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Lightening the mind with audiovisual stimulation as an accessible alternative to breath-focused meditation for mood and cognitive enhancement

Micah Alan Johnson[1,2], Ninette Simonian[1] & Nicco Reggente[1]✉

In this randomized, controlled, and double-blind experiment with a relatively large sample (*n* = 262), a novel technique of audiovisual stimulation (AVS) was demonstrated to substantially improve self-reported mood states by reducing several negative affects, including anxiety and depression, and enhancing performance on mood-sensitive cognitive tasks. Most of the AVS effects were highly similar whether binaural beats were present or not and regardless of the duration of experience. Remarkably, the mood benefits from AVS closely aligned with those achieved through breath-focused meditation with additional evidence that a brief AVS exposure of approximately five minutes may be sufficient or even optimal for improving mood to a comparable or greater degree than meditation sessions of equal or longer durations (11–22 min). These exciting findings position AVS as a promising avenue for mood and cognition enhancement and a potentially more accessible "plug-and-play" alternative to meditation, which is especially relevant considering the high attrition rates commonly observed in meditation practices.

Keywords Audiovisual stimulation, Mood, Meditation, Binaural, Stroboscopic, Technodelic

Humans have long been intrigued by the flickering effects of light and sound on the brain, mood, cognition, and health[1,2]. The phenomenon of audiovisual stimulation (AVS), also referred to as brainwave entrainment (BWE), audiovisual entrainment (AVE), or stroboscopic stimulation, is usually performed with electronic devices that rhythmically pulse both light (through closed eyelids) and sound at various frequencies in simple or complex patterns in order to modulate the brain, alter the mind, or improve health[3,4]. In recent years, there has been increasing interest in using AVS specifically to passively induce desired mood states. AVS is also integral to a new wave of so-called "technodelics"[5,6] or "cyberdelics"[7] designed to enhance one's mind and wellbeing, often by inducing a psychedelic-adjacent experience in a nonpharmacological fashion by producing visual perceptions of complex geometric patterns (i.e., form constants; Fig. 1B) akin to the hallucinogenic effects of LSD or psilocybin[8–12].

Empirical research into the neural mechanisms of AVS has demonstrated neuromodulatory effects such as alteration of EEG frequencies or complexity[9,10,13], neural entrainment[14–16], or neuroplastic changes[17,18]. These findings, pending further research, position AVS as a new form of noninvasive brain stimulation and neurotherapy. The empirical evidence for the psychological effects of AVS is more mixed, according to recent meta-analyses or reviews[1–4,19], since many studies have either supported or contradicted the ability of AVS to improve a wide variety of mental phenomena including stress, anxiety, depression, memory, attention and focus, cognitive decline, pain, and sleep. The exciting yet uncertain potential for AVS to enhance the brain and mind is complicated by the relatively few studies on this topic, many of which are undersampled and/or lack rigorous experimental methods of randomization, blinding, and controls.

Recreational interest in AVS has far outpaced the empirical research due to the recent proliferation of modern devices and apps which purport to have a variety of effects, such as increasing relaxation, reducing stress or anxiety or depression, enhancing focus, and elevating overall mood[7]. Despite the growing popularity, most of

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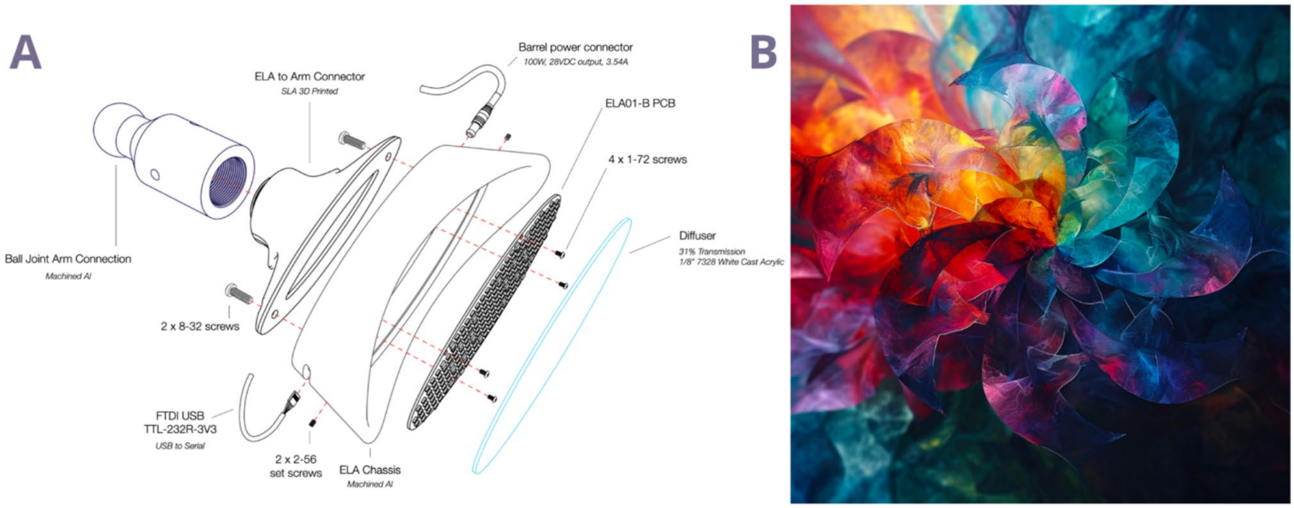

Fig. 1. Left Panel: The electronic light array (ELA) of 192 single-color LEDs with 8 color frequencies that shine through a diffuser that permits 31% transmission. The device is developed by INTO Technologies, Inc. (San Francisco, CA) and intended to induce visual phosphenes behind closed eyelids. Right Panel: Simulated depiction of the visual percept induced by the stroboscopic stimulation following the ELA 1 composition. Image generated using stable diffusion based artificial intelligence (Midjourney, v6) in response to prompts from phenomenological reports provided by N.R.

these claims are anecdotal without sufficient, if any, empirical validation. The anxiolytic effects of these AVS devices are especially touted despite the lack of clarity on their efficacy or underlying mechanisms. A distinct possibility is that the anecdotal reports of anxiety reduction could be attributed to other factors such as the act of sitting with closed eyes or the prolonged focus on a single stimulus—an increasingly rare practice in today's fast-paced society.

The present study aims to fill this knowledge gap through a comprehensive examination of AVS effects on various mood states, contrasting it with breath-focused, closed-eye meditation. Breath-focused meditation provides an ideal non-AVS control condition because it parallels the closed-eye nature and directed attention of AVS. Breath-focused meditation (i.e., focused attention of breath without voluntarily manipulating) as well as similar techniques of breathwork or breath control (i.e., focused attention of breath while voluntarily manipulating, such as in Pranayama, deep slow breathing, diaphragmatic breathing, etc.) have shown extensively documented benefits for mental, physical, and cognitive health[20–23], including effects from even a single session[24,25]. Similar to AVS, many different breathing techniques and meditation practices are also known for various neuromodulation effects depending on the type of practice, such as shifting alpha and theta band frequencies[26,27], entrainment[27–29], and neuroplastic changes to brain structure and function[30–34].

We investigated AVS effects with a particular device – dubbed the "Electronic Light Array" (ELA) developed by INTO Technologies Inc. (San Francisco, CA) – which produces synchronized visuospatial patterns of light and sound designed to encourage "relaxation, meditation, introspection, and other positive attributes" (Stephen Auger, INTO Technologies, Inc.). Binaural beats were included in the ELA experience for the purpose of enhancing its effects, due to previous evidence of their capacity for neuromodulation and enhancement of mood and cognition[19,35,36]. The ELA experience of audiovisual synchronization with binaural beats represents the AVS condition of primary interest (ELA1). For this study, an AVS control condition was created with similar audiovisual synchronization but without the binaural beats (ELA2). For a complete and technical description of the ELA device and both ELA1 and ELA2 conditions, please refer to the Supplementary Materials and our previous report[16].

To serve as a cornerstone for future work in this burgeoning field, the current study's experimental design was well-controlled, double-blind where possible, and fully randomized with a large sample size. With a mixed factorial design, we compared within-subjects effects on mood and mood-sensitive cognition between two timepoints (Pre and Post) and across nine between-subjects groups. Each group received one of three types of experience: AVS with binaural beats (ELA1), AVS without binaural beats (ELA2) serving as an AVS control condition, or breath-focused meditation (Meditation) serving as a non-AVS control condition. Each group engaged in this experience for one of three different durations (5.5, 11, and 22 min). Before and after each experience, we collected a battery of mood assessments (e.g., anxiety, depression, tension, etc.) and two mood-sensitive cognitive tasks – Stroop[37,38] and Local Global[39–42]. During the experience, participants' neural activity was recorded with a 64-channel EEG setup. These EEG results were recently reported in Frohlich et al. (2023). In the current paper, we report on the behavioral findings from the same experiment.

Our first research question was, to what degree do the experiences produce differential psychological effects? We hypothesized that participants' mood and cognitive function would show different degrees of improvement over time between the three types of experience (ELA1, ELA2, Meditation). We expected that AVS with binaural beats (ELA1) would outperform AVS without binaural beats (ELA2) and possibly also outperform, or perform as well as, a closed-eye, breath-focused meditation experience given some prior evidence for the psychological efficacy of audiovisual stimulation, although the evidence appears quite mixed and inconclusive[1–4,19]. Considering the high attrition rates in establishing a meditation practice (e.g., between 20 and 40% in some studies)[43–46], a passive yet engaging visual experience offering comparable benefits could significantly broaden access to therapeutic advantages, even from brief exposures, for a wider segment of the population. Technologically inclined individuals, particularly adolescents, may be more motivated or even prefer to use digital technologies as part of their mental health care. Due to increased accessibility, digital technology has been rapidly growing in popularity with novice and advanced, but not expert, meditators who appear motivated primarily to reduce negative affects like stress and anxiety[47,48].

Our second research question was, is there an optimal duration (i.e., "sweet spot") that maximizes efficacy? We hypothesized that longer durations would impart larger psychological benefits with the rationale that benefits should scale proportionally as a function of time spent engaged in the experience based on previous evidence of effects of practice, duration, and experience in meditation[49,50]. On the other hand, other meditation studies have provided counterevidence of null results from practice or increased duration[51,52]. Given that this remains an unresolved issue in meditation research that does not appear to have been investigated with audiovisual stimulation, we anticipate that our exploratory analysis of duration effects will provide an important contribution to both fields. We were also specifically interested to know whether, for any significant effects in any of the ELA1 duration groups, if those effects outperformed the effects of meditation at the same or higher duration level. This interest was motivated by the desire to inform users of AVS devices, like the ELA, about optimal durations of use, if any, for providing similar or greater benefits on mood and cognition when compared to a well-vetted alternative experience like meditation.

Our third research question was, are experiential effects influenced or moderated by participants' personality traits? This question was motivated by the well-known individual differences of personality traits[53], previous findings that not all people respond to impactful content in the same way[54,55], and prior evidence for trait measures moderating effects of AVS[10] and meditation[56]. We assessed trait moderation by testing for experimental interactions with two relevant traits, openness to experience and mindfulness, measured prior to the experiences. We were interested in the openness to experience trait given its history in accounting for individual differences in response to non-ordinary experience[57,58]. We hypothesized that higher openness should confer increased benefits similarly for all experiences. We were interested in mindfulness because it has been shown to help reduce a wide range of negative affect and positively influence meditation outcomes[56,59]. We also hypothesized that participants with lower trait mindfulness might require stronger and/or longer experiences for effects to show.

Methods

Experimental methods

Participants

A cohort of 286 individuals was enlisted through targeted Facebook advertisements aimed at adults residing within a 50-mile proximity of Santa Monica, CA. Twenty-three participants were either excluded or unable to complete the entire study due to voluntary withdrawal, technical issues, previously unreported color blindness, and failure to stay awake. Two participants were excluded from the Stroop Task and one participant was excluded from the Local Global Task due to misunderstanding the instructions. Consequently, the final full sample comprised 262 participants, ranging in age from 19 to 79 years ($M = 43.67$; $SD = 15.66$; 135 females). Compensation (cash or Venmo) for participants was set at $30 per hour, prorated to rounded-up 15-minute intervals. On-site parking validation was also provided.

Participants qualified for the study if they had no history of epilepsy, seizures, migraines, photo-light sensitivity, cataracts, corneal abrasions, keratitis, uveitis, hearing problems, and had normal or corrected-to-normal vision. Additionally, eligible participants were not currently using any photophobia-inducing or hearing-altering medications, including high doses of naproxen. Eligibility screening was executed via Castor ePRO (Amsterdam, Netherlands)[60]. Informed consent was obtained from all subjects and/or their legal guardian(s). All participants provided digital informed consent through Castor eConsent. This research study adhered to all ethical regulations and principles applicable to human participant research including the Declaration of Helsinki and the Ethics Code of the American Psychological Association. The Institutional Review Board at Advarra (Columbia, MD) approved all recruitment, informed consent, and testing procedures prior to initiating enrollment (Pro00048382).

A pre-enrollment power analysis ($p = 0.05$, power $= 0.80$) determined that 32 subjects were needed in each of the nine groups to detect a 20% reduction in STAI score— a meaningful reduction[61].

All participants completed questionnaires and tasks, both before (Pre) and after (Post) the experience, on a 15.6" 2021 Lenovo IdeaPad 3, using an auxiliary mouse. All questionnaires were administered through Castor ePRo[60], except the Global Anxiety-Visual Analog Scale (GA-VAS), which utilized paper and pencil. The Local-Global Task[62] and Stroop Task[63] were sourced from Pavlovia (https://pavlovia.org) and launched through PsychoPy2[64].

Bioperipherals were recorded using the CGX Aim II Physiological Monitoring device (Cogniomics, Inc.) and ECG electrodes (Skintact Inc.), recording Electromyography (EMG), Bio-Impedance-Based Respiration Rate, Heart Rate and Oxygen Saturation), and Galvanic Skin Response (GSR EEG signal (500Hz sampling rate) was acquired using a dual-amp 64-channel cap system (BrainVision, LLC), with data collected using Recorder (BrainVision, LLC), all connected to a 15.6" 2021 Lenovo Ideapad. Given the broad scope of this research effort, the EEG and bioperipheral results are not directly discussed in this manuscript but are reported elsewhere[16].

The stroboscopic is an electronic light array (ELA) prototype developed by INTO Technologies, Inc. (San Francisco, CA) to generate visual phosphenes through closed eyelids. The device utilized a set of 192 LEDs with 8 color frequencies, emitting light through a diffuser with 31% opacity (Fig. 1). To create a unique experience, the LEDs were programmed to pulse at specific frequencies, creating dynamic, time-varying patterns synchronized with a pre-recorded stereo audio track. The term "experience" is used herein to describe the combination of LED patterns and audio tracks, with detailed compositions provided in the Supplemental Materials.

The experimental audiovisual condition (ELA1) was created to induce a state of relaxation, featuring a composition of light and atmospheric auditory elements of diverse frequencies, including sounds of tanpura, gongs and bells, creating an atmospheric soundscape that was designed to simulate the experience of being in an acoustic space resembling a temple or cathedral (Jeff Bova, INTO Technologies, Inc.). A key component of the ELA experience is the embedding of binaural beats (in the musical key of D) tuned to the harmonic progression of the music while simultaneously beating at designated frequencies (i.e., alpha and theta) known to be involved in states of meditation and relaxation[59]. The combination of audiovisual synchronization across multiple frequencies was designed to maximize subject engagement and dynamic entrainment and to be more effective at inducing a deeper and more consistent state of relaxation and focus. See Supplemental Materials 1–2 for more information.

The active audiovisual control condition (ELA2) involved an asynchronous series of pulsing light frequencies, designed to modulate the 8 LED frequencies at irregular intervals which have been previously shown to not induce entrainment as compared to ELA1[16]. The intensity and lux output were matched between ELA1 and ELA2. The audio in ELA2 closely resembled the experimental condition, excluding the binaural beat rhythms. Lastly, the non-audiovisual control condition involved a simple eyes-closed meditation exercise where participants were instructed to focus on their breath, matching the durations of both ELA1 and ELA2 conditions (See Supplemental Materials for exact meditation instructions).

The ELA device was mounted on the edge of a desk and adjusted for each participant using a swivel (M!ka). Experiential compositions displayed by the ELA device were triggered using Ableton Live 10 via a Python3 Controller, Pylive (https://github.com/ideoforms/pylive) on a 13.3" 2020 Macbook Air. Lab Streaming Layer with LabRecorder (https://github.com/labstreaminglayer) was utilized to temporally synchronize our EEG, bioperipheral, and experimental time series (e.g., pre-experience rest ended, Ableton experience started, etc.) within an XDF file format. All participants sat in a powered recliner chair and wore wired earbuds (Sony XBA-100), attached to the audio jack of the computer. Figure 2 illustrates the experimental setup.

Behavioral questionnaires

All participants completed a battery of state-sensitive mood assessments both before, after, and one week following their participation. The pre-experience questionnaire also included validated trait questionnaires intended to account for individual differences in response to each of the experimental conditions.

Trait measures (pre timepoint only)

Five Facet Mindfulness Questionnaire (FFMQ)[65]: The 39-item FFMQ examines five factors of mindfulness derived through factor analysis of several independent mindfulness scales. These include: Observing - noticing sensations, thoughts and feelings (e.g. "When I'm walking, I deliberately notice the sensations of my body moving"); Describing - finding words to articulate experiences (e.g. "I'm good at finding words to describe my feelings"); Acting with Awareness - avoiding automatic pilot by focusing on the present activity (e.g. "When I do things, my mind wanders off and I'm easily distracted"); Nonjudging - refraining from evaluation of experiences (e.g. "I criticize myself for having irrational or inappropriate emotions"); and Nonreactivity - allowing feelings to come without reacting (e.g. "I perceive my feelings and emotions without having to react to them").

International Personality Item Pool (IPIP)[66]: IPIP is a public domain collection of over 3,300 personality assessments that measure dimensions like the "Big Five" personality traits. Of primary interest in this study, the Openness to Experience subscale measures intellectual curiosity, creativity, and openness to new ideas through 18 questionnaire items rated on a 5-point Likert scale.

State measures (pre and Post timepoints)

State-Trait Anxiety Inventory (STAI)[67]: STAI measures both temporary (state) and longstanding (trait) anxiety, often to distinguish anxiety from depressive disorders. This 40-item scale evaluates how respondents currently feel using items like "I am tense" and "I am worried" on a 4-point Likert scale from "Not at all" to "Very much so."

Profile of Mood States (POMS; short-version)[68]: The POMS questionnaire evaluates transient affective states by asking participants to rate (1–5 Likert) the degree to which 30 different mood-related words/statements (e.g., full of pep) describes how they feel in a particular moment.

Hospital Anxiety and Depression Scale (HADS)[69]: The 14-item HADS measures anxiety (7 items) and depressive (7 items) symptoms to assess severity in acute scenarios to screen for psychiatric disorders.

Global Anxiety-Visual Analog Scale (GA-VAS) is a single-item scale used to assess current anxiety levels[70]. Participants mark their current level of anxiety along a continuum between "no anxiety" to "extreme anxiety" presented visually as a 10-centimeter line. The distance of the mark from the low end is measured to quantify anxiety severity.

Outcome measures (Post timepoint only)

The Toronto Mindfulness Scale[71] is a self-report questionnaire used to evaluate state mindfulness after meditation. It contains 13 items assessing two distinct factors - Curiosity, representing an attitude of openness and interest; and Decentering, defined as metacognitive introspection that reduces rumination. The scale distinguishes mindful self-awareness from maladaptive self-focused thinking.

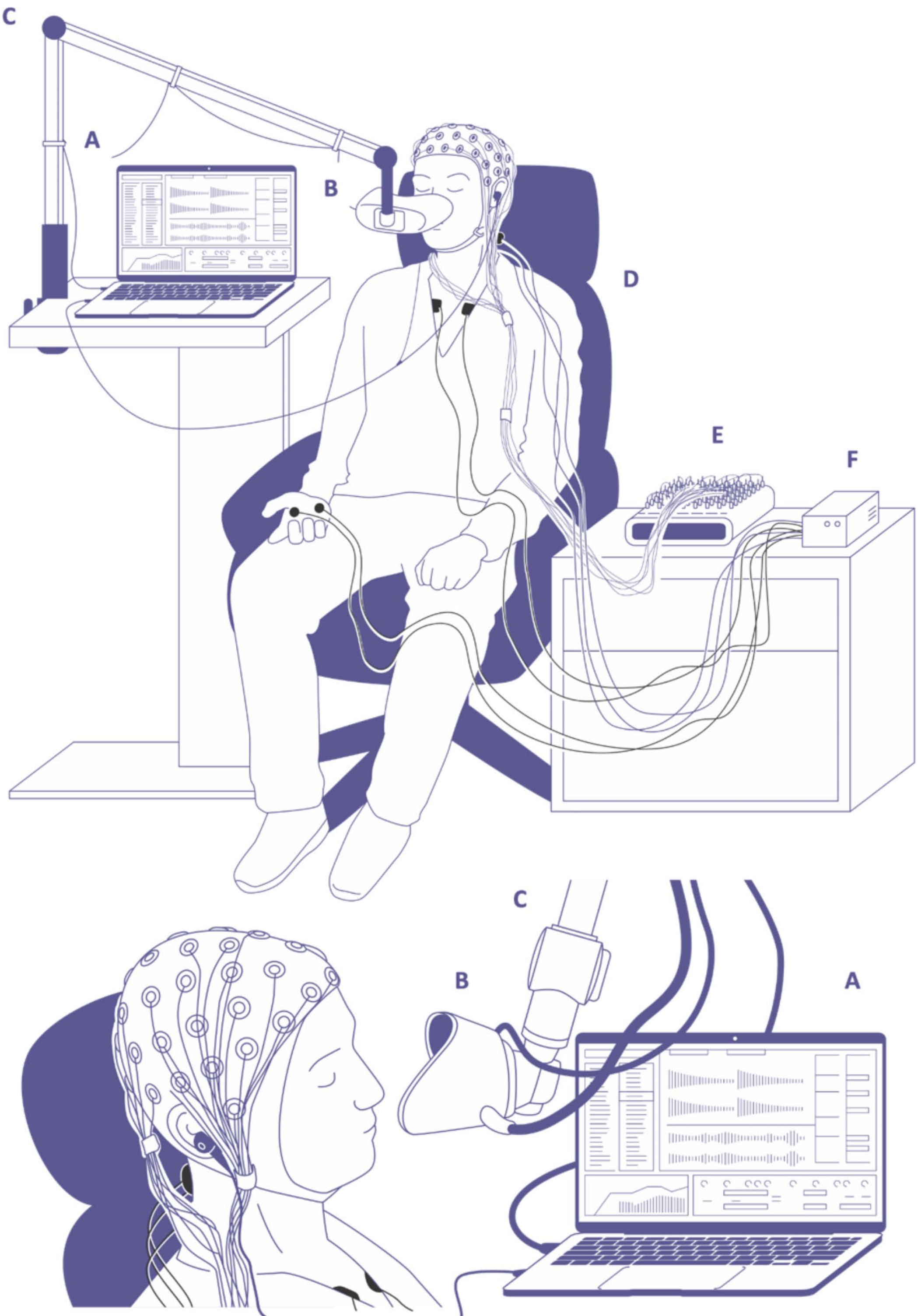

Fig. 2. Top Panel: Illustration of the experimental setup, showing the (A) MacBook running Ableton Live 10 and outputting audio through Sony XBA-100 earbuds and visual composition information to (B) ELA device affixed to the desk via a (C) M! ka arm mount swivel while participants sat in (D) a powered recliner. All participants were connected to a 64-channel EEG with a (E) dual-amplifier and a suite of bioperipherals connected to a (F) receiver. Bottom Panel: Profile view of the ELA device placed approximately five inches away from the participant's closed eyelids using the mount.

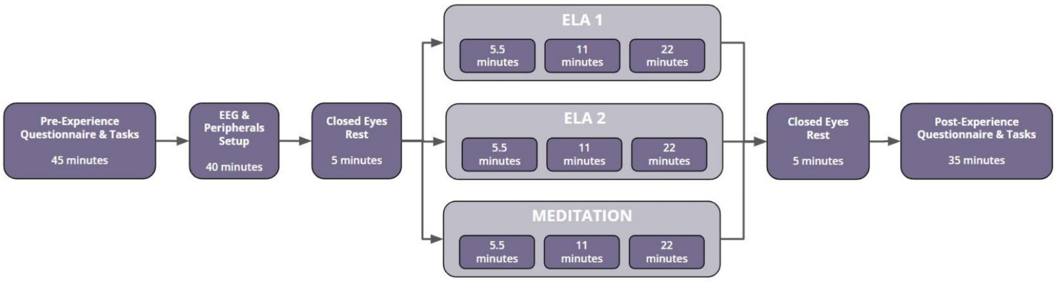

Fig. 3. Illustration of the experimental protocol showing each participant's shared (pre and post batteries) and group-specific experiences (ELA1, ELA2, or Meditation) that lasted either 5.5, 11, or 22 min. The total on-site portion of the experiment lasted approximately hours.

Group	Duration (min)	*n*	Gender (M/F)	Age Range	M	SD
ELA1	5.5	30	16/14	19–69	40.47	14.62
	11	29	13/16	22–73	45.66	16.57
	22	29	10/19	21–69	40.21	15.23
ELA2	5.5	29	15/14	23–79	50.31	15.74
	11	27	15/12	20–65	37.59	15.55
	22	28	9/19	21–67	44.43	14.86
Meditation	5.5	30	16/14	21–72	44.77	15.66
	11	30	16/14	19–71	46.60	16.71
	22	29	21/8	22–68	42.79	14.39

Table 1. Participant characteristics of the nine experimental groups created by combinations of different experiences (ELA1, ELA2, meditation) and durations (5.5 min, 11 min, 22 min). 'n' refers to group sample size. 'M' and 'F' refer to male or female. Age is reported in years. 'M' and 'SD' refer to the mean and standard deviation of age.

Behavioral tasks (pre and Post timepoints)

The Stroop color-word interference task assesses cognitive control[63]. Participants are shown color words (e.g., "red") printed in font colors that were either congruent (50% of 30 trials) or incongruent (50% of 30 trials) with the color word. Participants are instructed to rapidly name the color of the letters making up the color word while ignoring the word itself. Reaction times are often slower, and accuracy is often worse, during incongruent trials when the printed word and font color conflict (e.g. "red" in blue font) compared to congruent fonts, demonstrating involuntary reading interference.

The Local global task[62] presents large target letters composed of smaller distractor letters, which may be congruent (e.g., a large H made up of smaller Hs; 50% of 64 trials) or incongruent (e.g., a large H made up of smaller Ks; 50% of 64 trials). Participants must identify the small letters while ignoring the large letters, using the key press "H" or "K." Incongruent trials often yield slower reaction times and lower accuracy rates due to interference effects. Both of these behavioral tasks have been shown to be sensitive to levels of anxiety or depression[37–39,41,42,72]. allowing them to serve as more ecologically valid measures of state anxiety and depression compared to self-reports.

Procedure

The protocol flow (Fig. 3) was conducted as follows: Pre-Screening (at home) → Scheduling of applicable subject → Pre-Experience Questionnaire (35 min) → Experience (5.5, 11, or 22 min) → Post-Experiment Questionnaire (40 min) → One-Week Follow Up Questionnaire (40 min; same as post-experiment).

Randomization was conducted prior to site visitation using a single-site validated block randomization model (Castor EDC) with participants' sex as a randomization stratum across 9 groups (3 experiences x 3 durations). Groups were defined as ELA 1 (Electronic Light Array; i.e., the actual experience designed by INTO Technologies, Inc.), a meditation group (instructed to do closed-eye meditation using breath-focused awareness), and an active audiovisual control group (ELA 2; i.e., an experience designed by INTO Technologies, Inc. to control for total lumen and auditory output without the proprietary phase transitions and binaural beats used in the ELA 1 design). Each group consisted of three sub-groups where the experience length was either 5.5 min, 11 min, or 22 min resulting in a total of nine groups. The participant characteristics of these nine experimental groups are reported in Table 1 below.

Participants underwent temperature screening (iHealth Labs Inc.) and were provided N-95 masks upon arrival. They were introduced to the experimental protocol (i.e., pre-questionnaire, EEG and peripherals setup, experience, post-questionnaire) and informed that their "experience" would involve either a 5.5, 11, or 22-minute

	ELA1 (5.5 min)				ELA1 (11 min)				ELA1 (22 min)			
	Pre		Post		Pre		Post		Pre		Post	
Variable	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Anxiety (HADS)	7.53	3.35	3.40	2.87	4.72	3.41	1.55	2.19	6.14	6.28	3.31	3.76
Anxiety (STAI)	37.77	12.31	32.77	10.27	30.79	7.98	27.89	8.60	34.10	11.21	30.79	10.57
Anxiety (VA)	5.68	3.93	2.98	3.01	4.07	4.05	2.16	2.74	4.19	4.17	2.61	3.52
Depression (HADS)	6.10	3.69	4.83	3.46	3.72	3.07	3.86	2.97	5.72	3.46	4.79	2.87
Depression (POMS)	3.60	4.52	1.13	1.89	1.55	2.61	0.69	1.31	2.55	3.28	1.48	2.79
Tension (POMS)	4.03	4.23	2.07	2.48	2.21	2.11	1.35	2.50	2.89	3.74	2.14	3.62
Anger (POMS)	1.83	2.79	0.80	1.45	0.89	1.59	0.31	1.00	1.14	2.76	0.38	1.18
Fatigue (POMS)	4.87	4.79	3.00	3.37	4.38	4.09	3.07	3.85	5.21	4.83	3.93	4.47
Confusion (POMS)	4.30	2.60	3.43	1.69	3.76	1.33	3.59	2.03	4.59	2.79	3.83	2.48
Local Global	0.011	0.022	0.006	0.003	0.014	0.043	0.012	0.034	0.006	0.002	0.005	0.001
Stroop	0.081	0.241	0.058	0.171	0.185	0.355	0.121	0.338	0.077	0.322	0.051	0.227
	ELA2 (5.5 min)				ELA2 (11 min)				ELA2 (22 min)			
	Pre		Post		Pre		Post		Pre		Post	
Variable	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Anxiety (HADS)	6.28	4.26	2.97	4.26	7.22	4.35	3.19	2.42	5.93	3.68	2.18	2.72
Anxiety (STAI)	32.31	10.09	30.62	11.51	34.19	8.89	28.59	7.72	34.64	10.72	27.82	6.98
Anxiety (VA)	3.53	3.94	2.31	3.36	3.58	3.55	1.75	2.28	3.77	4.03	1.26	1.54
Depression (HADS)	3.97	2.72	3.52	2.42	5.26	3.52	4.41	2.22	4.32	2.79	3.43	2.36
Depression (POMS)	1.83	3.13	1.59	3.29	2.22	3.48	0.78	1.83	2.36	4.13	0.89	1.69
Tension (POMS)	2.93	3.43	2.38	4.42	3.00	2.62	1.78	2.23	2.57	3.45	1.00	2.13
Anger (POMS)	1.86	2.99	1.24	2.39	0.67	1.24	0.11	0.32	1.64	3.54	0.25	0.79
Fatigue (POMS)	3.62	3.78	3.00	3.11	4.44	4.94	3.19	3.32	4.54	3.95	2.68	2.96
Confusion (POMS)	4.62	2.35	3.72	1.96	3.82	2.11	3.00	2.08	3.68	2.75	3.32	1.36
Local Global	0.022	0.08	0.007	0.009	0.025	0.089	0.007	0.007	0.008	0.004	0.007	0.005
Stroop	0.139	0.417	0.075	0.335	0.11	0.32	0.105	0.258	0.189	0.423	0.012	0.007
	Meditation (5.5 min)				Meditation (11 min)				Meditation (22 min)			
	Pre		Post		Pre		Post		Pre		Post	
Variable	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Anxiety (HADS)	5.30	3.55	2.67	2.56	5.58	3.89	1.97	2.54	4.83	3.33	2.28	2.19
Anxiety (STAI)	31.87	11.54	28.43	8.94	33.16	11.56	28.42	7.57	32.24	9.64	28.93	7.71
Anxiety (VA)	3.33	3.91	1.34	2.08	4.70	4.37	1.97	2.61	3.96	3.83	1.32	2.05
Depression (HADS)	4.43	3.41	4.03	3.39	4.74	3.48	4.29	3.12	4.66	3.57	4.79	3.46
Depression (POMS)	2.67	4.25	1.30	2.18	3.07	4.49	1.39	2.64	1.52	1.98	0.97	1.66
Tension (POMS)	3.27	4.33	1.53	2.76	3.36	4.66	1.07	2.38	2.21	2.16	1.00	1.20
Anger (POMS)	1.40	2.66	0.40	0.77	1.87	4.06	0.29	1.27	1.10	2.48	0.28	0.88
Fatigue (POMS)	3.87	3.53	2.53	2.92	5.07	4.94	3.03	3.23	3.76	4.15	2.07	2.56
Confusion (POMS)	3.90	2.04	2.53	1.38	4.97	3.48	3.52	2.69	4.10	2.13	3.17	1.91
Local Global	0.007	0.003	0.006	0.002	0.006	0.002	0.006	0.003	0.014	0.026	0.006	0.002
Stroop	0.108	0.355	0.077	0.244	0.107	0.256	0.063	0.169	0.015	0.01	0.01	0.004

Table 2. Descriptive statistics of all dependent variables for each timepoint by experience and duration groups. 'M' refers to the mean and 'SD' refers to the standard deviation.

audiovisual stimulation or breath-counting exercise. The specific experiential group assignment was unknown to both the participant and the experimenter at this point. After giving instructions, the research assistant left the participants to complete the pre-experimental questionnaires and behavioral tasks in isolation. Participants were then instructed to remove accessories and silence phones before EEG cap fitting and bio-peripherals setup. EEG and peripheral physiological sensors were set up according to standard procedures. Details of this process and related results are outside the scope of this behaviorally-focused manuscript but can be found in Frohlich et al. (2023). Participants were seated in a recliner chair with earphones. All powered devices, except for the stroboscopic device, were unplugged prior to beginning the experience.

Participants began with a 5-minute eyes-closed relaxation period. The experimental script would then identify the randomized group assignment. The ELA1 and ELA2 groups were conducted double-blind, while the meditation group could not be due to the nature of the intervention.

For both ELA1 and ELA2, the device was positioned in front of their closed eyes, approximately five inches away from their eyes (Fig. 2). They were reminded of their ability to opt out and informed of the experience duration. Participants in the meditation group received instructions for a breath-focused awareness meditation before engaging in the practice; verbatim instructions are included in the Supplemental Materials. Following the experiential period, participants briefly opened their eyes before taking a second 5-minute rest.

Once completed, EEG and bio peripherals were removed, and the participant was offered the opportunity to use the restroom. A post-experience behavioral assay followed, including the Toronto Mindfulness Scale (TMS), HADS, POMS, STAI, GA-VAS, Global Task, and Stroop Task before being compensated and having their parking validated.

Statistical methods

Independent variables

The primary independent variables (IV) were timepoint (pre, post) as a categorical, within-subjects factor and both experience (ELA1, ELA2, meditation) and duration (5.5 min, 11 min, 22 min) as categorical, between-subjects group factors. The demographic variables of age and sex were also included to control for their potential effects. For the moderation analyses, two continuous variables measured at the Pre timepoint – openness to experience and trait mindfulness – were tested for interaction effects with the experience and duration factors.

Dependent variables

There were 12 primary outcome measures that were collected at both timepoints and used as dependent variables (DV) in separate models. Ten of these measures tracked different mood states: Anxiety (HADS), Anxiety (STAI), Anxiety (VA), Depression (HADS), Depression (POMS), Tension (POMS), Anger (POMS), Fatigue (POMS), Confusion (POMS), and Vigor (POMS). There were also two outcome measures that tracked task performance on the incongruent trials of the Stroop and Local Global tasks, where performance was measured by the ratio of reaction time (RT) divided by accuracy (ACC), here called RTACC, which decreases when task performance improves (e.g., either RT decreases or ACC increases). Only the results for the RTACC task measures are reported here, for simplicity and ease of interpretation, although both RT and ACC scores from each task were also separately tested in all models to confirm consistent results. There were also two additional outcome measures – Decentering and Curiosity – that were collected at only the Post timepoint.

Main models

Either generalized linear mixed models (GLMM) or generalized linear models (GLM) were used, depending on optimal model fitting (see Model Diagnostics section below). The primary research question of differential effects over time was tested as interactions in separate models for the three-way interaction (experience x duration x timepoint) and the relevant two-way interactions involving time (experience x timepoint, or duration x timepoint). All main effects (e.g., timepoint) within the different groups were also tested as part of these generalized models. Separate models were conducted for each DV that was collected at both timepoints. Demographic covariates (age and sex) were also included as main effects in all models. Given a priori hypotheses of differential time effects between experience and duration groups, post-hoc t-tests between timepoints, using the estimated means, were conducted for each of the experience groups (averaging across duration groups) as well as for each of the nested experience x duration groups.

Targeted comparisons (ELA1 vs. meditation)

In addition to the planned comparisons above, additional post hoc comparisons between ELA1 and Meditation were conducted for any DVs that showed significant timepoint effects for the ELA1 group at specific duration levels. These additional analyses were motivated by three questions. First, do any significant timepoint effects in the ELA1 5.5 min group outperform timepoint effects in any of the meditation duration groups? Second, do any significant timepoint effects in the ELA1 11 min group outperform the timepoint effects in the meditation 11–22 min groups? And third, do any significant timepoint effects in the ELA1 22 min group outperform timepoint effects in the meditation 22 min group? These comparisons were conducted with t-tests using the estimated means from the main models with corresponding effect sizes estimated with Cohen's d and 95% confidence intervals.

Moderation models

We hypothesized that participants' initial profile of openness to experience and mindfulness would moderate the potential experience effects. Moderation was modeled as interactions between each covariate and the experience and duration factors in separate GLMs using difference scores across time (post – pre) as the DVs. For each DV and each covariate, a separate GLM was conducted for the three-way interaction (experience X duration X covariate), each two-way interaction (experience X covariate, or duration X covariate), and all main effects combined. These GLMs were also applied separately to two of the DVs, curiosity and decentering, that were collected only at the post timepoint. Because we did not have any a priori hypotheses about differential moderation effects between nested levels of experience and duration, we conducted post-hoc t-tests for only the significant interaction terms.

Model Diagnostics

Extensive model diagnostics for the GLMs and GLMMs were conducted in RStudio[73] using the following packages: *glmmTMB*[74], *DHARMa*[75], and *emmeans.*[76] Each model was tested with either a generalized linear mixed model (GLMM), including subjects as a random effect on the intercept, or a generalized linear model (GLM) without the random effect, depending on model convergence and optimal fit. No random effects from the experimental factors (i.e., random slopes) were included in any models, due to lack of convergence or poor fit. Given the non-normal distributions of model residuals for most of the DVs, because of their highly skewed or kurtotic distributions, it was determined that either negative binomial, gamma, or t distributions (all with the identity link) were optimal or model fitting in order to ensure no substantial violations or problems with linearity, independence of errors, homoscedasticity, dispersion, zero-inflation, outliers, within-group normality of residuals, and saturation. If necessary, dispersion and zero-inflation adjustments were included to optimize model fitting.

Nonparametric tests

We complemented all parametric t-tests with corresponding nonparametric t-tests, which do not assume normality of residuals or equal variances, in order to increase statistical rigor and reliability of results. We used Wilcoxon signed-rank tests, using the *wilcoxsign_test* function from the *rstatix* package in R.

Multiple comparison correction

We implemented the widely used false discovery rate (FDR) method of correcting p values for multiple comparisons to optimally control for both Type I and Type II errors[77,78]. The FDR-corrected threshold for significance was chosen as $a = 0.05$ ($p < 0.05$). FDR correction was always performed across all DVs and separately for (1) the results of the main models across all interaction and main effects, (2) the post-hoc t-tests of the three-way interaction (i.e., experience x duration x timepoint) with separate corrections for the parametric and nonparametric p values, (3) the follow-up t-tests of the two-way interaction of primary interest (i.e., experience x timepoint) with separate parametric and nonparametric corrections, (4) the complex contrasts for the targeted analysis comparing ELA1 and Meditation, and (5) the moderation results across all interaction and main effects.

For each main effect or interaction effect from the main models, both uncorrected p values (p.raw) and FDR-corrected p values (p.fdr) were reported. For any post-hoc tests of the main model interactions or the targeted comparisons, FDR-corrected p values for both the parametric (p.par.fdr) and nonparametric (p.npar.fdr) tests were reported and jointly considered for interpreting statistical significance (i.e., both p.par.fdr < 0.05 and p.npar.fdr < 0.05).

Effect sizes

For all parametric t-tests from the main models or targeted comparisons, effect sizes were estimated with Cohen's d (labeled as *eff.par*) and interpretations were approximately based on the standard convention of small ($d = 0.3$), medium ($d = 0.5$), and large ($d = 0.8$). For all nonparametric t-tests, the effect sizes (labeled as *eff.*npar) were estimated, using the *wilcox_effsize* function from the *rstatix* package in R[79,80], based on the provided r value that varies from 0 to 1 (asymptotic) and is interpreted as small (0.10–0.3), moderate (0.30–0.5), and large (> 0.5).

Results

Descriptive statistics

Main models (interactions and Main effects)

Tables 3 and 4 summarize results from the main models. The main effect of timepoint (Table 3), which combined all experience and duration groups, was considered significant (p.fdr < 0.05) for each of the outcome measures except the HADS-derived depression scale, which showed the same numerical trend. There was a highly consistent pattern of decrease over time for all measures, indicating general improvement in mood states and improved performance on incongruent trials for both Stroop and Local Global tasks (i.e., lower RTACC scores indicate faster reaction times and/or higher accuracies). Effect sizes were reliable (i.e., the confidence intervals did not include 0) and consistently moderate to large for all variables except the POMS-derived depression and fatigue scales which had very small effects.

None of the interaction effects (Table 4) were considered statistically significant (p.fdr > 0.05), but there were two marginal interactions that we decided to investigate further. Depression (POMS) showed a marginally significant experience x duration x timepoint interaction which was driven by two lower-order interactions. There was a significant duration x timepoint interaction within only ELA2 ($F(2, 502) = 4.63$, $p = 0.0102$) such that depression decreased over time for the 11 min ($t(502) = -4.01$, $p = 0.0001$) and 22 min groups ($t(502) = -3.89$, $p = 0.0001$) but not for the 5.5 min group ($t(502) = -0.74$, $p = 0.4587$). Both 11 min and 22 min effects were significantly different from the 5.5 min group (11 min: $t(502) = 2.67$, $p = 0.0079$; 22 min: $t(502) = 2.43$, $p = 0.0154$) but not different from each other, $t(502) = -0.32$, $p = 0.7526$. There was also a significant experience x timepoint interaction for only the 5.5 min duration group ($F(2, 502) = 5.63$, $p = 0.0038$) such that depression decreased over time for both ELA1 5.5 min ($t(502) = -5.60$, $p < 0.0001$) and meditation 5.5 min ($t(502) = -3.42$, $p = 0.0007$) but not for ELA2 5.5 min ($t(502) = -0.74$, $p = 0.4587$). Both ELA1 and meditation effects were

Timepoint									
DV	Direction	eff.par (CI)	eff.npar (CI)	df1	df2	F	*p*.par.fdr	*p*.npar.fdr	sig
Anxiety (HADS)	Post < Pre	−1.57 (−1.79, −1.36)	0.75 (0.69, 0.81)	1	513	252.54	< 0.0001	< 0.0001	*
Anxiety (STAI)	Post < Pre	−0.51 (−0.71, −0.31)	0.53 (0.43, 0.62)	1	502	27.28	< 0.0001	< 0.0001	*
Anxiety (VA)	Post < Pre	−1.03 (−1.28, −0.79)	0.65 (0.57, 0.72)	1	513	76.70	< 0.0001	< 0.0001	*
Depression (HADS)	Post < Pre	−0.88 (−1.73, −0.02)	0.24 (0.12, 0.35)	1	516	4.06	0.1503	< 0.0001	~
Depression (POMS)	Post < Pre	−0.05 (−0.06, −0.04)	0.53 (0.44, 0.61)	1	514	88.59	< 0.0001	< 0.0001	*
Tension (POMS)	Post < Pre	−0.59 (−0.77, −0.42)	0.48 (0.37, 0.57)	1	514	63.74	< 0.0001	< 0.0001	*
Anger (POMS)	Post < Pre	−0.52 (−0.65, −0.39)	0.41 (0.31, 0.49)	1	514	63.63	< 0.0001	0.0130	*
Fatigue (POMS)	Post < Pre	−0.01 (−0.01, −0.01)	0.43 (0.33, 0.53)	1	513	49.42	< 0.0001	< 0.0001	*
Confusion (POMS)	Post < Pre	−0.53 (−0.77, −0.29)	0.35 (0.25, 0.46)	1	513	19.05	< 0.0001	< 0.0001	*
Local Global	Post < Pre	−0.53 (−0.80, −0.26)	0.52 (0.43, 0.61)	1	506	15.02	0.0004	< 0.0001	*
Stroop	Post < Pre	−1.44 (−1.75, −1.12)	0.63 (0.55, 0.72)	1	508	85.41	< 0.0001	< 0.0001	*

Table 3. Main effect of timepoint (pre vs. post) from the GLM or GLMM models, collapsing across experience and duration groups. 'DV' refers to the dependent variable. Performance on the Stroop and Local Global tasks refers to only the incongruent trials and was estimated as reaction time divided by accuracy. 'Direction' refers to the relative difference between timepoints. 'eff.par' refers to the parametric effect size (Cohen's *d*) with corresponding 95% confidence interval. 'eff.npar' refers to the nonparametric effect size (Wilcoxon signed-rank *r*) with corresponding 95% confidence interval. 'df1' and 'df2' are the first and second degrees of freedom for the F test with corresponding F value from the GLM or GLMM. 'p.par.fdr' refers to the parametric *p* value corrected by the false discovery rate method. 'p.npar.fdr' refers to the nonparametric *p* value corrected by the false discovery rate method. 'sig' refers to the statistical significance, where * indicates that both p.par.fdr < 0.05 and p.npar.fdr < 0.05, and ~ indicates that one is significant and the other is marginally significant ($p < 0.10$).

significantly different from ELA2 (ELA: $t(502) = -3.35$, $p = 0.0009$; 22 min: $t(502) = 1.83$, $p = 0.0680$) but not different from each other ($t(502) = -1.54$, $p = 0.1236$).

The other marginally significant interaction was the duration x timepoint interaction for Anger (POMS). There was a significant decrease in anger for each duration level (5.5 min: $t(512) = -3.85$, $p = 0.0001$; 11 min: $t(512) = -5.45$, $p < 0.0001$); 22 min: $t(512) = -5.32$, $p < 0.0001$). The decrease for 11 min was greater than the decrease for 5.5 min ($t(512) = 2.47$, $p = 0.0140$) and the decrease for 22 min was greater than the decrease for 5.5 min ($t(512) = 2.09$, $p = 0.0374$), with no significant difference between 11 min and 22 min effects ($t(512) = -0.45$, $p = 0.6559$).

Main models (Timepoint effects by experimental groups)

Because we were interested in fully assessing and comparing changes in mood profile for all experimental groups, we tested and compared simple main effects of timepoint for each experience group collapsing across duration groups (Table 5) and also for each experience and duration group (results summarized below, full details provided in Supplemental Materials, Tables S1-S3).

The results summarized in Table 5 show a highly consistent numerical pattern of decrease over time for all outcome measures for each experience group. These changes were considered statistically significant (both p.fdr and p.np.fdr < 0.05) for most but not all of the outcome measures. All three anxiety scales as well as other mood scales (tension, fatigue, confusion) and task performance improved significantly or at least marginally for each experience type with similar effect sizes that were mostly moderate to large. The two depression scales showed much less evidence for improvement across experiences, although there was some evidence that the POMS-derived depression scale improved more for ELA1 and meditation than for ELA2, which is consistent with the marginally significant three-way interaction reported earlier. The anger scale followed the same pattern but was not significant for any groups. Despite these apparent differences in timepoint effects between experiences, none of these differences were statistically significant, which is consistent with the lack of significant interactions in the main models.

The results of timepoint effects for each duration group within each experience type are summarized below with full details provided in the supplemental materials (Tables S1-S3). Across all groups, there was a highly consistent numerical pattern of decrease over time for all outcome measures. These changes were considered statistically significant (both p.fdr and p.np.fdr < 0.05) for several of the measures depending on groups. Most of the significant effects and largest effect sizes were observed for Anxiety (HAD and VA scales), Depression (POMS), Tension (POMS), Fatigue (POMS), and Stroop task.

Although none of the comparisons across groups were statistically significant, there were some notable differences that can be described qualitatively. The ELA2 5.5 min group stands out as showing drastically fewer significant timepoint effects when compared to the other ELA2 durations and all the other ELA1 and meditation durations. Only the ELA1 5.5 min group showed improvement in Anxiety (STAI) scale that was close to significant with an effect size much larger than the ELA2 5.5 min and Meditation 5.5 min groups. In contrast, only the ELA2 11 min and 22 min groups showed significant improvement on Anxiety (STAI) with the largest effect sizes. Finally, the meditation duration groups seemed to have the most significant changes over time.

	Duration x Timepoint						Experience x Timepoint						Experience x Duration x Timepoint					
DV	df1	df2	F	*p*.raw	*p*.fdr	sig	df1	df2	F	*p*.raw	*p*.fdr	sig	df1	df2	F	*p*.raw	*p*.fdr	sig
Anxiety (HADS)	2	511	0.23	0.7985	0.9049		2	511	1.43	0.2402	0.6606		4	501	0.87	0.4816	0.8903	
Anxiety (STAI)	2	502	0.24	0.7849	0.9049		2	502	0.39	0.6784	0.9049		4	502	0.35	0.8432	0.9049	
Anxiety (VA)	2	511	0.19	0.8299	0.9049		2	511	1.33	0.2664	0.6895		4	501	1.15	0.3320	0.7572	
Depression (HADS)	2	514	0.08	0.9237	0.9237		2	514	0.31	0.7345	0.9049		4	504	0.49	0.7470	0.9049	
Depression (POMS)	2	512	0.67	0.5121	0.8903		2	512	0.61	0.5463	0.8903		4	502	3.14	0.0146	0.0584	~
Tension (POMS)	2	512	0.48	0.6179	0.9049		2	510	1.46	0.2328	0.6606		4	500	1.12	0.3442	0.7572	
Anger (POMS)	2	512	3.97	0.0194	0.0711	~	2	512	1.07	0.3431	0.7572		4	502	0.79	0.5350	0.8903	
Fatigue (POMS)	2	511	0.20	0.8157	0.9049		2	511	1.48	0.2284	0.6606		4	502	0.67	0.6131	0.9049	
Confusion (POMS)	2	511	0.61	0.5424	0.8903		2	511	0.78	0.4612	0.8903		4	501	1.07	0.3719	0.7792	
Local Global	2	504	0.12	0.8841	0.9237		2	504	0.31	0.7372	0.9049		4	494	0.23	0.9214	0.9237	
Stroop	2	506	0.26	0.7723	0.9049		2	506	0.20	0.8226	0.9049		4	496	0.63	0.6384	0.9049	

Table 4. Interaction effects between timepoint (pre, post), experience (ELA1, ELA2, meditation), and duration (5.5 min, 11 min, 22 min) from the GLM or GLMM models. 'DV' refers to dependent variable. Performance on the Stroop and Local Global tasks refers to only the incongruent trials and was estimated as reaction time divided by accuracy. 'df1' and 'df2' are the first and second degrees of freedom for the F test with corresponding F value. 'p.raw' refers to the uncorrected p value of the F test. 'p.fdr' refers to the p value corrected by the false discovery rate method. 'sig' refers to the statistical significance of the p.fdr value, where * indicates p.fdr < 0.05 and ~ indicates p.fdr is marginally significant ($p < 0.10$).

DV	Direction	eff.par (CI)	eff.npar (CI)	*p*.par.fdr	*p*.npar.fdr	sig
ELA1						
DV	**Direction**	**eff.par (CI)**	**eff.npar (CI)**	***p*.par.fdr**	***p*.npar.fdr**	**sig**
Anxiety (HADS)	Post < Pre	−1.64 (−2.00, −1.29)	0.78 (0.60, 0.86)	< 0.0001	< 0.0001	*
Anxiety (STAI)	Post < Pre	−0.53 (−0.88, −0.18)	0.67 (0.45, 0.84)	0.0043	< 0.0001	*
Anxiety (VA)	Post < Pre	−1.14 (−1.52, −0.76)	0.66 (0.39, 0.84)	< 0.0001	< 0.0001	*
Depression (HADS)	Post < Pre	−1.09 (−2.67, 0.49)	0.57 (0.29, 0.76)	0.1796	< 0.0001	
Depression (POMS)	Post < Pre	−0.06 (−0.08, −0.04)	0.72 (0.55, 0.83)	< 0.0001	0.0064	*
Tension (POMS)	Post < Pre	−0.21 (−0.30, −0.10)	0.53 (0.22, 0.76)	0.0002	< 0.0001	*
Anger (POMS)	Post < Pre	−0.41 (−0.58, −0.22)	0.44 (0.09, 0.67)	< 0.0001	0.2717	
Fatigue (POMS)	Post < Pre	−0.01 (−0.01, −0.00)	0.38 (0.06, 0.66)	0.0005	< 0.0001	*
Confusion (POMS)	Post < Pre	−0.41 (−0.81, −0.00)	0.28 (0.02, 0.59)	0.0563	< 0.0001	~
Local Global	Post < Pre	−0.41 (−0.86, 0.03)	0.54 (0.24, 0.76)	0.0747	0.0014	~
Stroop	Post < Pre	−1.31 (−1.85, −0.78)	0.71 (0.45, 0.87)	< 0.0001	0.0034	*
ELA2						
DV	**Direction**	**eff.par (CI)**	**eff.npar (CI)**	***p*.par.fdr**	***p*.npar.fdr**	**sig**
Anxiety (HADS)	Post < Pre	−1.79 (−2.15, −1.42)	0.83 (0.74, 0.88)	< 0.0001	< 0.0001	*
Anxiety (STAI)	Post < Pre	−0.61 (−0.95, −0.26)	0.49 (0.20, 0.74)	0.0008	< 0.0001	*
Anxiety (VA)	Post < Pre	−0.79 (−1.19, −0.40)	0.66 (0.43, 0.83)	0.0002	< 0.0001	*
Depression (HADS)	Post < Pre	−1.14 (−2.56, 0.28)	0.07 (0.01, 0.42)	0.1215	< 0.0001	
Depression (POMS)	Post < Pre	−0.05 (−0.07, −0.03)	0.33 (0.03, 0.59)	< 0.0001	0.3877	
Tension (POMS)	Post < Pre	−0.22 (−0.33, −0.12)	0.49 (0.18, 0.76)	0.0002	0.0053	*
Anger (POMS)	Post < Pre	−0.42 (−0.61, −0.22)	0.40 (0.08, 0.66)	< 0.0001	0.2780	
Fatigue (POMS)	Post < Pre	−0.01 (−0.01, −0.00)	0.47 (0.15, 0.73)	0.0026	< 0.0001	*
Confusion (POMS)	Post < Pre	−0.45 (−0.85, −0.00)	0.14 (0.01, 0.51)	0.0370	< 0.0001	*
Local Global	Post < Pre	−0.67 (−1.15, −0.18)	0.44 (0.11, 0.72)	0.0082	0.0016	*
Stroop	Post < Pre	−1.45 (−2.11, −0.79)	0.56 (0.25, 0.82)	< 0.0001	0.0218	*
Meditation						
DV	**Direction**	**eff.par (CI)**	**eff.npar (CI)**	***p*.par.fdr**	***p*.npar.fdr**	**sig**
Anxiety (HADS)	Post < Pre	−1.39 (−1.72, −1.06)	0.59 (0.32, 0.81)	< 0.0001	< 0.0001	*
Anxiety (STAI)	Post < Pre	−0.39 (−0.74, −0.06)	0.39 (0.07, 0.68)	0.0271	< 0.0001	*
Anxiety (VA)	Post < Pre	−1.19 (−1.58, −0.81)	0.55 (0.23, 0.79)	< 0.0001	< 0.0001	*
Depression (HADS)	Post < Pre	−0.41 (−1.86, 1.05)	0.37 (0.05, 0.68)	0.5869	< 0.0001	
Depression (POMS)	Post < Pre	−0.05 (−0.06, -0.03)	0.62 (0.33, 0.80)	< 0.0001	0.0014	*
Tension (POMS)	Post < Pre	−0.32 (−0.43, −0.22)	0.33 (0.03, 0.64)	< 0.0001	0.0014	*
Anger (POMS)	Post < Pre	−0.59 (−0.81, −0.38)	0.40 (0.09, 0.64)	< 0.0001	0.1815	
Fatigue (POMS)	Post < Pre	−0.01 (−0.02, −0.01)	0.33 (0.02, 0.65)	< 0.0001	< 0.0001	*
Confusion (POMS)	Post < Pre	−0.74 (−1.15, −0.32)	0.35 (0.04, 0.64)	0.0008	< 0.0001	*
Local Global	Post < Pre	−0.52 (−0.96, −0.08)	0.53 (0.24, 0.77)	0.0261	0.0016	*
Stroop	Post < Pre	−1.54 (−2.00, −1.07)	0.87 (0.83, 0.87)	< 0.0001	0.0061	*

Table 5. Simple main effects of timepoint (pre vs. post) for each experience group (ELA1, ELA2, meditation), collapsing across duration groups, from the GLM or GLMM models. 'DV' refers to dependent variable. Performance on the Stroop and Local Global tasks refers to only the incongruent trials and was estimated as reaction time divided by accuracy. 'Direction' refers to the relative difference between timepoints. 'eff.par' refers to the parametric effect size (Cohen's *d*) with corresponding 95% confidence interval. 'eff.npar' refers to the nonparametric effect size (Wilcoxon signed-rank *r*) with corresponding 95% confidence interval. 'p.par.fdr' refers to the parametric *p* value corrected by the false discovery rate method. 'p.npar.fdr' refers to the nonparametric *p* value corrected by the false discovery rate method. 'sig' refers to the statistical significance, where * indicates that both p.par.fdr < 0.05 and p.npar.fdr < 0.05, and ~ indicates that one is significant and the other is marginally significant ($p < 0.10$).

Targeted comparisons (ELA1 vs. meditation)

Table 6 summarizes the additional analyses for our second research question that assessed how significant improvements in the ELA1 duration groups (based on results from table S1 in Supplemental materials) compared to changes in the meditation groups of similar or higher durations. The first two columns (DV and ELA1) indicate the outcome measures that were significant for those specific ELA1 duration groups, while the third column (meditation) indicates the comparison meditation duration group. None of the comparisons were

DV	ELA1	Meditation	Direction	eff.par (CI)	*p*.fdr
AnxietyHAD	5.5 min	5.5 min	ELA1 > Med	−0.76 (−1.56, 0.04)	0.6950
	5.5 min	11 min	ELA1 > Med	−0.27 (−1.07, 0.52)	0.9018
	5.5 min	22 min	ELA1 > Med	−0.74 (−1.55, 0.06)	0.6950
	11 min	11 min	Med > ELA1	0.22 (−0.55, 1.01)	0.9018
	11 min	22 min	ELA1 > Med	−0.24 (−1.04, 0.54)	0.9018
	22 min	22 min	ELA1 > Med	−0.23 (−1.07, 0.59)	0.9018
AnxietyVA	5.5 min	5.5 min	ELA1 > Med	−0.62 (−1.52, 0.27)	0.7440
	5.5 min	11 min	ELA1 > Med	−0.14 (−1.04, 0.75)	0.9018
	5.5 min	22 min	ELA1 > Med	−0.22 (−1.15, 0.7)	0.9018
	11 min	11 min	Med > ELA1	0.43 (−0.43, 1.31)	0.9018
	11 min	22 min	Med > ELA1	0.36 (−0.53, 1.26)	0.9018
	22 min	22 min	Med > ELA1	0.32 (−0.6, 1.26)	0.9018
DepressionPOMS	5.5 min	5.5 min	ELA1 > Med	−0.01 (−0.03, 0.003)	0.6950
	5.5 min	11 min	ELA1 > Med	−0.01 (−0.02, 0.01)	0.7939
	5.5 min	22 min	ELA1 > Med	−0.02 (−0.03, −0.01)	0.6950
	22 min	22 min	ELA1 > Med	−0.01 (−0.02, 0.01)	0.9018
Tension	5.5 min	5.5 min	ELA1 > Med	−0.04 (−0.17, 0.25)	0.9018
	5.5 min	11 min	Med > ELA1	0.18 (−0.04, 0.41)	0.6950
	5.5 min	22 min	ELA1 > Med	−0.03 (−0.19, 0.26)	0.9018
	11 min	11 min	Med > ELA1	0.18 (−0.06, 0.43)	0.6950
	11 min	22 min	Med > ELA1	0.03 (−0.2, 0.28)	0.9018
Fatigue	5.5 min	5.5 min	ELA1 > Med	−0.07 (−0.8, 0.65)	0.9018
	5.5 min	11 min	Med > ELA1	0.05 (−0.73, 0.62)	0.9018
	5.5 min	22 min	ELA1 > Med	−0.17 (−0.59, 0.94)	0.9018
Stroop	5.5 min	5.5 min	ELA1 > Med	−0.06 (−1.55, 1.42)	0.9295
	5.5 min	11 min	Med > ELA1	0.42 (−0.7, 1.55)	0.9018
	5.5 min	22 min	Med > ELA1	0.1 (−1.04, 1.26)	0.9018
	11 min	11 min	ELA1 > Med	−0.17 (−2.01, 1.67)	0.9018
	11 min	22 min	ELA1 > Med	−0.48 (−2.37, 1.4)	0.9018
	22 min	22 min	Med > ELA1	0.35 (−0.73, 1.43)	0.9018

Table 6. Post hoc comparisons, from the GLM or GLMM models, between ELA1 and meditation (Med) experiences based on any significant timepoint effects discovered in any of the duration groups for ELA1. 'DV' refers to dependent variable. Performance on the Stroop task refers to only the incongruent trials and was estimated as reaction time divided by accuracy. 'Direction' refers to the relative difference between ELA1 and meditation experiences. 'eff.par' refers to the parametric effect size (Cohen's *d*) with corresponding 95% confidence interval. 'p.fdr' refers to the p value corrected by the false discovery rate method. 'sig' refers to the statistical significance of the p.fdr value, where * indicates p.fdr < 0.05 and ~ indicates p.fdr is marginal (< 0.10).

considered statistically significant, which seems likely due to similar timepoint effects in all ELA1 and meditation groups. However, some notable patterns can be described qualitatively.

The first question was, do any significant timepoint effects in the ELA1 5.5 min group outperform timepoint effects in any of the meditation duration groups? There were no significant differences or reliable effect sizes (i.e., confidence intervals do not include 0), but there was a consistent numerical trend for the ELA1 5.5 min group to show higher improvement than the meditation 5.5 min group for all outcome measures and higher improvement when compared to the meditation 11 min and 22 min groups for specifically the anxiety and depression variables. For the other variables assessed, ELA1 5.5 min tended to underperform when compared to the meditation 11 min group. The second question was, do any significant timepoint effects in the ELA1 11 min group outperform the timepoint effects in the meditation 11–22 min groups? There were no significant differences or reliable effect sizes (i.e., confidence intervals do not include 0), but there was a slight numerical trend for meditation 11 min and 22 min groups to outperform the ELA1 11 min group. The third question was, do any significant timepoint effects in the ELA1 22 min group outperform timepoint effects in the meditation 22 min group? The results show no significant differences, no reliable effect sizes, and no consistent trends.

Moderation models

Tables 7 and 8 summarize the results of the moderation models for our third research question which tested whether participants' prior openness to experience (Table 7) or trait mindfulness (Table 8) moderated (i.e., interacted with) any of the experimental effects. There was no evidence of any moderation effects from openness. As main effects, openness was positively associated with both decentering and curiosity measures that were

	Openness					Experience x Openness					Experience x Duration x Openness				
DV	slope	SE	Z	*p*.fdr	sig	df1	df2	F	*p*.fdr	sig	df1	df2	F	*p*.fdr	sig
Anxiety (HAD)	−0.017	0.02	−0.88	0.7914		2	249	0.15	0.9250		4	239	0.29	0.9250	
Anxiety (STAI)	−0.055	0.03	−1.71	0.3877		2	249	3.52	0.1718		4	239	0.36	0.9250	
Anxiety (VA)	−0.034	0.01	−2.33	0.1341		2	249	0.45	0.9021		4	239	0.50	0.9207	
Depression (HAD)	−0.014	0.01	−0.99	0.7822		2	249	0.94	0.7914		4	239	3.47	0.1032	
Tension (POMS)	−0.007	0.01	−0.71	0.8530		2	249	1.28	0.7682		4	239	0.91	0.8530	
Fatigue (POMS)	−0.003	0.02	−0.16	0.9250		2	249	1.23	0.7682		4	239	0.70	0.8562	
Confusion (POMS)	−0.014	0.01	−1.28	0.6662		2	249	0.93	0.7914		4	239	0.58	0.9021	
Local Global	0.000	0.00	−0.33	0.9207		2	245	1.26	0.7682		n.c	n.c	n.c	n.c	
Stroop	0.000	0.00	−0.38	0.9172		2	247	0.97	0.7914		n.c	n.c	n.c	n.c	
Decentering	0.191	0.03	5.46	< 0.0001	*	2	249	0.09	0.9250		4	239	0.72	0.8562	
Curiosity	0.169	0.03	4.83	< 0.0001	*	2	250	0.12	0.9250		4	240	1.64	0.6167	

Table 7. Testing moderation of openness to new experience as interaction effects or main effect from the GLMs. 'DV' refers to dependent variable measured at each timepoint (except for decentering and curiosity which were measured only at the post timepoint). Performance on the Stroop and Local Global tasks refers to only the incongruent trials and was estimated as reaction time divided by accuracy. 'Slope' refers to the effect or the unstandardized beta coefficient of the association between openness and the DV, with corresponding standard error (SE) of the effect and Z value from the z-test. 'p.fdr' refers to the p value corrected by the false discovery rate method. 'sig' refers to the statistical significance of the p.fdr value, where * indicates p.fdr < 0.05 and ~ indicates p.fdr is marginal (< 0.10). 'nc' refers to models that did not converge.

	Trait Mindfulness					Experience x Trait Mindfulness					Experience x Duration x Trait Mindfulness				
DV	slope	SE	Z	*p*.fdr	sig	df1	df2	F	*p*.fdr	sig	df1	df2	F	*p*.fdr	sig
Anxiety (HAD)	61.684	14.04	4.39	0.0003	*	2	249	0.09	0.9250		4	239	0.38	0.9250	
Anxiety (STAI)	58.248	28.90	2.02	0.2309		2	249	0.37	0.9081		4	239	3.05	0.1341	
Anxiety (VA)	42.680	19.40	2.20	0.1718		2	249	0.09	0.9250		4	239	1.06	0.7914	
Depression (HAD)	28.998	10.71	2.71	0.0873	~	2	249	0.62	0.8562		4	239	1.57	0.6429	
Tension (POMS)	7.177	12.92	0.56	0.8562		2	249	0.57	0.8562		4	239	1.13	0.7822	
Fatigue (POMS)	18.684	12.78	1.46	0.5760		2	249	0.09	0.9250		4	239	1.28	0.7682	
Confusion (POMS)	3.845	8.88	0.43	0.9021		2	249	1.48	0.7236		4	239	1.87	0.5009	
Local Global	−0.003	0.00	−0.70	0.8530		2	245	0.33	0.9172		n.c.	n.c	n.c	n.c	
Stroop	−0.025	0.02	−1.55	0.5070		2	247	1.07	0.7822		4	237	11.01	0.0003	*
Decentering	87.615	24.58	3.56	0.0071	*	2	252	0.42	0.9021		n.c	n.c	n.c	n.c	
Curiosity	91.339	25.93	3.52	0.0071	*	2	250	1.30	0.7682		4	240	0.87	0.8530	

Table 8. Testing moderation of trait mindfulness to new experience as interaction effects or main effect from the GLMs. 'DV' refers to dependent variable measured at each timepoint (except for decentering and curiosity which were measured only at the post timepoint). Performance on the Stroop and Local Global tasks refers to only the incongruent trials and was estimated as reaction time divided by accuracy. 'Slope' refers to the effect or the unstandardized beta coefficient of the association between openness and the DV, with corresponding standard error (SE) of the effect and Z value from the z-test. 'p.fdr' refers to the p value corrected by the false discovery rate method. 'sig' refers to the statistical significance of the p.fdr value, where * indicates p.fdr < 0.05 and ~ indicates p.fdr is marginal (< 0.10). 'nc' refers to models that did not converge.

acquired only the post timepoint, such that participants with higher openness tended to have higher decentering and curiosity levels. There was also a consistent numerical pattern, although none considered significant, for openness to be inversely associated with all mood changes such that participants with higher openness tended to show larger decreases (i.e., more improvement) in the mood scales.

Similar to openness, trait mindfulness also was significantly positively associated with decentering and curiosity—unsurprising given that the latter two are derived from the Toronto Mindfulness Scale. There was also a consistent numerical trend for trait mindfulness to be positively associated with mood changes such that participants with higher trait mindfulness tended to show smaller decreases (i.e., less improvement) in the mood scales, but this association was only significant for the Anxiety (HAD) scale and marginally significant for the Depression (HADS) scale.

There was only one significant result of moderation. Trait mindfulness interacted with both experience and duration effects when predicting change in Stroop performance. This three-way interaction was explored with nested duration x trait mindfulness interactions within each experience type. The duration x trait mindfulness interaction was not significant for ELA1 ($F(2, 237) = 1.80$, $p = 0.1669$), but it was significant for ELA2 ($F(2, 237) = 8.61$, $p < 0.001$) and for meditation ($F(2, 237) = 24.43$, $p < 0.0001$). For ELA1, only the 5.5 min group showed a reliable association of trait mindfulness with Stroop improvement (b = -0.082, SE = 0.03, 95% CI = [−0.142, −0.022]), but there were no significant differences in this association between the other ELA1 duration groups (p.fdr > 0.05). For ELA2, only the 22 min group showed a reliable association of mindfulness with Stroop improvement (b = −0.186, SE = 0.03, 95% CI = [−0.231, −0.142]) which was significantly different from the 11 min group ($t(237) = 3.90$, $p < 0.001$) and the 5.5 min group ($t(237) = 2.72$, $p < 0.05$). For meditation, all three duration groups showed reliable associations of trait mindfulness with Stroop improvement: 5.5 min (b = 0.149, SE = 0.04, 95% CI = [0.074, 0.226]), 11 min (b = -0.095, SE = 0.02, 95% CI = [−0.135, −0.057]), and 22 min (b = 0.087, SE = 0.03, 95% CI = [0.037, 0.137]). The 5.5 min effect was significantly larger than the 11 min effect ($t(237) = 5.56$, $p < 0.0001$), and the 11 min effect was also significantly larger than the 22 min effect ($t(237) = −5.66$, $p < 0.0001$), with no significant difference between 5.5 min and 22 min effects ($t(237) = 1.35$, $p = 0.1773$).

Discussion

In this scientifically rigorous experiment (i.e., randomized, controlled, and double-blinded when feasible, with a large and heterogeneous sample), we discovered strong evidence that audiovisual stimulation (AVS), with the ELA device, can substantially improve mood states by reducing several negative affects (anxiety, depression, tension, fatigue, and confusion) and by improving performance on two mood-sensitive cognitive tasks (incongruent trials for Stroop and Local Global). The mood benefits appeared overall quite similar between the two AVS conditions (ELA1 and ELA2) and the three duration levels (5.5, 11, and 22 min), with some interesting differences and issues discussed below. The ELA effects were mostly on par with the mood benefits observed from breath-focused meditation, supporting the idea that AVS may be an effective and more approachable alternative to meditation for reducing anxiety, depression, and other negative affect. Across all experiences, durations, and mood measures, most of the effect sizes were moderate to large, indicating high potential for meaningful impact.

The improvement of most mood measures was very similar between the AVS condition with binaural beats (ELA1) and the AVS control condition without binaural beats (ELA2). This similarity was surprising given prior evidence of neural entrainment and mood improvement from binaural beats[19,35,36], including our previous discovery of strong entrainment effects from ELA1 but not ELA2 or meditation[16]. One hypothesis is that the mood effects may be independent of the entrainment effects and perhaps dependent on other neuromodulatory effects currently unexplored. To more thoroughly investigate this apparent paradox of similar behavioral effects despite different neural effects, we plan to conduct additional analyses combining both data types that would have been outside the purview of this current behaviorally focused investigation. This will be an important contribution to AVS research given that most studies and devices using binaural beats seem to assume that any observed behavioral effects are caused by entrainment or other neural mechanisms without even measuring or testing them[19].

A major aim of this study was to determine if there might be an optimal duration of the ELA1 experience that maximizes its efficacy on mood states. Several results indicate that the shortest duration (5.5 min) might be the “sweet spot”. First, within ELA1 only, the 5.5 min duration showed the largest effect sizes across most measures (followed by the 22 min duration), but the opposite trend was observed for ELA2 and meditation. Second, the POMS depression scale showed some evidence for potential interactive effects such that ELA1 and meditation, but not ELA2, were especially beneficial at the 5.5 min duration. A similar pattern was also observed for the STAI anxiety scale. Finally, in the targeted comparisons between ELA1 and meditation, although none were statistically significant, there were some trends based on numerical differences and effect sizes that were consistent with the possibility that the ELA1 5.5 min group may consistently perform as well or even better than the meditation 5.5 min group for all measures and in comparison to the other meditation durations (11 min, 22 min) for the anxiety and depression measures. These results combined indicate that around only five minutes of ELA1 exposure might be sufficiently long or even optimal for acutely enhancing mood states and may confer similar or greater benefits compared to equal or longer durations of breath-focused meditation. This is an exciting finding that could position the ELA device, and potentially other AVS technologies (e.g., virtual reality), as an advantageous “plug and play” substitute for the acute mood benefits of meditation which may be more approachable for more technologically-inclined people, particularly youth[47]. It is essential to qualify these assertions by recognizing that our results are limited to acute, state effects and are not positioned to make any claims about the long-term benefits of either breath-focused meditative practices or sustained use of AVS technologies. While our study demonstrates comparable short-term anxiolytic effects between a single session of AVS and breath-focused meditation, it’s important to note that mindfulness achieved through extended meditative practices offers a more comprehensive and trait-level range of benefits beyond mere acute anxiolytic effects.

Another aim of this study was to see if any of the experiential effects on mood states were moderated by participants' baseline levels of openness to experience or trait mindfulness. Overall, the evidence for trait moderation was limited and not rapidly interpretable. This was unexpected given well-known individual differences in personality traits and previous findings that not all people respond to impactful content in the same way[55]. At least one prior study found that AVS effects were moderated by some traits[10], but not mindfulness or openness, consistent with our lack of observed effects. However, we did find strong and clear main effects of higher levels of trait mindfulness and openness predicting higher levels of curiosity and decentering after the experience. Lower trait mindfulness levels also appeared associated with higher reductions in HADS-derived anxiety and depression measures, which was a numerical (nonsignificant) trend for all other mood measures, potentially indicating that the people who were most in need showed the most benefits. There was an opposite numerical (nonsignificant) trend for higher levels of openness to be associated with higher reductions in all negative affects, which was expected and consistent with the idea that participants who were more open-minded and curious should be more receptive to and influenced by these new experiences.

Conclusions

To conclude, we have demonstrated substantial evidence that a single session of AVS, with or without binaural beats, may acutely improve a variety of mood states similar to, or even greater than, a single session of breath-focused meditation. Mood improvement from AVS was observed similarly across all duration levels with some evidence that only 5 min of exposure may be sufficient, or even optimal, for conferring similar or greater benefits from meditation at equal or longer durations. Pending further research, these exciting findings could position the ELA device, and potentially other AVS devices, as an effective tool for mood enhancement in recreational and clinical settings as well as a potentially advantageous technological alternative to meditation.

Strengths, limitations, and future directions

Relatively few empirical studies, and even fewer with optimal experimental procedures, have assessed the effects of AVS on mood, which so far appear to be quite mixed and inconclusive, despite the increasing popularity of AVS devices and their claims of diverse mood benefits. The present study appears to be one of the most rigorous investigations of this topic with an experimental design that leveraged randomization, double-blinding when feasible, two control conditions (an AVS experience without binaural beats, and a non-AVS meditation experience), and a relatively large sample size of 262 individuals across a wide age range (18–79 years). We also conducted statistically rigorous analyses: generalized linear (mixed) models with extensive quality control, use of both parametric and nonparametric analyses when feasible, multiple comparisons corrections, and emphasis on effect sizes with confidence intervals. These methods strengthen interpretations of potential causality, increase statistical reliability of results, and bolster the generalizability, ecological validity, and meaningfulness of these findings.

However, interpretations of potential causality, although optimized by our experimental procedures, could have been improved by also assessing participants' expectations, given well-known potential for expectation or placebo effects[81]. Expectation effects may have influenced the results to at least some degree, given that most mood measures improved over time regardless of experimental conditions. Another limitation is that our analyses of AVS effects on numerous mood measures, while advantageous for assessing the multidimensional nature of mood states, required relatively conservative, although appropriate, multiple comparison correction of statistical significance, which likely contributed to the relative lack of significant differences between experimental conditions. To offset this potential limitation, we focused on effect sizes when feasible, which are often more informative and useful than tests of significance[82]. Finally, the highly non-normal distributions of most mood measures prevented us from using traditional multivariate analyses to assess effects across the whole mood profile.

Another potential limitation is that the ELA1 experimental condition performed very similarly overall to ELA2 as the AVS control condition. The relative lack of differential effects between these experimental and control conditions may have been due to a potential ineffectiveness of the binaural beats in ELA1 (which were not present in ELA2). We interpret these findings as indicating that the enhancing effects of AVS may be independent of binaural beats; in other words, either ELA1 or ELA2 may be used as a potentially therapeutic intervention in lieu of breath-focused meditation. However, we also found some evidence that the shorter duration (5.5 min) of ELA1 might be more effective than ELA2 (and Meditation) for some of the depression and anxiety measures. A final limitation to emphasize is that none of the targeted comparisons between ELA1 and Meditation were statistically significant, so although there were some consistent numerical trends and effect sizes suggesting the possibility that 5.5 min of ELA1 may outperform similar or longer durations of breath-focused meditation, it may be more likely that both experiences are equally effective at any durations. Given that the current study may be the first to have investigated optimal durations of audiovisual stimulation, especially in comparison to breath-focused meditation, these exploratory findings are pending replication from future empirical research.

The preliminary outcomes of this investigation, while demonstrating promising potential for societal benefit, highlight the imperative for subsequent, more nuanced research. This should involve a systematic dissection of each distinct element, such as visual stroboscopic stimulation and binaural beats, to evaluate their individual contributions. Future studies ought to integrate neuroimaging methodologies to discern interindividual variability in responses. Such an investigative strategy is critical to ascertain if the extent of neural entrainment in individuals is proportionate to the observed efficacy of these stimuli. Future research will also be necessary to determine the extent to which the effects observed for the healthy individuals in this study would replicate, be attenuated, or enhanced in clinical settings, especially for individuals with mood disorders. While the AVS technology used in this study (from INTO) was a sophisticated research version, it's important to note that more accessible alternatives are emerging. INTO is launching a consumer version of this product, which is expected to make this technology more widely available. Additionally, other options are entering the market, such as free mobile applications that utilize a smartphone's flashlight to produce white stroboscopic effects (e.g., Lumenate), which may approximate some of these effects. As with many technological innovations, we anticipate that as production scales up and technology improves, AVS devices will become increasingly affordable and accessible to a broader audience. Broadening the scope of this research to encompass a variety of AVS or binaural beat apparatuses, heterogeneous participant demographics, diverse mood assessment tools, and clinical applications is essential for a comprehensive understanding of these complex interactions. This expansion of research scope, coupled with the increasing accessibility of AVS technology, could pave the way for more widespread adoption and application of these mood-enhancing techniques in both everyday use and clinical settings.

Data availability

All data necessary to replicate the results of this study will be deposited in the Figshare repository 'Lightening the Mind: Comparing Audiovisual Stimulation and Meditation for Mood and Cognition Enhancement' (https://figshare.com/projects/Lightening_the_Mind_Comparing_Audiovisual_Stimulation_and_Meditation_for_Mood_and_Cognition_Enhancement/196216) and accessible after peer-review and acceptance of this manuscript for publication. The corresponding author (N.R.) could also be contacted for direct request of these data.

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Author contributions

Study conceptualization, design, and procurement of funding: N.R. Study logistics, recruitment, and implementation: N.R., N.S. Data analysis: M.J. All authors participated in the review of the statistical analyses and writing of all versions of the manuscript.

Declarations

Competing interests

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Author contributions

Study conceptualization, design, and procurement of funding: N.R. Study logistics, recruitment, and implementation: N.R., N.S. Data analysis: M.J. All authors participated in the review of the statistical analyses and writing of all versions of the manuscript.

Additional information

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