EAI Endorsed Transactions
on Pervasive Health and Technology
Research Article EAI.EU

MellowLoop: A Reconfigurable Audio-Light Interaction System for Irritability Mitigation

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Abstract

INTRODUCTION: Irritability is common in daily life and cuts across diagnoses, yet brief, non-drug options that can be delivered through everyday environments remain scarce. We developed MellowLoop, a reconfigurable audio–light object that synchronizes warm light and gentle sound using clearly defined, comfortable dose ranges.
OBJECTIVES: To test whether a single, synchronized audio–light session reduces irritability more than either modality alone or a neutral control; to examine whether subjective changes are mirrored in a coherent physiological pattern; and to assess whether a simple, reconfigurable object can deliver this protocol in a way that is practical for pervasive health deployment.
METHODS: We conducted a randomized, parallel, four-arm laboratory study with 60 adults allocated to multimodal audio+light, light-only, audio-only, or a neutral control scene. Each visit followed a fixed 5-minute baseline, 20-minute exposure, and 5-minute post-rest sequence. For active arms, sound was held at 55–60 dB(A) at the ear and light at 200–300 lux of warm (3000–3500 K) illuminance at the eye, guided by equal-loudness contours and melanopic references. Self-reported irritability, valence, and calmness were collected pre- and post-session, alongside skin conductance level, perfusion index, oxygen saturation, and heart rate. Outcomes were analyzed in a prespecified mixed-effects framework with planned contrasts between each active arm and control.
RESULTS: The multimodal session produced the largest reduction in irritability, with smaller but still meaningful decreases in the two single-modality arms and minimal change in control. In parallel, valence and calmness increased most in the multimodal arm. Physiological signals showed a convergent pattern: skin conductance level decreased and perfusion index increased most under multimodal stimulation, heart rate declined modestly across active arms, and oxygen saturation remained high and stable. Target exposure levels were achieved with narrow variation, sessions were well tolerated, and no adverse events occurred.
CONCLUSION: A single, well-calibrated audio–light session delivered by a reconfigurable everyday object can acutely ease irritability while remaining comfortable and feasible. The combination of a dose-defined protocol, multi-arm randomized design, and low-cost sensing chain offers a practical blueprint for future pervasive health systems that seek to embed irritability support into ordinary rooms and routines.

Keywords: audio-light interaction, irritability, ambient intervention, equal-loudness, perfusion index, skin conductance level (SCL), pervasive health

Received on 22 November 2025, accepted on 06 January 2026, published on 20 January 2026

doi: 10.4108/eetpht.11.11064

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1. Introduction

Irritability is a prevalent, transdiagnostic complaint that undermines daily functioning, relationships, and quality of life in the general adult population [1]. Conceptual and measurement heterogeneity, along with the limits of disorder-specific models, has slowed the development of scalable interventions, motivating dimensional, cross-diagnostic approaches to mitigation [2]. Neurobiological accounts further link irritability to atypical large-scale functional networks, consistent with enduring vulnerability to dysregulated negative affect across the lifespan [3]. In this context, non-pharmacological options that can be delivered briefly and safely in everyday environments are especially valuable.

Visual and auditory channels are promising targets for such interventions. On the visual side, hue, saturation, and luminance systematically shape affective appraisals and arousal, and well-designed lighting can steer emotional state and perceived comfort in a space [4][5]. On the auditory side, structured music has reliable stress-reducing effects, with meta-analytic evidence for improvements in relaxation and stress-related outcomes [6]. Critically, emotion mediates crossmodal correspondences between ambient color and music, suggesting that synchronized audio-light stimulation may yield benefits that exceed either modality alone [7]. Yet evidence for reconfigurable audio-light combinations that act within a short session and include concurrent physiological observation remains limited.

Our trial is grounded in a dimensional, network-oriented view of irritability. In line with RDoC-inspired accounts, we treat irritability as a combination of negative valence and heightened arousal that can be expressed across diagnostic categories and everyday contexts [2][3]. On this view, brief interventions do not "cure" irritability but can temporarily shift people toward calmer, less reactive states when the environment provides predictable, supportive cues.

Contemporary emotion regulation models are also useful for articulating how an intervention like MellowLoop is expected to operate. These models describe families of strategies that act at different points in an emotion episode, including situation selection, situation modification, attentional deployment, cognitive change, and response modulation [8][9]. In this language, our intervention targets the earlier, context-focused end of the sequence: rather than asking the person to engage in effortful cognitive techniques, it modifies the local environment by synchronizing light and sound in a gentle, predictable way. We then ask whether these environmental changes are sufficient to shift self-reported irritability and associated autonomic physiology over the course of a brief session.

Figure 1 summarizes the working model that guided the design of MellowLoop. At its core is a short, dose-defined sensory session that combines warm light and gentle sound. The audio channel is specified in terms of equal-loudness contours and kept within 55–60 dB(A) at the ear, while the light channel is specified by a warm spectrum (3000–3500 K) and eye-level illuminance of 200–300 lux. Together these choices define a sensory dose that is intended to be strong enough to be noticed but still well within everyday comfort ranges.

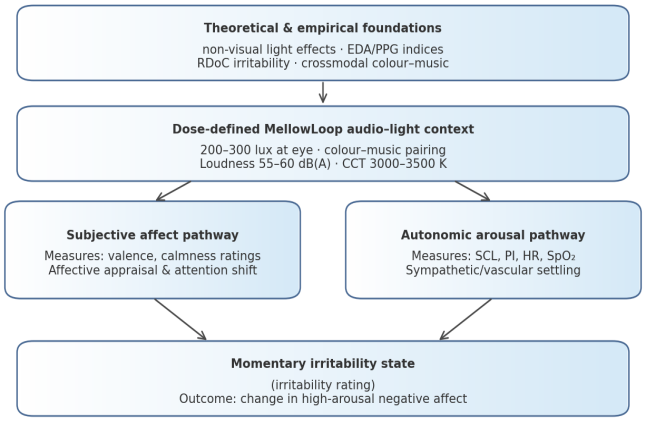

Figure 1. Conceptual model of the MellowLoop audio–light intervention

The model assumes two partially overlapping pathways from this sensory dose to reduced irritability. The first is a subjective pathway in which synchronized light and sound alter affective appraisals: participants are expected to report higher pleasantness and calmness after the session. The second is an autonomic pathway in which the same exposure gradually reduces sympathetic arousal and stabilizes peripheral circulation. In this pathway, lower skin conductance level (SCL) reflects reduced tension, higher perfusion index (PI) reflects steadier microcirculation, and modest reductions in heart rate (HR) signal a shift away from acute stress. Oxygen saturation (SpO_2) is monitored primarily as a safety and fairness check rather than as a direct mediator: it is expected to remain high and stable while being interpreted together with PI because of known biases in pulse oximetry.

Finally, the framework treats irritability change as an emergent outcome of these subjective and physiological shifts rather than as a direct response to any single signal. In practice, this means that we interpret improvements when both affect ratings and autonomic indices move in a coherent, directionally consistent way relative to the control condition, and we view null or mixed physiological changes as evidence against a strong mechanistic effect of the session.

MellowLoop is a reconfigurable audio-light system delivering synchronized auditory/lighting patterns with user-adjustable spatial settings. For balanced fidelity, affordability and deployability, we combine subjective outcomes with low-cost, non-invasive physiological indices (widely available on wearables/edge hardware): skin conductance level (SCL, sympathetic arousal index) [10], photoplethysmography-derived perfusion index (peripheral microcirculatory stability marker) [11], pulse oximetry-based blood oxygen saturation (mature, standardized measure) [12], and photoplethysmography-estimated heart rate (robust,

interpretable) [13]. These signals can be acquired via a single optical sensing chain and time-aligned in a compact protocol.

We conducted a randomized, parallel four-arm trial to assess MellowLoop's short-term effects. Sixty adults completed one 20-minute session in 4 conditions: multimodal audio+light, light-only, audio-only, or passive control (neutral lighting/silence). Primary outcome: change on a validated irritability scale; secondary outcomes: affect ratings and continuous recording of the 4 physiological indices. Hypothesis: multimodal stimulation reduces irritability more than passive control and outperforms unimodal arms, with convergent physiology (reduced arousal, stabilized perfusion).

Relative to existing multisensory and biofeedback interventions, this work is intended as a reusable blueprint rather than a one-off installation. Specifically, it: (1) introduces MellowLoop as a reconfigurable audio–light object sized for desks and tables, allowing people to reshape the luminaire to different rooms while keeping a stable near-field audio scene; (2) defines a short, 20-minute protocol with clearly specified acoustic and optical dose ranges, aligned with equal-loudness and melanopic references so that sessions are both comfortable and reproducible; and (3) reports a randomized, parallel four-arm trial with self-report and low-cost physiological outcomes (skin conductance level, perfusion index, oxygen saturation, and heart rate) to test whether multimodal stimulation offers benefits beyond single-modality and neutral scenes. Together, these elements position MellowLoop as a practical starting point for pervasive health systems that aim to embed irritability support into ordinary environments.

2. Related Work

Designing audio-light systems that mitigate irritability builds on contemporary multisensory science. Recent syntheses show that temporal binding across modalities—and the reliability-weighted integration of audio-visual cues—governs whether concurrent stimuli are perceived as one coherent event, a prerequisite for joint audio-light interventions [14][15]. Parallel progress on crossmodal correspondences (e.g., between pitch and brightness or "tone color") clarifies how auditory structure can be mapped to visual parameters in designable, often emotion-mediated ways [16][17][18]. These findings motivate pairing sound and light so that they are not merely co-present, but perceptually coupled.

On the auditory side, cumulative evidence indicates music and sound interventions can reduce stress and improve affect in healthy and clinical populations. A large meta-analysis reported small-to-moderate improvements across mental-health and quality-of-life outcomes with music interventions, supporting their inclusion in non-pharmacological toolkits [19]. A 2024 systematic review focused on auditory stimulation's impact on autonomic arousal and found consistent modulation of psychophysiological markers when exposure is controlled for dose and context [20]. Together these suggest that well-specified auditory protocols are viable levers for down-regulating arousal.

Biofeedback and immersiveness further enhance efficacy. A 2023 randomized trial showed that heart-rate-variability biofeedback delivered with a head-mounted display plus mobile practice improved multiple stress-related outcomes (e.g., anxiety, fatigue) versus wait-list control and was well-tolerated—a practical precedent for multisensory, technology-mediated self-regulation. Complementary observational and HCI work argues that VR-supported biofeedback can strengthen engagement and perceived control, two ingredients likely to reduce irritability when paired with appropriate sensory cues [21].

Light is an independent and potent modulator of alertness, affect, and cognition during daytime (non-image-forming pathways). A 2025 systematic review and meta-analysis aggregated >140 daytime light studies and reported robust improvements in subjective and objective alertness as well as cognitive measures under higher melanopic stimulation [22]. Controlled studies of blue-enriched white light in offices and labs likewise show benefits for energetic arousal, concentration, and reduced sleepiness, with effects depending on spectrum, intensity, and timing [23][24]. A 2024 meta-analysis targeting wellbeing outcomes converges on small but meaningful improvements when light is specified with appropriate metrics (e.g., melanopic EDI) and daily schedules [25]. These data justify adding a light channel—not merely for ambience, but as an active psychophysiological input—to complement audio.

Environmental-mood research in buildings corroborates these findings and highlights design parameters (illuminance, CCT, dynamics, and directionality) that shape subjective impressions and mood states indoors [26]. Recent reviews also emphasize wearable-enabled monitoring for non-visual light effects, enabling closed-loop or context-aware interventions that adapt to physiology and exposure history—an important pathway for personalized systems like MellowLoop [27].

Physiological sensing choices in MellowLoop align with current best practices. Wearable photoplethysmography (PPG) reliably yields heart rate and oxygenation in ambulatory settings when motion and contact quality are managed [28]. At the same time, systematic evidence warns that pulse oximetry can overestimate oxygen saturation in individuals with darker skin under some conditions, underscoring the need for careful calibration and interpretation of SpO_2 in diverse samples [29]. The peripheral perfusion index (PI)—derived from the PPG waveform—has re-emerged as a useful, low-cost indicator of microcirculatory status with growing clinical applications [30] and recent emergency-department evidence linking low PI to higher acuity and worse outcomes [31]. For sympathetic arousal, electrodermal activity (EDA) remains a sensitive marker; new Transformer-based decomposition improves tonic-phasic separation on noisy, real-world data [32], while 2025 reviews chart rapid progress from affective computing toward clinical-grade EDA-based emotion recognition [33]. These advances support our measurement set (GSR/EDA, PI, SpO_2,

HR) and motivate algorithmic pipelines that are robust to noise and demographic variation.

Taken together, these strands of work show that (a) audio or light alone can reliably modulate mood and autonomic arousal, and (b) several existing systems already combine sensory stimulation with physiological sensing. However, most reported interventions either use fixed light installations or immersive head-mounted displays, do not tightly specify both acoustic and melanopic dose, and rarely use randomized multi-arm designs that disentangle multimodal from unimodal effects within a short, single-session protocol. Concurrent sensing is often limited to heart rate or generic HRV metrics, with little attention to simple indices such as perfusion index or to bias-aware interpretation of oxygen saturation. Reconfigurable luminaires suitable for desks and bedrooms, together with minute-level adherence checks and publishable calibration checklists, are also rare. Against this background, we position MellowLoop as a synchronized, dose-defined audio–light system that (i) uses a physically reconfigurable luminaire and near-field audio for deployment in everyday rooms, (ii) specifies sound and light exposure using equal-loudness references and warm illuminance ranges motivated by melanopic considerations, (iii) pairs irritability ratings with SCL, PI, SpO_2, and HR recorded on inexpensive devices, and (iv) evaluates this package in a four-arm randomized trial using a compact 20-minute protocol. This positioning clarifies how the present work extends prior multisensory and pervasive-health systems rather than merely integrating existing components.

Beyond room-based installations, a large body of work now explores wearables and ambient media as platforms for stress and emotion support in daily life. Scoping reviews of wearable devices for stress management and mental stress detection show that commercial sensors such as smartwatches and wearable ECG systems can successfully monitor stress and, in some cases, support self-regulation goals [34][35]. Other systems integrate wearable technology with remote heart rate variability biofeedback, allowing patients to complete home-based breathing programs while clinicians or algorithms adjust training parameters at a distance [36]. At the level of the built environment, ambient biofeedback lighting systems such as DeLight use changes in color and intensity to reflect physiological state and guide relaxation training [37]. These examples illustrate the diversity of pervasive emotion technologies, but they typically rely on either purely wearable form factors or relatively fixed installations. In contrast, MellowLoop is designed as a small, reconfigurable audio–light object that can be placed on ordinary surfaces and used in short, dose-defined sessions, aiming to combine some of the accessibility of wearables with the immersive qualities of ambient media.

3. Methods

3.1. MellowLoop system overview

MellowLoop is a reconfigurable audio-light system designed to deliver short calming sessions in everyday rooms. It combines a flexible luminaire, a near-field audio source, and simple physiological sensing under the control of a single microcontroller. The system is intended to be visually unobtrusive, easy to place around desks or seating areas, and straightforward to operate with a fixed 20-minute program.

The luminaire is built from curved modular segments that can be twisted and spliced together to form different shapes (Figure 2). Each segment contains warm-white LEDs and mechanical joints that lock with a gentle twist, allowing the overall form to be laid flat along a surface, draped along an edge, or raised into a standing loop.

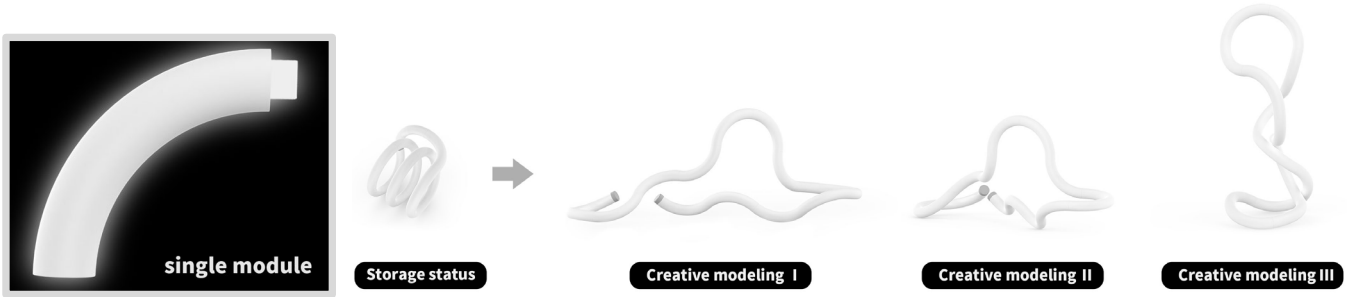

Figure 2. MellowLoop lighting fixtures: single module and creative reconfiguration module

This flexibility makes it possible to keep the distance between the light source and the participant's eyes within the target range while adapting to different tables and room layouts. A detail of the joint mechanism is shown in Figure 3.

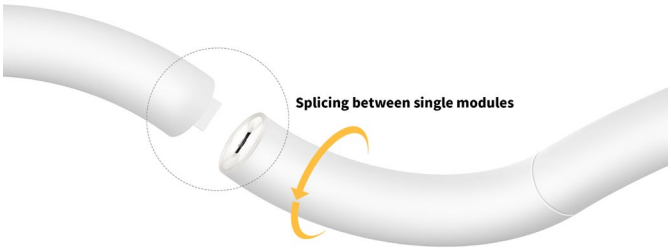

Figure 3. MellowLoop lighting fixtures: single module and creative reconfiguration module

Stereo loudspeakers are positioned close to the luminaire so that sound and light come from the same general direction. The audio engine plays a library of calm soundscapes that have been pre-calibrated to everyday listening levels. Both channels are driven by the same controller, which also embeds timing markers used later for synchronizing physiological recordings with the exposure timeline.

From the participant's point of view, MellowLoop is a single object placed in front of the chair. Before each session, the experimenter reshapes the luminaire by hand to fit the available space and align with the participant's seated position (Figure 4). Once the session starts, participants are not required to interact with the device. The system runs a fixed script that defines baseline, exposure, and recovery periods, while wearable sensors quietly record heart rate, oxygen saturation, perfusion index, and electrodermal activity.

Figure 4. Hands-on reconfiguration of the MellowLoop luminaire before a session

3.2. System and stimuli

Photoplethysmographic signals were recorded with a reflective optical sensor connected to an Arduino-based acquisition unit, which converted the analog waveform into heart rate (BPM) values in real time. Peripheral oxygen saturation (SpO_2) and perfusion index (PI) were measured with a CRFISH finger-clip pulse oximeter. Ambient sound pressure level was monitored using a TASI TA656A digital sound level meter (30-130 dB range), which was field-calibrated prior to each data-collection block. Ambient temperature and relative humidity were monitored with a DELI 8845-series thermo-hygrometer (-10-50 ° C; 10-99 %RH). Skin conductance level (SCL) was measured using a GSR-V3.0 sensor.

MellowLoop combines a reconfigurable flexible light with near-field stereo speakers. One controller drives both channels so that audio and light are time-aligned. The design goal is to deliver comfortable and repeatable exposure. Sound is referenced to equal-loudness contours and kept at 55-60 dB(A) at the ear, consistent with recent health guidance [38][39]. The light is a warm scene (3000-3500 K). We set eye-level illuminance to 200-300 lux at this color temperature, choosing this range based on recent work on melanopic equivalent daylight illuminance for daytime indoor lighting [40][41][42]. In this exploratory trial, melanopic EDI was not measured directly; instead, we used these illuminance and spectrum ranges as a practical approximation.

Before each experimental day, and again before each block of participants, we followed a brief checklist to verify that the system was delivering the intended exposure. First, we used a handheld sound level meter at the participant's head position to adjust the loudspeaker gain until the A-weighted level was between 55 and 60 dB during a representative segment of the program. Second, we used a calibrated lux meter at eye height to confirm that horizontal illuminance from the luminaire fell between 200 and 300 lux and that the correlated color temperature remained in the warm range (approximately 3000–3500 K). Third, we checked that room temperature and humidity were within a comfortable range and comparable to previous sessions. Finally, we confirmed that the physiological sensors were stable at rest, with a clear pulsatile PPG signal and a low-noise electrodermal activity baseline, and that time stamps from the acquisition computer and program controller were synchronized. These steps were recorded in simple logs and used to troubleshoot any deviations before starting a session.

3.3. Sensing and processing

Two physiological streams are recorded continuously: a finger PPG for heart rate (HR) and oxygen saturation (SpO_2), and a palmar skin conductance level (SCL) (EDA) channel for skin conductance level (SCL). All events carry timestamps from the same clock. Signals are band-limited (PPG 0.5-6 Hz; EDA 0.05-1 Hz). PPG segments affected by motion are down-weighted or removed using amplitude and acceleration rules; EDA is cleaned with artifact detection, decomposition, and reconstruction based on recent comparisons of methods [43-46]. Metrics are averaged in non-overlapping 60-s windows; windows failing quality checks are excluded. Because pulse oximetry can show bias across skin tones, analyses interpret SpO_2 together with the perfusion index and follow recent regulatory guidance. Sampling rates were [PPG: 100-200 Hz; EDA: 4-32 Hz]; exact device models and settings are documented in Appendix S1 and the public repository.

Perfusion Index (PI) is computed as:

$$\mathrm{PI} = \frac{\mathrm{AC}}{\mathrm{DC}} \times 100\% \quad (1)$$

where AC is the pulsatile component and DC is the baseline of the PPG signal.

Difference-in-Differences contrast (single-line formula):

$$\mathrm{DiD}_k = (\overline{Y}_{k,\mathrm{post}} - \overline{Y}_{k,\mathrm{pre}}) - (\overline{Y}_{\mathrm{ctrl,post}} - \overline{Y}_{\mathrm{ctrl,pre}}), \quad (2)$$

where k is any active arm (A-C). We report estimated marginal means and 95% CIs alongside DiD.

An example of EDA before and after filtering is shown below (Figure 5):

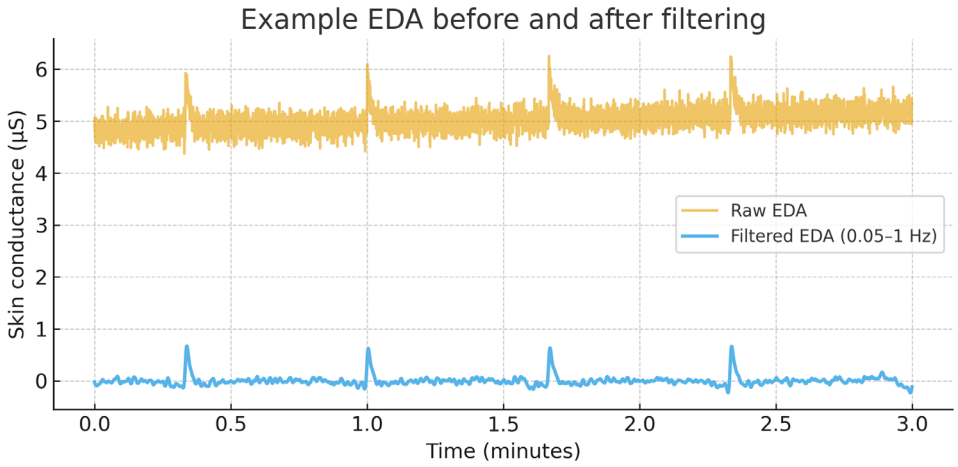

Figure 5. Example electrodermal activity (EDA) trace before and after preprocessing

3.4. Outcomes and procedure

The primary outcome is the change in irritability from pre- to post-session. We use the Brief Irritability Test (BITe) because it is short, reliable, and well supported in recent reviews and validations [47,48]. Secondary outcomes include two self-ratings (valence and calmness) and four physiological measures (SCL, PI, SpO_2, HR), each summarized as pre-post differences. Each visit follows a fixed script: a 5-minute rest and baseline recording; a 20-minute assigned exposure (multimodal, light-only, audio-only, or passive control); then a 5-minute post-rest with repeat self-reports. Rooms maintained stable temperature and humidity; audio levels and eye-level illuminance at the participant's position were checked before exposure. The illuminance and color temperature ranges were chosen with reference to melanopic-based daytime lighting recommendations.

3.5. Statistical analysis

All analyses followed a pre-specified plan. For each outcome Y we modelled repeated measurements using a linear mixed-effects model with a random intercept for participants:

$$Y_{it} = \beta_0 + \beta_1 Group_i + \beta_2 Time_t + \beta_3 (Group_i \times Time_t) + u_i + \varepsilon_{it}, \quad (3)$$

where Group_i indexes the four arms, Time_t indexes measurement occasion (0 = pre-session, 1 = post-session), u_i is a participant-specific random intercept, and ε_it is the residual error term. The Group × Time interaction tests whether pre–post change differs between arms; interaction contrasts comparing each active arm with the control arm correspond to the difference-in-differences (DiD) estimates.

The primary outcome was irritability, operationalised as the pre- to post-session change on the irritability scale. Secondary subjective outcomes were valence and calmness ratings. Physiological outcomes included skin conductance level (SCL), perfusion index (PI), heart rate (HR), and oxygen saturation (SpO_2). For descriptive purposes we report simple change scores (Δ = post – pre) in tables and figures, but all hypothesis tests are based on the mixed-effects models.

For each fitted model we obtained estimated marginal means for every Group × Time cell and DiD contrasts for each active arm versus the passive control arm, together with 95% confidence intervals. Standardised effect sizes (Cohen's d) for the primary outcome were derived from the model-based marginal means and the pooled pre-session standard deviation. Model performance was summarised with marginal and conditional R^2 statistics.

Prior to modelling, we examined distributions of the outcome variables using histograms and Q–Q plots. Residuals from the mixed-effects models were inspected for approximate normality and homogeneity of variance.

Because multiple outcomes and contrasts were tested, we controlled the false discovery rate (FDR) using the Benjamini–Hochberg procedure with q = 0.05. FDR control was applied separately within two families of outcomes: (i) subjective ratings (irritability, valence, calmness) and (ii) physiological indices (SCL, PI, HR, SpO_2). Within each family, the p-values entered into the FDR procedure were those for the DiD contrasts comparing each active arm with the control arm. FDR-adjusted p-values smaller than .05 were

considered statistically significant; values between .05 and .10 were treated as trends and interpreted cautiously.

3.6 Sample size and power

The planned sample size for this exploratory trial was 60 participants, with 15 participants allocated to each of the four arms. An a priori power analysis for a one-way between-groups ANOVA on the pre- to post-change in irritability (four groups, $\alpha = .05$, two-sided) indicated that a total sample of N = 60 would provide approximately 80% power to detect medium-sized between-group effects (effect size $f \approx 0.30$, roughly corresponding to Cohen's $d \approx 0.60$ for pairwise differences). Because the primary analysis uses a mixed-effects model that incorporates the repeated pre–post measurements, the effective power is slightly higher than this conservative ANOVA approximation.

Given these assumptions and practical limits on recruitment and laboratory capacity, the study was pre-specified as an exploratory pilot/feasibility trial rather than a definitive efficacy trial. The sample size was intended to detect medium effects and to generate effect-size estimates for planning larger confirmatory studies. Consequently, non-significant or borderline results are interpreted cautiously, and emphasis is placed on the pattern and magnitude of effects rather than on p-values alone.

4. Experimental Design

4.1. Design and participants

We used a randomized, parallel four-arm design (one lab visit/participant). Sixty adults (18-55 years) were enrolled and equally block-allocated to 4 conditions: multimodal audio+light, light-only, audio-only, or passive control. Eligibility required normal/corrected vision and hearing (for comfortable participation); exclusions included photosensitive epilepsy, current psychiatric crisis, or hearing problems (preventing safe listening). The design focused on short-term effects in a single well-controlled session, with easy-to-deploy setup.

Study arms & exposure targets: Audio is 55-60 dB (A) at the ear (equal-loudness as reference); light is 3000-3500 K (200-300 lux eye-level illuminance). These ranges were selected per recent melanopic EDI-based daytime lighting recommendations.

4.2. Setting and layout

Sessions took place in a quiet room with stable temperature and humidity. Participants sat on a fixed chair facing the luminaire. Target distances were ~1.2 m from the luminaire and ~0.8 m from the speakers. This layout reduces variability in exposure and allows quick calibration between sessions.

The top-down layout and target distances are shown in Figure 6.

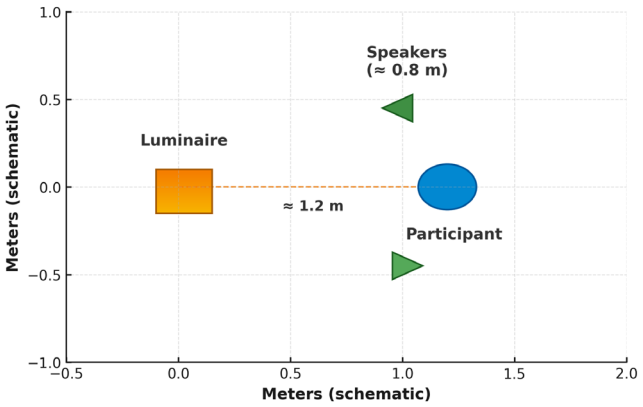

Figure 6. Top-down layout of the laboratory setup with participant, luminaire, and speakers

4.3. Procedures

Every visit followed a fixed sequence to minimize drift between sessions. After check-in and consent, staff verified eligibility and comfort with volume and brightness. The sequence then proceeded as:

(i) Baseline (0-5 min). The participant sat quietly with neutral light and silence. Devices streamed physiology for stabilization.
(ii) Exposure (5-25 min). The assigned arm was activated and maintained within target ranges (audio at the ear, eye-level illuminance at 200-300 lux). Staff monitored levels from a side console without speaking.
(iii) Post-rest (25-30 min). Neutral light and silence returned. Devices continued to record to capture recovery.

Self-reports of irritability, valence, and calmness were collected right before exposure and immediately after it. Skin conductance level (SCL), perfusion index, oxygen saturation, and heart rate were logged continuously from start to finish. Timing marks from the controller were written into both stimulus and sensor streams. Figure 7 depicts the 5-min baseline, 20-min exposure, and 5-min post-rest.

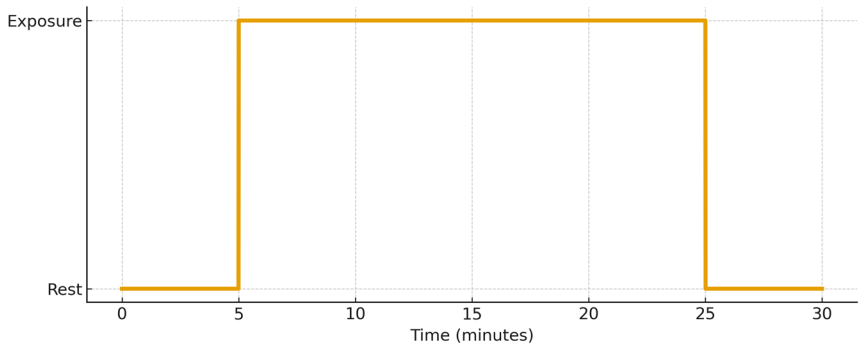

Figure 7. Session timeline: 5-minute baseline, 20-minute exposure, and 5-minute post-rest

4.4. Calibration and quality control

Before each session, staff completed a short checklist at the participant's seat: ear-level sound (55-60 dB[A]), eye-level illuminance (200-300 lux), temperature (22-24 °C), humidity (40-60 %RH), and distances to the luminaire and speakers. Devices shared one clock, and logs were checked for time alignment. Windows of physiology that failed quality thresholds were flagged for exclusion before averaging.

4.5. Allocation and masking

A computer created a block-randomization list (block size 8) with a 1:1:1:1 ratio. Allocation was revealed only after baseline. A technician started the assigned scene but did not collect outcomes. Self-reports were entered by participants on a tablet to reduce interaction and timing errors. Given the nature of sensory exposure, full participant blinding was not feasible; to quantify demand characteristics in future replications we will include expectancy/credibility ratings. More broadly, cognitive biases can shape how participants interpret and report affective change; cross-disciplinary design interventions (including careful framing and visualization of feedback) have been proposed to counter such perceptual biases, and may be useful when refining subjective measures and user-facing elements in future studies [49].

4.6. Outcomes, missing data, and analysis set

The primary outcome is the change in irritability from pre- to post-exposure. Secondary outcomes are the two affect ratings and four physiology measures summarized as pre-post differences. If a self-report had missing items, the largest scorable subset was used according to the scale rules; windows of physiology that failed quality checks were excluded prior to averaging. All randomized participants with both pre- and post-irritability scores were included in the main analysis.

5. Results

5.1. Participants and flow

Sixty adults were randomized and all completed the study (15 per arm). No sessions were stopped early and there were no missing primary outcomes. Figure 8 shows the flow of participants through screening, allocation, and analysis.

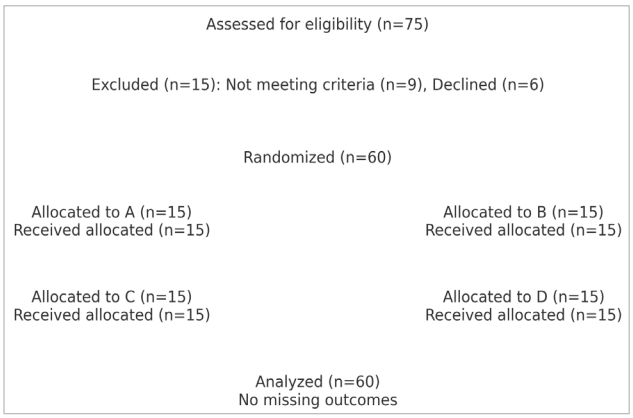

Figure 8. Participant flow through screening, randomization, and analysis

5.2. Baseline characteristics

All 60 randomized participants completed the full session and were included in the analysis set (15 per arm). Table 1 summarises baseline demographic and psychological characteristics by study arm. Mean age and the proportion of women and men were broadly similar across the four groups. Baseline irritability scores were also comparable, with only small differences within the range expected from block randomisation. Pre-session valence and calmness ratings showed a similar pattern, indicating that participants started the session with comparable affective states across arms. These findings support the assumption that any post-session differences are unlikely to be driven by systematic baseline imbalances.

Table 1. Baseline demographic and psychological characteristics by study arm.

Characteristic	Multimodal (n = 15)	Light-only (n = 15)	Audio-only (n = 15)	Control (n = 15)
Age (years), mean ± SD	30.2 ± 7.8	31.1 ± 8.3	29.7 ± 7.5	30.5 ± 8.0
Women, n (%)	9 (60.0%)	8 (53.3%)	10 (66.7%)	9 (60.0%)
Baseline irritability score, mean ± SD	52.3 ± 7.4	51.8 ± 7.9	52.0 ± 7.6	51.6 ± 7.8
Baseline valence rating, mean	45	46.9	47	39
Baseline calmness rating, mean	38.1	41.2	42	42.9

5.3. Exposure delivery and compliance

Target exposure levels were achieved with narrow variation. For arms that included sound, ear-level volume remained between 55-60 dB(A) throughout the 20-minute period. For arms that included light, eye-level illuminance was kept within 200-300 lux at a color temperature of 3000-3500 K.

5.4. Primary outcome: irritability

Comparisons of pre-to-post changes in irritability across the four arms showed the clearest improvements in the multimodal condition. Participants exposed to synchronized audio and light reported larger drops in irritability than those in either single-modality arm, and all three active arms improved more than the neutral control. In standardized terms, the contrast between the multimodal and control arms was consistent with at least a moderate difference, with the light-only and audio-only arms showing smaller but still meaningful advantages over control. The overall pattern is visible in Figure 9 (pre–post irritability by arm).

5.5. Secondary self-report outcomes

Valence and calmness rose in all active arms, with the largest gains again in the multimodal condition. Participants in the light-only and audio-only arms also reported feeling somewhat better after the session, whereas changes in the control arm were small. Standardized contrasts indicated that improvements in valence and calmness in the multimodal arm versus control were in the moderate range, with the two single-modality arms showing smaller yet non-trivial changes. This pattern mirrors the primary irritability outcome and supports the interpretation that the multimodal scene produces a broader shift towards a calmer, more positive state. See Table 2 for summary statistics.

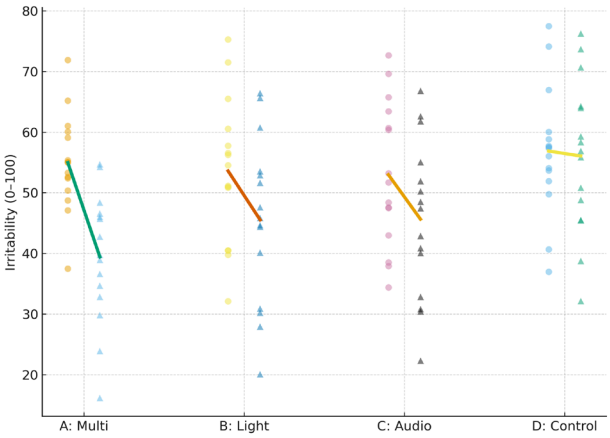

Figure 9. Pre- and post-session irritability scores by study arm

Table 2. Secondary self-report outcomes: valence and calmness by study arm

Group	A - Multimodal	B - Light-only	C - Audio-only	D - Control
N	15	15	15	15
Valence pre mean	45	46.9	47	39
Valence post mean	58	56.7	52.4	40.8
Valence change mean	12.98	9.82	5.33	1.78
Valence change SD	6.17	3.55	4.13	4.56
Calmness pre mean	38.1	41.2	42	42.9
Calmness post mean	52.7	48.3	49.2	46.2
Calmness change mean	14.62	7.17	7.21	3.28
Calmness change SD	4.38	6.01	5.19	6.25
Valence change Cohen's d (vs control)	2.06	1.97	0.82	0.00
Calmness change Cohen's d (vs control)	2.10	0.63	0.68	0.00

5.6. Physiological outcomes

Changes in physiology aligned with the self-report results but were smaller in absolute magnitude. Across arms, the multimodal condition tended to show the greatest shift towards lower arousal and more stable perfusion, with the two single-modality arms in between and the control arm showing little change. Although the standardized effects were generally in the small-to-moderate range, the direction of change was consistent across skin conductance, perfusion index, and heart rate, reinforcing the view that the session nudged the autonomic state towards a quieter profile rather than producing large, abrupt shifts.

- Skin conductance level (SCL). SCL decreased most in the multimodal arm (about -0.8 µS), followed by light-only (-0.5 µS) and audio-only (-0.4 µS), with a small change in control (-0.1 µS). See Figure 10 and Table 3a to 3d.
- Perfusion index (PI). PI increased in all active arms, suggesting steadier peripheral circulation: multimodal +0.35, light-only +0.20, audio-only +0.18, control +0.05 (Figure 11; Table 3a to 3d).

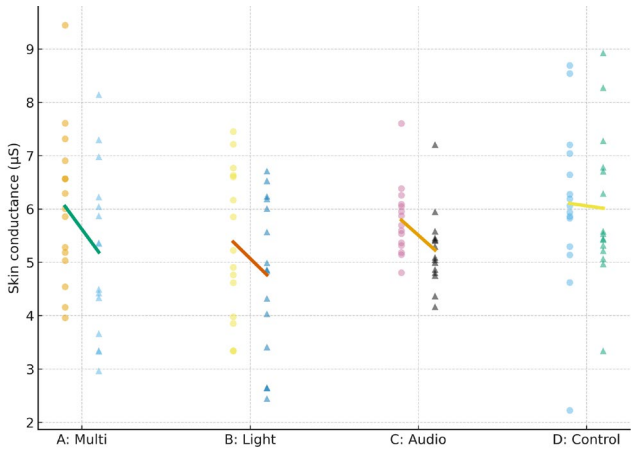

Figure 10. Change in skin conductance level (SCL) from pre- to post-session by study arm

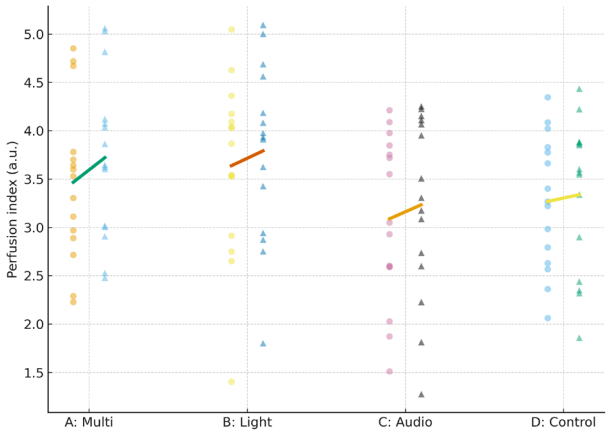

Figure 11. Change in perfusion index (PI) from pre- to post-session by study arm

Table 3a. Skin conductance level (SCL) before and after the session by study arm

Group	A_Multimodal	B_Light	C_Audio	D_Control
Pre_SCL_µS	6.05	5.38	5.79	6.1
Post_SCL_µS	5.19	4.76	5.23	6.01
Change_SCL_µS	-0.857	-0.617	-0.561	-0.091
ChangeSD_SCL_µS	0.41	0.43	0.302	0.529
N	15	15	15	15
Change Cohen's d (vs control)	-1.62	-1.09	-1.09	0.00

Table 3b. Perfusion index (PI) before and after the session by study arm

Group	Pre_PI	Post_PI	Change_PI	ChangeSD_PI	N
A_Multimodal	3.47	3.72	0.254	0.217	15
B_Light	3.64	3.79	0.153	0.255	15
C_Audio	3.09	3.23	0.144	0.293	15
D_Control	3.27	3.34	0.07	0.27	15
Change Cohen's d (vs control)			0.75	0.32	0.26

Table 3c. Oxygen saturation (SpO_2) before and after the session by study arm

Group	A_Multimodal	B_Light	C_Audio	D_Control
Pre_SpO2_pct	97.75	97.71	98.15	97.81
Post_SpO2_pct	97.82	97.7	98.13	97.75
Change_SpO2_pct	0.071	-0.01	-0.013	-0.056
ChangeSD_SpO2_pct	0.102	0.154	0.079	0.144
N	15	15	15	15
Change Cohen's d (vs control)	1.02	0.31	0.37	0.00

Table 3d. Heart rate (HR) before and after the session by study arm

Group	A_Multimodal	B_Light	C_Audio	D_Control
Pre_HR_bpm	72.82	72.2	74.48	74.66
Post_HR_bpm	69.81	70.45	72.42	74.17
Change_HR_bpm	-3.01	-1.747	-2.065	-0.492
ChangeSD_HR_bpm	2.165	1.527	1.992	1.907
N	15	15	15	15
Change Cohen's d (vs control)	-1.23	-0.73	-0.81	0.00

- Oxygen saturation (SpO_2). SpO_2 remained high and stable across arms; small declines were smallest in active arms (multimodal ≈ 0.00%, light-only -0.05%, audio-only -0.05%, control -0.10%). See Figure 12.

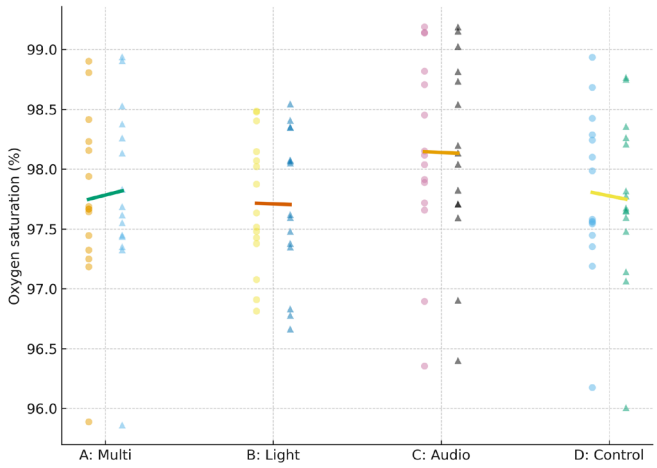

Figure 12. Change in oxygen saturation (SpO_2) from pre- to post-session by study arm

- Heart rate (HR). HR showed a modest reduction, most in the multimodal arm (-3.0 bpm), then light-only (-1.8 bpm) and audio-only (-1.5 bpm), with minimal change in control (-0.5 bpm). See Figure 13.

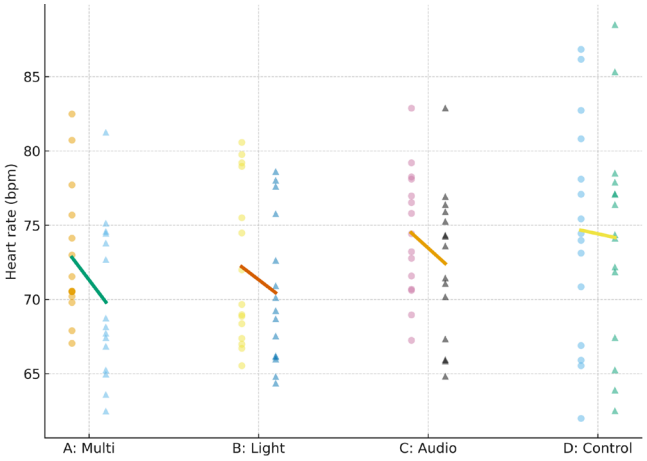

Figure 13. Change in heart rate (HR) from pre- to post-session by study arm

5.7. Sensitivity analyses and data quality

Results were unchanged when (a) excluding physiological windows that failed quality checks, (b) adjusting for baseline irritability, and (c) stratifying by perfusion index bands when examining SpO_2. Manipulation checks confirmed that sound and light levels stayed within targets throughout exposure. Device logs showed synchronized timestamps with a single clock.

5.8. Adverse events and protocol deviations

No adverse events were reported in any arm. There were no protocol deviations that affected exposure delivery or data collection, and all randomized participants with complete pre- and post-session measures were included in the primary analysis set.

6. Discussion

This trial set out to test whether a short, carefully dosed audio–light session delivered by a compact reconfigurable object could meaningfully reduce irritability. In a randomized four-arm design, the multimodal condition produced the largest reductions in irritability and the biggest gains in valence and calmness, with both single-modality arms also improving more than the neutral control. These changes were modest in size but consistent in direction and were achieved within a single 20-minute session that was well tolerated.

Conceptually, these findings are consistent with our dimensional view of irritability and with contemporary emotion regulation frameworks. Rather than asking people to engage in effortful cognitive techniques, the intervention modifies the local environment by synchronizing warm light and gentle sound in a predictable way. The working model sketched in Figure 1 treats irritability as an emergent property of a distributed network of appraisals, arousal, and bodily

state; in this view, even small nudges to context and autonomic tone can accumulate over repeated exposures.

The physiological results support this interpretation, although they are smaller in absolute magnitude than the self-report changes. Across arms, the multimodal condition tended to show the clearest shift towards lower arousal and more stable perfusion, with the single-modality arms again sitting between multimodal and control. Skin conductance level decreased and perfusion index increased most clearly in the multimodal arm, while heart rate declined modestly across active arms and oxygen saturation remained high and stable. This pattern is more consistent with a gentle move towards a quieter autonomic profile than with large, abrupt physiological shifts.

In the broader context of irritability and stress interventions, these effects place MellowLoop between simple rest breaks and more intensive training-based programmes. Established approaches such as mindfulness apps, breathing exercises with heart rate variability biofeedback, and immersive virtual reality relaxation can sometimes achieve larger or longer-lasting changes, but they also demand more user effort, sustained attention, and specialised hardware. Our ambient session does not replace these options; instead, it offers a complementary route: a short, largely passive adjustment of the local environment that can run alongside ordinary activities and may be easier to adopt as an initial or adjunctive step.

From an implementation perspective, the system is intentionally simple: a compact reconfigurable luminaire, near-field loudspeakers, and low-cost sensors integrated into a single object. In offices, such a device could be placed on desks or shared tables and triggered during short scheduled pauses; in homes, it could be used in bedrooms or living rooms as part of an evening wind-down routine; in clinics, it could support brief pre- or post-appointment decompression periods in waiting areas. Future deployments could further benefit from privacy-preserving, human-centered multimodal frameworks (e.g., federated learning) that enable cross-site model improvement while keeping sensitive mental-health related data local, which is especially relevant when scaling to clinics, homes, or pediatric screening contexts [50]. Because the exposure is defined in terms of light, sound, and duration rather than a fixed physical layout, facilities teams and researchers can adapt the configuration to local constraints while still approximating the tested dose. User experience and long-term usability will be central in any such deployment. The present trial suggests that a warm, moderately bright, and gently audible scene is tolerable and acceptable for a single 20-minute session, but over repeated use people may wish to adjust timing, content, and appearance. Future versions will likely need simple mechanisms for personalisation and rotation of audio–light patterns, while preserving the core dose parameters and allowing the object to sit comfortably within existing furniture and décor.

Several limitations should temper these conclusions. The study was conducted in a single laboratory with healthy adults, so generalisability to clinical populations and to noisier, more complex real-world settings remains uncertain. The intervention was tested over a single session only, so we do not know how quickly any benefits might accumulate, fade, or change with repeated use. The sample size, while adequate for detecting small-to-moderate effects in the primary outcome, limits the precision of estimates for some secondary measures. These limitations point directly to next steps. Future work should test multi-session protocols, extend to more diverse and clinically enriched samples, compare different schedules and patterns of exposure, and examine how MellowLoop-style objects interact with more active strategies such as guided breathing or brief cognitive exercises. In parallel, implementation studies in homes and workplaces can help determine when a quiet, ambient route is preferable and when more intensive approaches are needed.

7. Conclusion

This study shows that a single 20-minute session combining warm light and gentle sound, delivered by a compact reconfigurable object at well-defined everyday levels, can acutely reduce irritability. The effects are moderate in size but consistent across self-reported irritability, valence, and calmness, and they were achieved without discomfort or adverse events. The accompanying changes in skin conductance level, perfusion index, and heart rate, although smaller in absolute magnitude, move in directions that are coherent with a calmer autonomic state.

Beyond this specific result, the work offers a practical blueprint for building and testing similar systems. The protocol specifies clear dose ranges for light and sound, a simple multi-arm trial structure, and a low-cost sensing chain that can be reproduced or adapted by other groups. By treating the device as an everyday object rather than a specialised medical instrument, the design invites integration into ordinary rooms and routines while remaining transparent about exposure and measurement.

Taken together, these elements point towards a broader direction for pervasive health technologies: small, reconfigurable artefacts that quietly modify local environments to support emotional regulation. Future studies that extend this approach to repeated sessions, more diverse users, and real-world settings will be able to test how far such ambient interventions can contribute to everyday irritability support and how best to combine them with more active strategies such as breathing exercises or brief cognitive techniques.

Ethical statement

The study was approved by the Institutional Review Board of Zhongkai University of Agriculture and Engineering.

Conflict of Interest Statement

No potential conflict of interest was reported by the authors.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Acknowledgements.
This research was funded by the 2024 Guangdong Provincial Department of Science and Technology "Guangdong Rural Science and Technology Commissioner Project: Jiangdong Vegetable, Rice, and Agro-Cultural Tourism Industry Brand Building and Promotion" (Project No. KTP20240829); the Construction of science and technology plan project content in Jiangdong Town, Chaoan District, Chaozhou City (Project No. D125211E7); and the 2024 Chaozhou City Chaoan District Science and Technology Special Fund: Construction of Ecological Industry Innovation Talent Cultivation Base under the "Hundred, Thousand, Ten Thousand Project" (Specialized Town Transformation and Upgrading Project).

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