 BPM), the system automatically activates a relaxation mode by opening the simulated window and dimming the light. LED intensity is also adjusted according to ambient light conditions to maintain visual comfort within low to moderate illumination levels. Integrated testing demonstrates that the system operates stably and responsively during continuous use. This prototype highlights the potential of low-cost microcontrollers to support adaptive biophilic environments that can respond to human physiological conditions through real-time control of lighting and ventilation.*

Keywords: adaptive biophilic space, Arduino Uno, biometric sensors, visual comfort, adaptive ventilation

1. Introduction

Advances in computational technology over the past two decades have driven a significant shift in architecture, moving from static spatial systems toward environments capable of dynamically adapting to their users. This approach, commonly referred to as responsive architecture or adaptive environments, describes spaces controlled through sensors, actuators, and real-time digital logic. Humans communicate through signs and symbols expressed in dance, painting, architecture, and other forms; thus, perception in architecture extends beyond form into interaction. Responsive architecture enables buildings to sense, process, and act upon environmental data, creating interactive spatial experiences for users [1].

At the same time, the concept of biophilic design has gained broad recognition as a design strategy proven to enhance mental health, psychological comfort, and stress recovery. Exposure to natural elements plays a significant role in accelerating patient recovery [2]. Biophilic design can be achieved through natural lighting, ventilation, organic materials, and multisensory elements, all of which contribute to improved well-being and cognitive performance [3]. However, in architectural practice, biophilic design is generally implemented passively and therefore cannot adjust in real time to changes in user conditions.

Meanwhile, developments in biometric sensor technology have opened new opportunities for digital architecture to respond more directly to human physiological states. Heart rate can be used as a physiological indicator of stress through parameters such as Beats Per Minute (BPM) and Heart Rate Variability (HRV) [4].

Physiologically, HRV and BPM reflect the activity of the autonomic nervous system, which regulates stress and emotional responses. HRV is influenced by the balance between sympathetic and parasympathetic nervous systems; thus, variations in HRV and BPM can serve as non-invasive indicators of psychological stress [5][6]. Meta-analytic studies show that psychological stress is consistently associated with reduced parasympathetic activity, reflected in decreased HRV and increased heart rate [7]. Therefore, BPM is positioned in this research as an initial physiological indicator representing user stress conditions.

There is significant potential for integrating biometric sensors into smart interiors to enhance user comfort [8]. However, research integrating biophilic design, adaptive architecture, and biometric sensors within a single spatial system model remains very limited.

This gap highlights the need to explore adaptive biophilic spaces based on biometric data, where space not only provides natural elements but also dynamically responds to users' psychophysiological conditions [9]. This direction aligns with current digital architecture research focused on human-centered intelligent environments [10].

To address this gap, this study develops a prototype of an adaptive biophilic space based on biometric sensors using the Arduino platform. The system employs a heartbeat sensor to detect user stress levels and a Light Dependent Resistor (LDR) to measure environmental lighting conditions. The collected data activate a servo motor simulating natural window openings and PWM-controlled LEDs functioning as adaptive lighting. This model demonstrates how low-cost microprocessor technology can serve as the foundation for responsive spaces that support psychological comfort.

Previous studies have explored partial aspects of such systems, including lighting automation for well-being [11], environmental sensors in adaptive spaces [12], and heart-rate-based stress monitoring [13]. However, no prior research has fully integrated biometric stress detection with adaptive biophilic responses—specifically lighting and ventilation—within a single architectural prototype.

This research develops an initial model of digital biophilic architecture utilizing biometric data to create more personalized, adaptive, and healing-oriented spatial experiences. The model is relevant for meditation rooms, workplaces, healthcare facilities, and future architecture based on human-centered adaptive systems.

Biophilic Design

The concept of biophilic design originates from the idea that humans possess an innate tendency to connect with nature (biophilia) [14]. In architecture, biophilic design has been systematically developed to emphasize that integrating natural elements into space can improve health, productivity, and psychological well-being [13]. Zhong, Schröder, and Bekkering [15] classify biophilic design into three main categories:

1. **Nature in the Space** (e.g., natural light, natural ventilation, natural sounds)
2. **Natural Analogues** (e.g., organic patterns, natural colors)
3. **Nature of the Space** (e.g., calming spatial qualities, prospect and refuge)

Empirical studies by Browning and Downton [2][16] demonstrate that biophilic design reduces stress, enhances cognitive function, and improves sleep quality and mood. Additionally, Kellert [14] showed that exposure to natural elements can accelerate hospital patient recovery.

In this study, biophilic design is interpreted as a spatial system capable of responding to human psychophysiological conditions rather than merely presenting natural elements passively. The research focuses on the **Nature in the Space** category—particularly lighting and ventilation—as these elements are most easily modified through digital systems.

Healing Environment

The concept of a healing environment refers to spaces designed to support recovery processes through stress reduction, comfort enhancement, and positive stimulation. Research in neuro-architecture and environmental psychology indicates that environmental qualities such as natural light, fresh air, natural sounds, and specific aromas can influence the parasympathetic nervous system, lower heart rate, stabilize blood pressure, and reduce anxiety levels [17].

Studies by Putri et al. [18][19] found that spaces incorporating natural elements can reduce anxiety and physiological stress responses. Soft lighting has also been shown to reduce psychological tension.

In this study, the term healing environment does not imply clinical medical treatment but rather refers to an environment that supports psychological and physiological comfort through adaptive regulation of lighting and ventilation in response to human bodily conditions. The goal is stress reduction and enhanced comfort, not direct medical intervention.

Smart & Adaptive Architecture

Digital architecture extends beyond 3D modeling and form computation to include sensor and actuator integration that enables responsive environments. Heerwagen [20] introduced the term Interactive Architecture to describe buildings capable of detecting environmental conditions, processing information, and responding automatically.

Purwanto [21] argues that adaptive responsiveness in buildings is a critical step toward human-centered smart spaces. The use of sensors and real-time monitoring technologies allows buildings to adjust behavior according to actual user conditions.

Gao and Spence [22] further describe a shift toward data-driven design, where spatial behavior is determined by biometric sensors, environmental sensors, and algorithms.

In this research, Arduino functions as a microcontroller connecting inputs (biometric and light sensors) to outputs (window servo motor and LED dimming system), creating a real-time adaptive environment.

Biometric Sensors in Architecture

Biometric data such as heart rate, HRV, and respiration are increasingly used to measure user stress and comfort levels. Firdaus, Khairunnisa, and Riris [23] demonstrate that BPM and HRV are valid indicators of stress and mental workload. Physiologically, HRV and BPM are linked to autonomic nervous system activity reflecting stress responses and emotional regulation [5][6]. Meta-analytic evidence confirms that psychological stress correlates with decreased HRV and increased heart rate due to heightened sympathetic nervous activity [7].

Subekti [24] introduced wearable sensors to control room lighting based on user stress levels, indicating a new direction for responsive architecture that integrates physiological sensors rather than relying solely on environmental data. In this study, a heartbeat sensor is used as a low-cost biometric representation to detect user stress levels.

Arduino Uno as a Microcontroller Platform

Arduino is an open-source microcontroller platform widely used in interactive research prototypes due to its low cost, ease of programming, and compatibility with various sensors. Heerwagen [20] notes that Arduino is ideal for digital design experimentation, including interactive installations and smart building prototypes.

In this study, Arduino Uno connects:

1. **Heartbeat Sensor** – detects stress
2. **LDR (Light Dependent Resistor)** – measures light intensity
3. **Servo Motor** – simulates ventilation
4. **PWM LED** – simulates adaptive lighting

This combination enables the development of an adaptive biophilic architectural system at a prototype scale.

Environmental Sensors in Architectural Context

Sensors are essential components of adaptive environments, functioning as tools to read real-time environmental conditions. In this prototype:

1. **Heartbeat sensor (pulse sensor)** – measures BPM as a stress indicator [25].
2. **LDR (Light Dependent Resistor)** – measures room light intensity [26].

These sensors serve as a bridge between human conditions, environmental conditions, and spatial responses.

Actuators as Spatial Response Elements

Actuators are mechanical or electronic devices that generate physical changes within space. In this prototype, actuators represent architectural elements:

1. **Servo Motor** – regulates window or shading openings.
2. **PWM-Controlled LED** – creates dynamic lighting to simulate natural ambience.
3. **Speaker/Buzzer** – produces water-sound effects as a relaxation stimulus.

These actuators allow the space to automatically adjust environmental conditions in a manner analogous to how living organisms maintain homeostasis.

2. Research Methods

This study employs an experimental prototyping approach to test a small-scale interactive system before its application in a real spatial environment. This approach enables the simulation of adaptive spatial behavior and allows measurement of system responses to changes in both user physiological conditions and environmental parameters.

The research adopts an experimental prototyping method by constructing a scaled spatial model capable of simulating adaptive responses based on biophilic design principles. This method was selected because it concretely demonstrates how a sensor–actuator system operates in generating a responsive healing-oriented environment. The study also applies a quasi-experimental framework, as it examines the relationship between spatial conditions and the activation of biophilic elements through formulated control logic.

System Design and Architecture

The adaptive biophilic spatial system was designed using two primary sensors and two actuators. The heartbeat sensor functions as a biometric parameter to identify user stress levels, while a Light Dependent Resistor (LDR) measures ambient light intensity. Both inputs are processed by an Arduino Uno microcontroller, which subsequently controls the actuators: a servo motor (to simulate window openings) and a PWM-controlled LED (to regulate adaptive lighting conditions).

Biometric Measurement (Heartbeat Sensor)

The heartbeat sensor is placed on the user's fingertip to capture photoplethysmography (PPG) signals. The heart rate value (Beats Per Minute / BPM) is used as a simplified physiological parameter to represent user stress levels.

A stress threshold is defined at 90 BPM, based on literature indicating that elevated heart rate is associated with physiological stress conditions. When BPM exceeds this threshold, the system activates adaptive responses such as increasing natural ventilation simulation and adjusting lighting conditions to promote relaxation.

Although Heart Rate Variability (HRV) is defined as the variation in intervals between heartbeats and provides more detailed stress analysis, this study utilizes BPM as an initial and more practical indicator for detecting stress-related physiological changes within a prototype system.

Environmental Measurement (LDR Sensor)

Ambient light intensity is measured using a Light Dependent Resistor (LDR) configured within a voltage divider circuit. While LDR sensors do not directly measure illuminance in lux units, the generated analog values are proportionally mapped to represent low, medium, and high lighting conditions within indoor space.

This mapping enables the system to determine whether additional artificial lighting (LED PWM) should be activated or dimmed to maintain visual comfort consistent with biophilic lighting principles.

Adaptive Lighting Control (PWM System)

Pulse Width Modulation (PWM) is employed to regulate LED brightness by adjusting the duty cycle of the electrical signal. By varying the pulse duration, the system produces dynamic lighting levels that simulate natural lighting fluctuations, contributing to a calming and adaptive atmosphere.

Experimental Logic

The adaptive control logic operates as follows:

- **If BPM > 90** → Servo motor opens (simulated natural ventilation) + LED brightness adjusted to calming level.
- **If ambient light is low** → LED brightness increases proportionally.
- **If BPM returns to normal range** → System stabilizes to default lighting and window position.

This logical framework demonstrates how physiological and environmental inputs can directly influence spatial behavior in real time.

System Components Overview

Table 1. Components of the Adaptive Biophilic Prototype System

Category	Component	Main Function
Input (Sensor)	Heartbeat Sensor	Detects user BPM as an indicator of physiological stress level
	Light Dependent Resistor (LDR)	Reads ambient light intensity to regulate adaptive lighting
Processor	Arduino Uno R3	Processes sensor data, executes adaptive logic, and controls actuators
Output / Actuator	Servo Motor	Simulates window opening as a stress-response mechanism
	LED PWM	Regulates lighting brightness to create an adaptive biophilic atmosphere

Overall, this experimental prototype demonstrates how low-cost microcontroller systems can integrate biometric and environmental sensing to produce real-time adaptive spatial responses. The model serves as a foundational step toward human-centered intelligent environments that dynamically adjust to users' psychophysiological conditions, supporting visual comfort and stress-responsive ventilation within biophilic architectural frameworks.

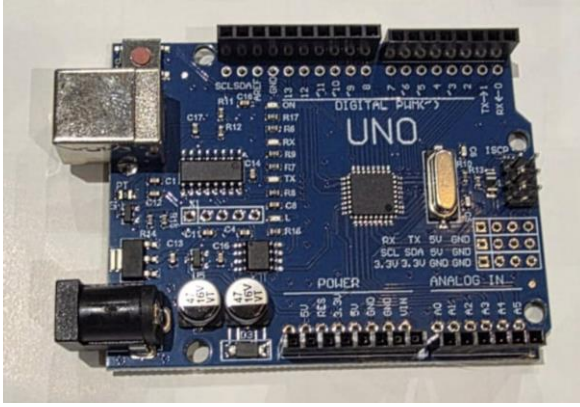

Figure 1. Arduino Uno

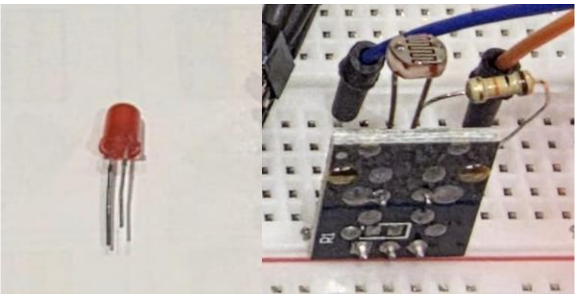

Figure 2. LED (Left) and Photoresistor/LDR (Right)

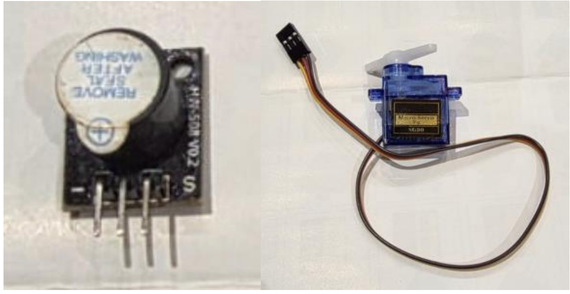

Figure 3. Buzzer (Left) and Mini Servo Motor (Right)

Figure 4. 0.96 Inch I2C OLED Display

Table 2. Adaptive Response Logic

Sensor Input	**Condition**	**Interpretation**	**System Response (Actuator)**
Heartbeat (BPM)	BPM > threshold (e.g., > 90 BPM)	User is experiencing stress	- Servo opens window (±30–45°) - LED dimmed (low PWM)
Heartbeat (BPM)	BPM ≤ threshold	Normal condition	- Servo remains closed or at default position - LED at normal brightness level
LDR (Light)	Low LDR value (dark room)	Insufficient natural light	LED brightness increases (high PWM)
LDR (Light)	High LDR value (bright room)	Abundant natural light	LED dimmed (reduced PWM)

The system prioritizes the user’s physiological condition as the primary trigger. When BPM exceeds the predefined threshold, the space automatically enters **stress mode**, activating the servo to simulate window opening and reducing LED brightness to decrease visual stimulation. Conversely, when BPM returns to normal levels, actuators revert to their default state.

The light sensor (LDR) functions as an environmental balancing mechanism, adjusting LED brightness according to available natural light to maintain visual comfort. The integration of both sensors enables real-time spatial responses aligned with both user physiology and environmental conditions.

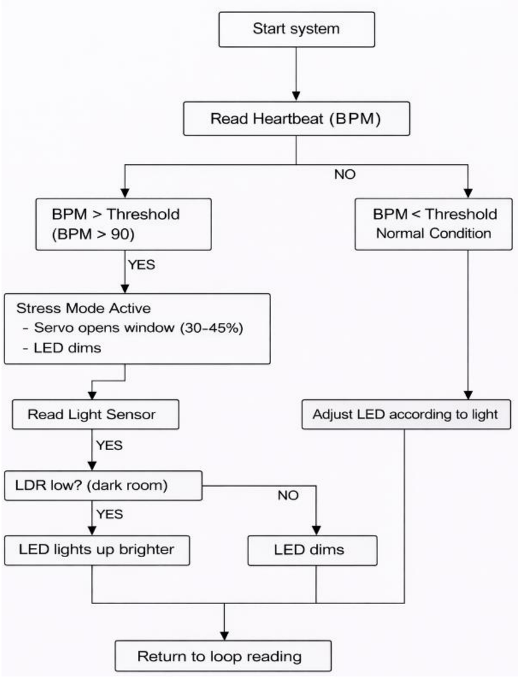

Figure 5. Adaptive Sensor Logic Diagram

Table 3. Electronic Circuit Design of the Prototype System

Component	Connection	Function in the System
Heartbeat Sensor	Signal → A0 VCC → 5V GND → GND	Measures BPM as an indicator of the user's stress level.
LDR (Light Dependent Resistor)	LDR → 5V Resistor 10 kΩ → GND Midpoint of divider → A1	Reads light intensity through a voltage divider to determine LED brightness level.
Servo Motor (Window Simulation)	Signal → D9 VCC → 5V GND → GND	Controls window opening (0–45°) in response to the user's stress level.
LED PWM (Adaptive Lighting)	Anode → 220Ω Resistor → D5 (PWM) Cathode → GND	Simulates room lighting that can be dimmed or brightened according to environmental conditions.

The electronic circuit design of this prototype was developed to ensure optimal integration between sensors, processor, and actuators. The heartbeat sensor is connected to analog pin A0 as the primary input to detect changes in the user's BPM, while the LDR is arranged in a voltage divider configuration with a 10 kΩ resistor to produce a stable analog signal to pin A1, enabling gradual detection of light intensity. The servo motor, functioning as a window-opening simulation, is controlled through digital PWM pin D9, while the LED for adaptive lighting is connected to PWM pin D5 via a 220Ω resistor to regulate light intensity using pulse width modulation techniques. The entire circuit was assembled on a breadboard and initially tested through Tinkercad simulation to ensure signal stability, sensor reading validity, and actuator responsiveness before physical implementation.

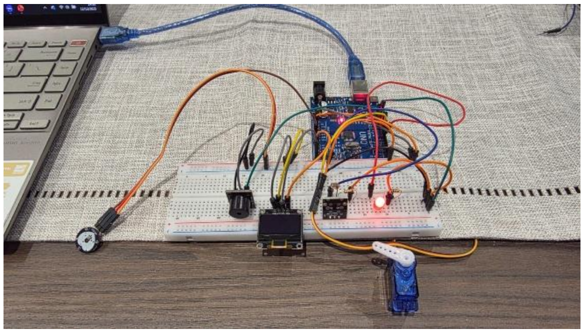

Figure 4. Arduino Circuit

Table 4. Prototype System Testing Procedure Stages

Testing Stage	Process Description	Observed Parameters	Success Criteria
1. Heartbeat Sensor Testing	The user places a finger on the sensor, and BPM values are read via the Serial Monitor.	BPM readings, signal stability.	BPM values are read stably; BPM changes produce consistent digital output.
2. Stress Threshold Calibration	Determining the BPM limit (e.g., > 90 BPM) as a system activation indicator.	System response to BPM changes.	Servo and LED change status according to the threshold.

Testing Stage	Process Description	Observed Parameters	Success Criteria
3. Light Sensor (LDR) Testing	The LDR is covered or exposed to light to vary resistance values.	LDR analog values, LED PWM changes.	LED becomes brighter in darkness and dimmer in bright conditions.
4. Servo Motor Testing	Sending PWM control signals to move the servo angle from 0°–45°.	Servo opening angle, smoothness of movement.	Servo moves stably to the expected angle without jitter.
5. LED PWM Testing	Gradually changing PWM values from 0–255.	LED light intensity.	Intensity changes proportionally according to PWM values.
6. System Integration Testing	Integrating BPM and LDR readings with servo and LED responses.	Sensor–actuator synchronization.	All components operate according to real-time adaptive logic.
7. System Stability Test (Loop Test)	The system runs for 10–15 minutes without intervention.	Response consistency; absence of crashes.	The system remains responsive and stable throughout operation.
8. Data Documentation	Recording BPM values, LDR values, servo angle, and LED PWM.	All system digital output values.	Data can be analyzed and validated for discussion.

System testing was conducted in stages to ensure that each component functioned properly before being integrated into the adaptive system. Testing began with the calibration of the heartbeat sensor to obtain stable BPM readings as a stress indicator, followed by light sensor testing to ensure appropriate LED responses to changes in environmental light intensity. The servo motor was tested to verify the accuracy of the opening angle as a representation of adaptive ventilation. After all components were verified, integration testing was performed to assess whether the system could respond simultaneously and in real time to changes in BPM and light levels. A stability test was subsequently conducted to ensure the system operated reliably over a longer duration. (See Table 5. System Integration Test Results)

Table 5. System Integration Test Results

Scenario	BPM	Light Condition (LDR)	Servo Response	LED Response	Notes
1	78	Bright	0°	PWM ±60	Normal condition, window closed, LED dim.
2	97	Slightly Dim	35°	PWM ±80	Stress mode active: window opens, LED remains relatively dim.
3	100	Dark	40°	PWM ±120	User stressed + dark room: window remains open, LED slightly increased to maintain comfort without being too bright.

3. Discussion

The results of the heartbeat sensor and servo testing indicate that the initial test was conducted to ensure the heartbeat sensor could read BPM values stably and trigger servo movement according to the logic presented in Table 2. Users were tested under two conditions: a resting state (relaxed) and after performing light physical activity (e.g., brisk walking in place for approximately ±1 minute). BPM values were read via the Serial Monitor and recorded simultaneously with the servo opening angle.

Table 6. Results of Heartbeat Sensor and Servo Movement Testing

User Condition	BPM Range Detected	System Interpretation	Servo Angle (±)	Simulated "Window" Status
Relaxed / seated calmly	72–85 BPM	BPM ≤ 90 → normal	0°	Closed
After activity	95–105 BPM	BPM > 90 → stress mode	30–45°	Open (active ventilation)

The table shows that the prototype successfully distinguishes between normal and stress conditions based on BPM values. When BPM exceeds the threshold of 90, the servo shifts from 0° to 30–45°, simulating window opening as a biophilic response to provide a sensation of fresh air and psychological relief. The servo movement operated smoothly (see Table 6. System Integration Test Results).

3.1 Results of LDR Sensor and LED PWM Testing

The next test focused on the LDR sensor and LED PWM to verify the system's ability to regulate adaptive lighting. The LDR was exposed to varying conditions: covered by hand (dark), typical room lighting, and direct lamp exposure (very bright). Analog LDR values were recorded and compared with LED intensity output.

Table 7. Results of LDR and LED Lighting Testing

Room Condition	System Interpretation	LED PWM Value (indicative)	Visual Impression of LED
Dark room	Insufficient natural light	220–255	Very bright
Moderate lighting	Adequate illumination	140–180	Moderately bright / comfortable
Very bright room	Abundant light, potential glare	40–80	Dim

The results demonstrate that the LED responds proportionally to changes in LDR values. The darker the room, the higher the PWM value and the brighter the LED; conversely, as the room becomes brighter, the PWM value decreases and the LED dims.

Previous studies indicate that light functions not only as a visual element but also significantly influences psychological and physiological conditions. Light acts as a primary modulator of circadian rhythms, mood, and stress responses through both direct and indirect neurological pathways [27].

Based on indoor lighting comfort standards, relaxation or ambient lighting typically ranges between approximately 100–300 lux, while taskrelated activities require higher illumination levels of around 300–500 lux. Indoor lighting levels correlate with emotional atmosphere, where lighting that is too dim or too bright can reduce psychological comfort, while moderate lighting provides the most optimal mood condition [28]. These findings support the implementation of adaptive lighting in the prototype as a strategy to create a more calming spatial atmosphere.

In this prototype, LED regulation is simulated to represent these illumination ranges, where lower PWM values simulate dim, calming light, and higher PWM values simulate normal lighting conditions.

The LDR-based system enables compensation for natural light fluctuations by increasing LED intensity when the room is dark and reducing it when sufficient natural light is available. Although the spectral composition of LED light differs from sunlight, this study focuses primarily on light intensity as the key parameter influencing visual comfort.

3.2 Results of Heartbeat–LDR–Servo–LED Integration Testing

Following individual component testing, an integration test was conducted to evaluate whether the system could respond to two simultaneous inputs under more realistic conditions.

The testing scenarios were as follows:

1. The user in a relaxed state, with a bright room condition.
2. The user experiencing stress (increased BPM), while the room remained bright.
3. The user stressed, with the room made darker (e.g., main light turned off). (See Table 7. System Integration Test Results)

From these scenarios, it can be observed that the system was able to:

1. Activate stress mode when BPM increased.
2. Continuously adjust the LED according to lighting conditions.
3. Prevent logical conflicts between heartbeat and LDR commands (the servo was controlled by BPM, while the LED was controlled by a combination of BPM–LDR inputs).

The system was then operated continuously for approximately ±15 minutes according to the procedure outlined in Table 5. During this period, the user repeatedly increased and decreased BPM (through light activity and relaxation), while lighting conditions were also varied.

Observation Results:

1. The Arduino did not experience hang or restart.
2. BPM and LDR values remained readable without extreme noise spikes.
3. The servo moved according to BPM changes without random movements.
4. The LED adjusted intensity with delay still within acceptable limits.

The testing results indicate that the prototype consistently implemented the principles of adaptive biophilic space. When BPM exceeded the 90 threshold, the system automatically opened the “window” via the servo and adjusted LED lighting. This response aligns with the *Nature in the Space* concept, where ventilation and light quality are used to help reduce stress and enhance visual comfort. The integration of biometric data and adaptive lighting control in this system is consistent with health science findings showing that light and environmental conditions can influence stress regulation in the body. Changes in lighting conditions may affect the autonomic nervous system, reflected in BPM and HRV variations [5] & [27].

LDR-based lighting control successfully maintained illumination within a more comfortable range. The LED intensity increased when the room was dark and dimmed when the room was overly bright.

From a digital architecture perspective, the integration of the heartbeat sensor and LDR with Arduino demonstrates a simple implementation of smart and adaptive architecture, in which space reads user and environmental data and responds in real time through actuators. The limitations of this prototype include the use of a relatively simple BPM threshold and the small physical scale of the model. However, as an initial model, the system successfully demonstrates that biometric data and light sensors can serve as a foundation for controlling spatial elements that support a healing, human-centered environment.

4. Conclusion

This study successfully developed an Arduino-based adaptive biophilic space prototype integrating physiological and environmental sensors. The system utilizes heart rate (BPM) as an indicator of user stress levels and light intensity as an environmental parameter to generate real-time spatial responses through simulated window openings and lighting adjustments.

When the BPM value exceeds the predetermined threshold, the system automatically activates relaxation mode by increasing ventilation and reducing light intensity to minimize visual stimulation. This mechanism demonstrates that biophilic design principles can be implemented not only passively but also adaptively, by using users' physiological data as the basis for controlling spatial elements.

The findings of this study are supported by medical literature indicating that BPM and HRV are associated with stress regulation mechanisms, as well as neurophysiological research demonstrating that light influences emotional states and human stress regulation.

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