Encouraging Breath: Increasing Out-of-Session DMHI Engagement using a Shape-Changing Biofeedback Physicalization within a Longitudinal RCT

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Figure 1: Experimental setup comprising the Digital Mental Health Intervention (DMHI), the shape-changing biofeedback physicalization called 'Ankor', and the Biopac Respiration Transducer.

Abstract

Out-of-session or "homework" engagement is a primary limiting factor in clinical mental health outcomes. Despite weekly practitioner contact, adherence to prescribed Digital Mental Health Interventions (DMHIs) typically drops by 96.1% within two weeks. We evaluate Ankor, a handheld shape-changing biofeedback physicalization, as an adjunct to standard audio-guided mindfulness. In a longitudinal randomized controlled study (N=69), participants were assigned to Ankor+audio or audio-only control across six weekly 15-minute laboratory sessions, with optional DMHI use between sessions. Relative to control, Ankor yielded a 351% increase in total DMHI practice initiations and, by week 2, maintained 29.4% active users versus 2.9% in control, indicating substantially higher out-of-session engagement and reduced early disengagement. These findings demonstrate the capacity of shape-changing biofeedback physicalizations to extend adherence to DMHIs, highlighting kinaesthetic interactions as a promising design pathway for sustaining engagement in mental health interventions.

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CCS Concepts

• **Human-centered computing** → **Empirical studies in HCI**; **Haptic devices**; • **Hardware** → *Emerging interfaces*; • **Applied computing** → *Consumer health.*

Keywords

Physicalization, Biofeedback, Shape-Change, Mental Health, Longitudinal Study, Randomized Control Trial, Breath, Engagement

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1 Introduction

In the evolving field of therapy, Digital Mental Health Interventions (DMHIs) are increasingly used outside of face-to-face sessions or within blended frameworks, offering automated self-help activities that reinforce learned skills [16]. These activities, often referred to as therapeutic "homework", are known to improve treatment outcomes, with 68% of patients who complete them showing greater improvement compared with 32% who do not [40]. However, despite their recognized benefits, adherence to these practices continues to be consistently low. A national survey found that 93% of mental health professionals report only low to moderate task compliance [33, 39], and usage data shows that users typically complete only 40% of DMHI content [31], with active engagement dropping to just 3.9% after two weeks [11, 14].

Cultivating therapeutic outcomes can therefore be challenging if individuals do not consistently adhere to the practice. Neurocognitive mechanisms of adherence are anchored in intention, motivation, and self-regulation, which are essential for initiating, maintaining, and enhancing interventions such as mindfulness, ensuring continuity [84]. The formation of a consistent practice habit is particularly critical, especially as users face challenges in building mindfulness into daily routines [24]. Behavioural challenges, such as difficulty finding time, negative responses to one's own practice, and a lack of external motivation, significantly impact engagement, leading users to abandon DMHIs prematurely [24]. Self-discipline and effort are often required to overcome these challenges, which underscores the importance of designing interventions that support habit formation and reduce barriers to engagement. Interactive technologies, particularly those utilizing biofeedback, can help by facilitating immersive experiences and aiding individuals in overcoming these behavioural barriers through sensory stimuli that promote deeper engagement and adherence [9, 23, 53, 67].

However, the efficacy of biofeedback significantly hinges on the design and presentation of the bio-data [43, 76, 91]. For example, displaying pulmonary data via digital readouts, line graphs, or charts often fails to engage users meaningfully, as these formats may be perceived as mundane and unintuitive [91]. Further, despite an improved effect of aesthetic or ambiguous designs [95, 100], users still need to retain eye contact with the interface, which may not facilitate deeper therapeutic experiences or embodied awareness [20, 56, 89], detracting from the intervention's ability to foster learnt skills [45]. In contrast, multimodal biofeedback systems, which integrate haptic feedback, show a higher potential for enhancing user engagement and stress management [19, 43, 99]. They facilitate more intuitive user interactions by translating physiological signals into more comprehensive multisensory experiences, by leveraging the emotional and psychological significance of touch [38, 65].

Artefacts that are designed to physicalize breathing often leverage their inherent physical properties to support users to focus on their internal physiology; a foundational approach to promote and support well-being in therapy [1, 30, 69]. They translate breathing data into tangible experiences [38] through static or dynamic feedback [75]. Static feedback often involves fixed sinusoidal waveforms that rhythmically illustrate breathing patterns [4, 5, 41], and dynamic feedback provides real-time, continuous biofeedback, adjusting to the user's physiological states [43, 60, 99]. Yet, among the methods utilised for representing breath—optical [29, 82, 100], vibrational [41, 52, 104], and shape-changing [18, 35, 46, 51, 90, 98]—it is the shape-changing interfaces that offer the most expansive possibilities [2, 38] due to their ability to dynamically alter their form. However, while immediate engagement benefits have been observed within shape-changing biofeedback physicalizations [35, 61, 96, 98], how these interactions influence psychological and physical engagement over time and outside of therapeutic sessions is still lacking empirical evidence [8].

Existing work explores shape-changing physicalizations in therapeutic and well-being contexts through short-term, prototype-driven studies. In clinical settings, systems such as a clippable pneumatic device for regulating anxiety-related breathing and an actuated environment for supporting yoga-based breathwork were deployed as adjuncts to formal interventions [18, 61]. For everyday personal well-being, handheld and wearable artefacts act as tools for stress reduction, including a portable 'breathing friend' that synchronizes with users' respiration and a tactile breath pacer shown to support relaxation during bedtime routines [52, 96]. In mindfulness and contemplative practice, shape-changing interfaces can act as embodied attentional anchors; a haptic cushion and granular respiratory feedback system have demonstrated improvements in respiratory awareness and meditative focus by externalizing internal bodily rhythms [35, 51]. Playful and affective regulation approaches with expressive wearables and modular haptic accessories can also mitigate anxiety and provide momentary emotional relief during episodes of heightened stress [53, 98, 105]. Collectively, these systems reveal the breadth of applications of shape-changing physicalizations, yet their evaluations predominantly focus on short-term or in-the-moment effects, leaving open the question of whether they can foster sustained psychological and physical engagement in digital interventions over extended periods.

To address this gap, we present a six-week Randomized Controlled Trial (RCT) that integrates a shape-changing biofeedback physicalization into a validated DMHI mindfulness programme and examines its impact on both psychological and physical engagement with out-of-session activities. Specifically, we compare two conditions: an evidence-based DMHI mindfulness program [73] and the same program augmented with Ankor, a physical device that expands and contracts in real time to mirror the user's breathing [26]. This comparison provides empirical evidence on engagement differences between an active control and experimental condition, investigating whether in-session physicalization promotes continued practice outside the intervention. This work contributes empirical evidence on the feasibility of improving out-of-session engagement through weekly exposure to a shape-changing biofeedback physicalization.

2 Background

Ankor is a shape-changing biofeedback physicalization that responds in real time to a respiration signal from a chest-strap transducer. When the user inhales, the artefact expands, with the surface

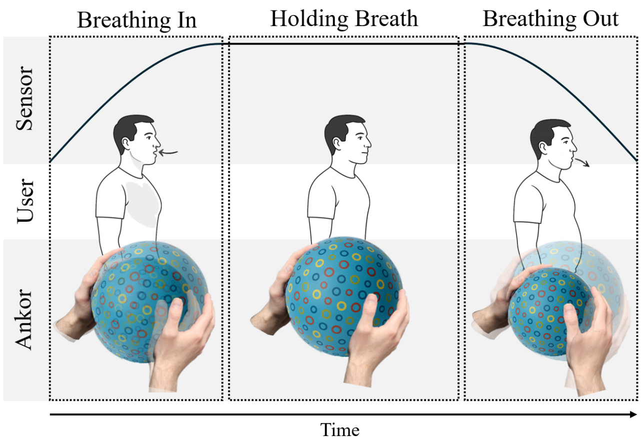


Figure 2: The different shape-changing states of Ankor, in relation to user interaction and chest sensor output.

area, volume, and internal pressure increasing; becoming larger and firmer in the hands. When the user exhales, it contracts and softens, bringing the hands closer together and making the surface easier to indent. This kinaesthetic feedback lets users feel their breath data embodied in a tangible object, as the sensor captures respiration and Ankor processes and responds to it (see Figure 2).

This physicalization process is useful because breathing extends beyond mere oxygen intake for physiological sustenance. It plays a crucial role in enhancing well-being in therapy [1, 30, 69], acting as a mechanism for managing stress and emotional states [72, 85, 101]. In contrast to less directly controllable physiological responses such as heart rate or brain waves, breathing serves as an input signal that users can deliberately regulate. This controllability allows them to perceive immediate psychological and physiological changes arising directly from their actions, whereas other biosignals primarily reflect downstream outcomes of prior processes.

However, despite its apparent simplicity and its foundational role in many therapeutic techniques, sustaining controlled and mindful breathing over extended periods (5–15 minutes) remains a challenge for many individuals [8, 24, 64]. Maintaining continuous attention to the breath requires considerable discipline and the capacity to remain attuned to internal bodily sensations [24, 49]. While even infrequent practice has been shown to confer measurable benefits, the consistency and quality of engagement strongly influence outcomes [24, 40].

In skill acquisition, not all forms of practice are equally effective; deliberate and purposeful practice, characterised by clearly defined goals, feedback, and sustained effort, is markedly more beneficial than simply engaging in structured or naïve practice, which may lack individualisation or depth [3]. In the context of mindfulness, this distinction underscores that quality and intentionality of engagement, rather than the mere repetition of breathing exercises, are what drive meaningful improvements in capacity and well-being [14].

Therefore, integrating kinaesthetic feedback has the potential to enhance attentional focus on the breath, thereby increasing both the psychological salience and emotional significance of the practice [26]. In this manner, Ankor was specifically designed to biomimetically mirror the alveolar structure of the lungs, enabling high-fidelity, bimanual kinaesthetic interaction that is directly coupled to the natural rhythm of respiration; further incorporating design principles associated with positive affect, such as circular geometries [27] and abstract representations of mental health concepts, to support a more engaging and affectively meaningful user experience.

The empirical evaluation of a Physical Artefact for Well-being System (PAWS) demonstrated its efficacy in augmenting a mindful breathing activity [26]. In a single session RCT (N = 58) comparing audio-guided breathing with and without a shape-changing biofeedback physicalization, participants in the experimental condition reported significantly greater reductions in both physiological and subjective indices of anxiety. Specifically, those using the device reported an average 75% reduction in self-reported anxiety and were 56% more resilient to worry-induced thoughts.

Even so, the previous evaluation primarily addressed 'in-the-moment' psychological engagement, without examining potential carry-over effects beyond the immediate intervention. Questions therefore, remained around whether the observed benefits might have been attributable to transient factors such as novelty, whether improvements would persist once the device was withdrawn, and to what extent advantages would be maintained with periodic use. The study in this paper was designed to address these knowledge gaps through a six-week study and improved system design.

2.0.1 System Overview. In previous work, the PAWS permitted only a static mode of expansion and contraction, limiting its ability to reflect the dynamic qualities of respiration [26]. For example, if a user inhaled for four seconds, a solenoid valve would remain open for that exact duration, inflating the spherical artefact through pneumatic circuitry. While functionally synchronised, this implementation did not capture critical respiratory nuances such as tidal volume, which represents the variation in the amount of air exchanged with each breath. As a result, participants reported that the interaction failed to convey the full richness of their pulmonary function, thereby constraining the depth of experiential engagement.

To overcome these constraints, Ankor was developed to enhance the original PAWS functionality [26] by incorporating an adaptive feedback response mechanism that simulates the dynamic respiratory variations within each breath. To achieve this, Ankor utilises a proportional pressure regulator paired with a vacuum generator to precisely control the airflow into and out of the artefact. The inflation and deflation processes can be calculated and adjusted in real-time, more accurately replicating the user's physiological breathing patterns and characteristics (see Figure 3).

3 Methodology

To explore the long-term engagement effects of interaction with a shape-changing biofeedback physicalization, this study employs a six-week single-blind RCT, integrating two intervention components: Ankor and a mindfulness DMHI[1]. Participants underwent unique and overlapping longitudinal assessments for three distinct study time points: Week one 'baseline' (T1), week two-to-five 'mid-intervention' (T2-T5), and 'end-of-intervention' at week six

[1]Approved by the University of Bath Research Ethics Committee Ref. Num. 23 064

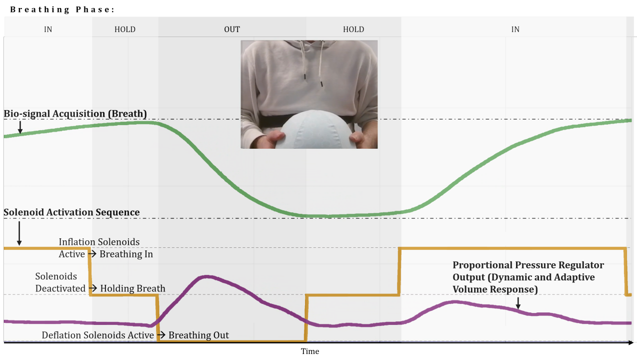


Figure 3: Real-time bio-signal data acquisition in conjunction with the solenoid activation sequence and proportional pressure regulator output. The yellow line indicates the solenoid circuit activation sequence. The green line displays the real-time bio-signal input from the chest respiration transducer, while the purple line shows the output from the proportional pressure regulator.

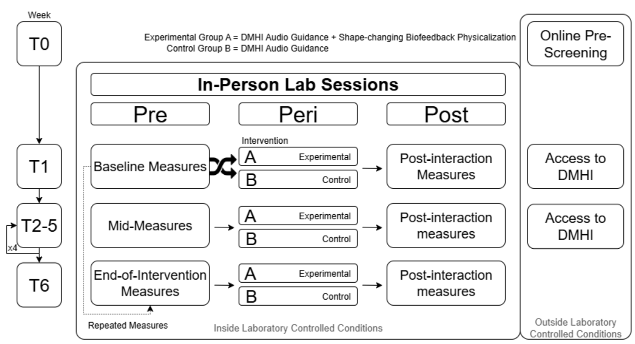


Figure 4: Illustrated study design, depicting a high-level procedure overview across the six weeks.

(T6)[2]. Following baseline measurements at T1, participants were randomly assigned to an experimental group or a control group (see Figure 4). The experimental group used Ankor in addition to listening to guidance from evidence-based audio via the DMHI over six independent in-person lab sessions. The control group listened only to evidence-based audio guidance via the DMHI across six independent in-person lab sessions. Outside of these sessions, all participants had access to the same DMHI via their smartphones.

3.1 Eligibility

Adults aged 18 years and above and who owned a compatible smartphone (iOS 15.0+ or Android 8.0+ capable of running the Medito app) were eligible, provided they scored below 44 on the Warwick-Edinburgh Mental Well-being Scale (WEMWBS). This cut-off captures the population most at risk of mental health issues [54, 97]. Scores of 41–44 correspond to "possible" (mild) depression, while scores below 41 correspond to "probable" depression; selecting a threshold of 44 thus includes individuals experiencing clinically meaningful distress who remain suitable for a self-directed digital intervention without therapist oversight [54]. Restricting entry to this range also minimises ceiling effects on positive-valence measures and increases the sensitivity to detect upward change during the six-week trial. Exclusion criteria included being under 18, current pregnancy, ongoing psychotherapy or psychopharmacological treatment, or any formally diagnosed mental-health condition; applicants scoring below 36 were referred to local clinical services and not enrolled. Recruitment was conducted using an online eligibility pre-screening survey, which was circulated through email channels and poster advertisements.

[2]No follow-up beyond T6 was conducted, as extending data collection beyond the structured intervention period would have coincided with a period of atypical routines (winter break), increasing the likelihood of confounding influences.

Session	Audio Track Title
1	Introduction to Mindfulness
2	Non-Judgement
3	Science of Meditation
4	The Present Moment
5	Manage Negative Emotions
6	Body Scan

Table 1: Medito tracks used in weekly lab-based sessions.

3.2 Setting

In both experimental A, and control group B conditions, participants were required to attend one-hour in-person weekly sessions in a comfortable research lab. The DMHI, Medito [58], was accessible to all participants outside sessions and accessed through a unique login. For those using Ankor during sessions, they held the pneumatically actuated shape-changing biofeedback physicalization between their hands, which changed in size with relation to their breathing. For the audio-only control group, they were instructed to sit comfortably with no instruction as to hand placement. Both groups wore headphones which delivered pre-planned mindfulness audio tracks from the evidence-based programme. To ensure continuity, both groups wore a respiration chest strap during sessions, where only the experimental condition utilized the captured data to replicate biosignals. Participants were either awarded £20 or course credits for study completion; however, all were notified that DMHI engagement between in-person sessions had no impact on incentives.

3.3 Intervention

The DMHI was developed by Medito and validated in a separate RCT [73]. In-lab sessions were part of a 'mindfulness pack', which through audio guidance, introduces an individual to the basic concepts, history and benefits of mindfulness; see Table 1. These sessions lasted 15 minutes each week in both the experimental and control conditions. Outside of the sessions, participants had access to Medito and were encouraged to practice once a day using its extensive catalogue of interventions. Figure 8 (see Appendix) shows screenshots of the DMHI. At the time of use, persuasive content included push notifications, streaks, praise for track completion, social facilitation, and an attractive interface.

3.4 Outcome Measures

Outcome measures aimed to capture both the degree of sustained user engagement and the potential therapeutic gains associated with once-a-week shape-changing biofeedback physicalization interaction. This began with primary measures that gauge psychological and physical engagement, reflecting how motivated and active participants remained throughout the study. Next, the secondary outcomes examined mental well-being, mindfulness, and interoceptive awareness, to see whether heightened engagement with Ankor and the DMHI also fostered meaningful improvements in participants. By using a combination of self-report scales, physiological data, and app-usage metrics, the goal was to ascertain how effectively the interoperation of a new modality supports participants' intentions to practice and if this translated into greater therapeutic benefits over a six-week period.

3.4.1 Primary outcome measure. The primary outcome measure of the study was engagement, both psychological, classified as consisting of motivation, intention, commitment, and belief, and physical, classified as attendance and retention to an intervention [8]. Table 2 details the instances in which measures were taken.

Psychological engagement measures consisted of the Situational Motivation Scale (SIMS) [32], to assess the constructs of intrinsic motivation, identified regulation, external regulation, and motivation across the study duration, and aspects of the Flow State Scale (FSS) [37], which included the dimensions of unambiguous feedback, concentration on task at hand, loss of self-consciousness, transformation of time, and autotelic experience for post-interaction insights. During the intervention stages of T1 and T6, Heart Rate Variability (HRV) was captured through electrocardiogram (ECG) electrode placement to assess sympathoexcitatory subcortical circuit inhibition, enabling comparisons between self-regulatory efforts [15, 100, 101].

Physical engagement was assessed using DMHI metrics, tracking Medito app usage in four categories: 'access' logged when the app is opened, 'started' logged when an audio track is initiated, 'completed' logged when an audio track is finished, and 'query' logged when searching for a specific track to achieve a desired outcome. Self-assessment practice frequencies were given at the start of each session following T1 to compare self-report and metric findings.

3.4.2 Secondary outcome measures. Secondary outcomes include multiple mental well-being outcomes, mindfulness skills, and interoceptive awareness. Well-being was assessed using the WEMWBS [54, 93], and the Depression Anxiety Stress Scales (DASS) [62] to examine changes in negative emotional states of depression, anxiety and stress. HRV was used to examine changes in well-being due to known correlations among psychological flexibility, social approach behaviours, and reduced risk of mental illness [12, 42]. Mindfulness was measured using the Embodied Mindfulness Questionnaire (EMQ) [45], which aims to fully integrate the body and mind-body connection in conceptualizing and operationalizing mindfulness, thereby providing a means to interpret learnt skills. The Multidimensional Assessment of Interoceptive Awareness (MAIA-2) [21] was utilized to examine changes in the sensation, interpretation, and integration of internal somatic signals for which correlations are known between poor interoceptive awareness and difficulties with emotion awareness and emotion regulation [71].

3.5 Procedure

Screening participants involved the completion of an online eligibility questionnaire at T0. Post-screening, participants signed up and attended their individual Session 1 (T1). Baseline measures of WEMWBS, DASS, EMQ, and MAIA-2 were completed before undergoing a randomized allocation into either the experimental Ankor or audio-only control group. Participants were equipped with electrodes and a respiration strap to capture electrocardiographic and pneumographic responses during a 5-minute rest period and the 15-minute intervention. Post-interaction measures included the SIMS and FSS. The DMHI, Medito, was introduced to all participants to practise out-of-session skills, provide support, and manage emotions. Participants were informed that the in-lab sessions utilized components of the DMHI and that they could access additional mindfulness activities outside of in-person sessions through the app. Beyond optional in-app push notifications, no other reminders were given.

Weeks 2–5 followed the same pattern: WEMWBS was completed pre-intervention, and FSS and self-report practice effort post-intervention. T6 replicated the initial measures to assess changes over the intervention, including WEMWBS, DASS, EMQ, MAIA-2 pre-intervention, and SIMS and FSS post-intervention. Physiological data was again captured.

3.6 Data Analysis

As outlined below, analyses were theory-driven and aligned to pre-specified psychological constructs. For each validated self-report scale (MAIA-2, EMQ, SIMS, FSS, DASS), separate General Linear Models (GLMs) were applied with baseline covariates. Subscales were interpreted as theoretically grounded dimensions within each construct rather than as independent hypotheses.

3.6.1 Self-Report. To evaluate group differences across experimental group A and control group B for self-report scales of SIMS, FSS, DASS, WEMWBS, EMQ, and MAIA-2, a GLM with baseline scores as a covariate was employed using equation 1. Standardized (Cohen's d) effect sizes were calculated using the standardized effect estimates divided by the baseline pooled standard deviations; illustrated via Figure 5.

$$\text{End-of-intervention} = \beta_0 + \beta_1 \text{Group} + \beta_2 \text{Baseline} + \epsilon \quad (1)$$

Equation 1. Representation of the GLM employed to analyze the influence of treatment on end-of-intervention outcomes, enabling the isolation of the treatment effect from variations due to baseline scores. The equation models end-of-intervention scores as a function of group assignment and baseline scores. Here, β_0 is the intercept, β_1 measures the effect of the treatment group A versus control group B, β_2 captures the influence of baseline scores on outcomes, and ϵ represents the model's error term.

	T1			T2 – T5			T6		
	Pre	*Peri*	*Post*	*Pre*	*Peri*	*Post*	*Pre*	*Peri*	*Post*
SELF-REPORT MEASURES									
Depression [DASS-D]	*Pre*						*Pre*		
Anxiety [DASS-A]	*Pre*						*Pre*		
Stress [DASS-S]	*Pre*						*Pre*		
Well-being [WEBWBS]	*Pre*			*Pre*			*Pre*		
Mindfulness [EMQ]	*Pre*						*Pre*		
Interoception [MAIA-2]	*Pre*						*Pre*		
Motivation [SIMS]			*Post*						*Post*
Flow [FSS]			*Post*			*Post*			*Post*
App Practice Frequency						*Post*			*Post*
PHYSIOLOGICAL MEASURES									
Electrocardiogram (ECG)	*Pre*	*Peri*					*Pre*	*Peri*	
Pneumographic	*Pre*	*Peri*			*Peri*		*Pre*	*Peri*	
DIGITAL ENGAGEMENT METRICS									
App Access									*Post*
Audio Tracks Started									*Post*
Audio Tracks Completed									*Post*
Searched Queries									*Post*
INTERVENTIONS									
Control group A (Audio Only)		*Peri*			*Peri*			*Peri*	
Experimental group B (Ankor + Audio)		*Peri*			*Peri*			*Peri*	

Table 2: Time points in weeks of measures and metrics recorded across and within sessions. The abbreviations of pre, peri, and post, represent pre-intervention, peri-intervention, and post-intervention time points, respectively.

To evaluate the differences in self-report practice frequencies between group A and group B, response data across multiple sessions was aggregated, and then the Chi-Square Test of Independence was employed.

3.6.2 Physiological Measures. The objective of the psychological engagement analysis was to assess the impact of group affiliation on the delta root mean square of successive differences (ΔRMSSD) in HRV, independent of time point measurements. To evaluate whether being in group A positively affects ΔRMSSD values, reflecting better autonomic control than other groups, a linear regression model was employed, as shown in equation 2. The analysis was conducted separately for T1 and T6, ensuring that the effects of the group could be isolated within each session, without the confounding influence of time. To evaluate ΔRMSSD baseline changes, an independent t-test was carried out on T1 and T6, 5-minute pre-intervention readings.

$$\Delta\text{RMSSD}_{ij} = \beta_0 + \beta_A g_i + \beta_j + e_{ij} \quad (2)$$

Equation 2. Modelling the Delta RMSSD values as a linear sum of an intercept, the group, and time. Where i is an index for the participant, j is an index for the time step, g_i is 1 if the i-th participant belongs to group A, 0 otherwise, e_{ij} is the residual error term for the i-th participant at the j-th time step, and β_0, β_A, and β_j are the coefficients of the intercept, the effect on ΔRMSSD if the participant belonged to group A, and the effect on ΔRMSSD at the j-th time step respectively.

3.6.3 Digital Engagement Metrics. To investigate differences in total user engagement between group A and group B, DMHI data was aggregated for each group, with a Z-test being applied to assess statistical differences. This total engagement was determined by summing the counts of event interactions such as app access, starting audio tracks, completing audio tracks, and query searches across the six weeks for each unique user. To measure differences in the number of unique active users engaged across the six weeks, a Mann-Whitney U test was employed and corrected using the Bonferroni method.

4 Results

Out of the 71 eligible individuals who completed T1 baseline measures, one from each group dropped out for personal reasons during the six weeks. Therefore, 69 participants who scored under 44 on the WEMWBS at T0 completed the study: See Table 3 for demographic and WEMWBS split after randomization.

The results generated from participants are segmented between *Physical Engagement*, which details the actual vs perceived out-of-session DMHI metrics, *Psychological Engagement*, which outlines the findings from self-report measures (SIMS & FSS) and RMSSD values, and *Well-being*, *Mindfulness*, and *Interoceptive Awareness*

Demographics	Group A (n=34)	Group B (n=35)
Gender		
Female	30 (88.2%)	30 (85.7%)
Male	4 (11.8%)	5 (14.3%)
Age		
18–24	32 (94.1%)	33 (94.3%)
25–34	1 (2.9%)	0 (0%)
35–44	1 (2.9%)	0 (0%)
45–54	0 (0%)	2 (5.7%)
Ethnicity		
White	22 (64.7%)	20 (57.1%)
Asian	4 (11.8%)	5 (14.3%)
Black	3 (8.8%)	2 (5.7%)
Mixed	3 (8.8%)	5 (14.3%)
Other	2 (5.9%)	3 (8.6%)
WEMWBS Mean (SD)	38.35 (4.50)	37.69 (7.02)

Table 3: Demographic information of participants and their WEMWBS scores at T1.

outcomes, which highlight potential benefits beyond direct engagement. Figure 5 is a forest plot of the standardized group differences of self-report measures, with the full statistical analysis viewable in the Figure 9 (see Appendix). Figures 6a and 6b illustrate DMHI metrics, with Figure 10 (see Appendix) displaying actual vs perceived DMHI user engagement across the six weeks for one event category. Finally, Figure 7 is the generated RMSSD physiological comparisons at T1 and T6, which were captured during the in-person session experiences.

4.1 Physical Engagement

Across all metrics, total DMHI engagement for 'accessed' (z = 10.76, p < 0.001***), 'started' (z = 20.72, p < 0.001***), 'completed' (z = 9.42, p < 0.001***), and 'queried' (z = 6.16, p < 0.001***) was significantly higher in those who experienced Ankor once a week in comparison to group B; see Figure 6a. Similarly, across the six weeks, significantly more group A participants engaged with the DMHI than control group B across all metrics of 'accessed' (t = 30, p = 0.016*), 'started' (t = 32.5, p = 0.006**), 'completed' (t = 26, p = 0.013*), and 'queried' (t = 24, p = 0.001**), see Figure 6b.

Notably, perceived engagement levels diverged substantially from actual DMHI use. Self-reported practice frequencies showed little variation across weeks, with no significant differences detected (X^2(4, N = 69) = 0.07, p = 0.999), suggesting participants believed their engagement to be consistent over time. However, objective usage data revealed marked fluctuations and an overall decline. Figure 10 (see Appendix) illustrates this discrepancy, underscoring a systematic overestimation of engagement when based solely on self-report measures.

4.2 Psychological Engagement

Except for amotivation (F(1,66) = 4.044, p = 0.048*), no statistically significant group differences were detected for SIMS. However, all dimensions followed a similar directional trend, indicating a broader shift in motivation to self-manage across both conditions, with greater group-favourable effects observed in group A. For the FSS, all dimensions similarly showed greater group-favourable effects, with no statistically significant group differences detected. The dimensions of autotelic experience, concentration on task at hand, loss of self-consciousness, and transformation of time showed statistical individual baseline improvements, detailing a self-perceived shift in flow as practice progressed.

However, physiological measures captured during the intervention experience, visible via Figure 7, revealed contradictory findings. At baseline T1 (β_A = 7.463, CI = [2.624, 12.305], t = 3.034, p = 0.003**) and T6 (β_A = 7.463, CI = [4.120, 12.529], t = 3.895, p < 0.001***) group A saw a significant increase, independent of time points.

While self-reported measures of flow showed no significant differences between groups, physiological data revealed elevated self-regulation efforts in group A, as evidenced by higher HRV (RMSSD) values. This suggests that Ankor enhanced psychological engagement via autonomic pathways that participants were not consciously aware of. Notably, changes across sessions were not compared because different mindfulness activities were employed in those sessions; see Table 1.

4.3 Well-being

At T6, the experimental Ankor group A (M = 48.8, SD = 7.3) reported significantly higher mental well-being than the audio-only control group B (M = 45.0, SD = 8.6), via the WEMWBS (F(1,66) = 4.086, p = 0.047*). For DASS, between-group differences were not significant. However, both groups showed significant DASS improvement relative to their own baselines, indicating meaningful within-group gains. For physiological baseline measures of group A at T1 (M = 53.4, SD = 35.2) and T6 (M = 56.4, SD = 36.8), and group B at T1 (M = 56.9, SD = 31.6) and T6 (M = 64.2, SD = 38.5), no significant differences were found in HRV scores across groups (t = -0.668, df = 63, p = 0.506).

4.4 Mindfulness

Interaction with Ankor was associated with favourable shifts across multiple dimensions of embodied mindfulness, suggesting sensitivity to the intervention at the construct level rather than through isolated subscale effects. Three dimensions appeared particularly responsive and may reflect underlying mechanisms of engagement. First, *disconnection from the body* (F(1,66) = 7.047, p = 0.0099**) reflects the ability to sustain awareness of one's body over time; here, group A showed more favourable post-intervention scores, indicating greater continuity of bodily attention. Second, *awareness of the mind–body connection* (F(1,66) = 22.380, p < 0.001***) captures the capacity to notice bidirectional associations between mental and bodily states; this dimension showed the strongest relative sensitivity to Ankor, potentially reflecting cognitive–somatic integration processes. Finally, *acceptance of feelings and bodily sensations* (F(1,66) = 7.207, p = 0.009**) relates to the ability to remain present with physical and emotional sensations without disengagement or avoidance. These patterns, taken together, indicate that

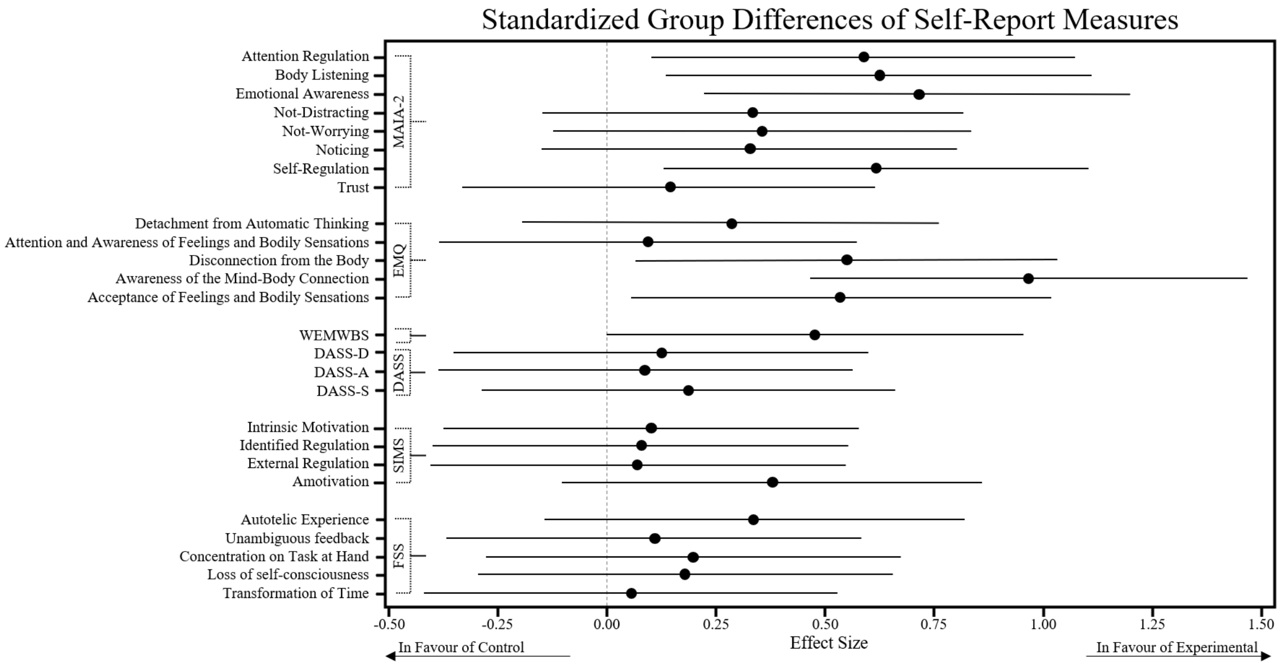


Figure 5: Standardized group differences for MAIA-2, EMQ, WEMWBS, DASS, SIMS, FSS. Each point represents the effect size (Cohen's d) for the difference between the experimental group A and control group B at six weeks (T6), with error bars depicting 95% confidence intervals (CIs). Effect sizes greater than zero suggest a favourable outcome for group A, whereas those less than zero would indicate a favourable outcome for group B.

Ankor may primarily support mechanisms related to embodied awareness and affective regulation.

4.5 Interoceptive Awareness

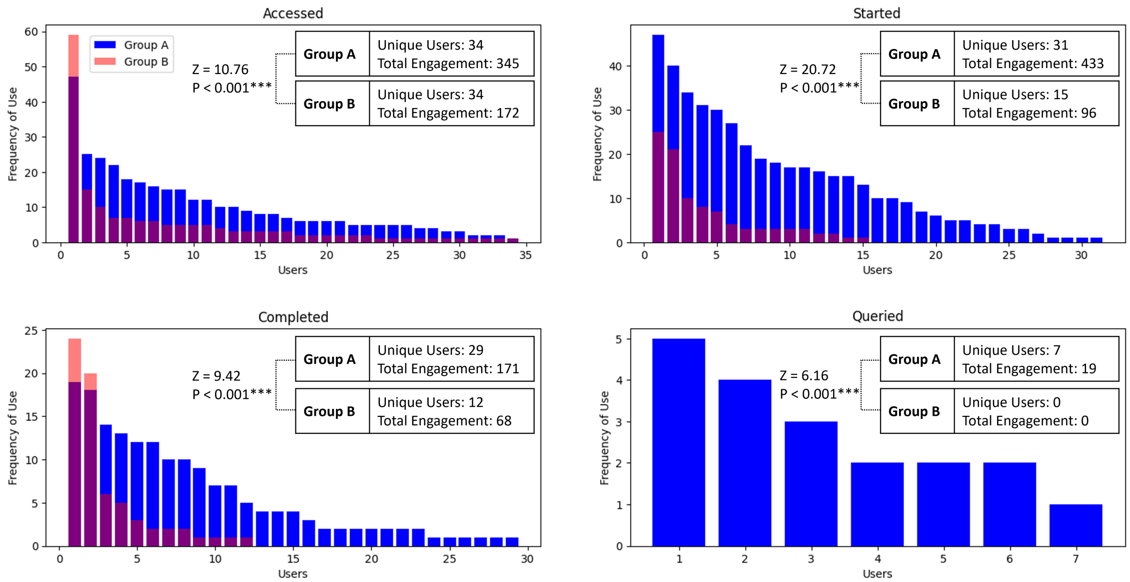
Similarly, interaction with Ankor facilitated greater interoceptive awareness for four out of eight MAIA-2 dimensions compared to the audio-only condition, where all except *noticing* individual baseline differences were significant. Ankor was shown to significantly increase dimensions of *attention regulation* ($F(1,66) = 7.580$, $p = 0.008^{**}$) the ability to sustain and control attention to body sensation, *body listening* ($F(1,66) = 8.417$, $p = 0.005^{**}$) the ability to actively listen to the body for insight, *emotional awareness* ($F(1,66) = 10.440$, $p = 0.002^{**}$) the awareness of the connection between body sensations and emotional states, *not-distracting* ($F(1,66) = 7.580$, $p = 0.008^{**}$) the inference of an adaptive tuned-in relationship to unpleasant sensations, and *self-regulation* ($F(1,66) = 7.930$, $p = 0.006^{**}$) the ability to regulate psychological distress by attention to body sensations.

5 Discussion

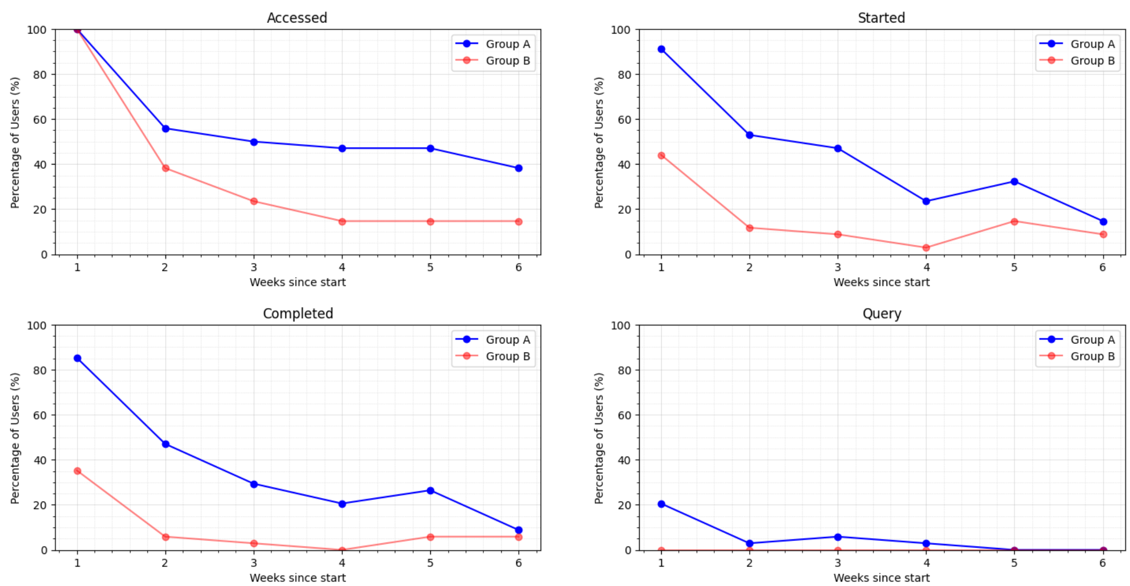
This work provides empirical evidence of how incorporating a shape-changing biofeedback physicalization ("Ankor"), into weekly mindfulness sessions can affect user engagement and intervention outcomes in a six-week DMHI RCT. Our primary findings show that participants who engaged with Ankor in once-a-week, 15-minute sessions exhibited significantly greater engagement; both in *physical* terms (e.g., more frequent at-home DMHI practice initiations, higher practice completion rates, and improved user retention) and in *psychological* terms (e.g., increased experiential self-regulation efforts), compared to those in an audio-only control condition. In addition, secondary outcome measures of well-being, mindfulness, and interoceptive awareness indicated higher comparative efficacy for the Ankor condition, with the experimental group achieving more favourable effect sizes (Figure 5) and a coherent pattern of improvements across related dimensions (Figure 9, see Appendix).

5.1 Engagement

5.1.1 Overview. In this study, 15-minute weekly interactions with Ankor led to substantial increases in out-of-session engagement with the mindfulness app. The experimental group not only had a greater number of *active users* between lab sessions, but also markedly increased at-home practice frequency, initiating 433 Medito tracks compared to 96 in the control group (a 351% increase) and completing 171 tracks compared to 68 in the control group (a 151.5% increase). After two weeks post-download, the audio-only control group's usage had fallen in line with known low-adherence trends (around 3.9% retention [11]), with only 1 out of 35 participants (2.9%) completing any mindfulness practice. By contrast, participants in the Ankor condition maintained an active practice rate of 29.4% at week 2, indicating greater sustained engagement with the DMHI platform. Notably, only the experimental group made use of the app's optional "query" function, whereas none in the control group did. This suggests that the tactile biofeedback experience may motivate users to explore more of the app's resources, counteracting the common pattern in which users engage with only about 40% of available content in such interventions [31].



(a) User engagement frequency across six weeks. Group A and group B are displayed as separate, independent datasets overlaid for visual comparison. Users within each group are ordered by engagement level.



(b) The percentage of unique users actively engaged with the DMHI.

Figure 6: Digital engagement patterns. (a) Total interaction frequency per user. (b) Weekly engagement trends per week. Each subplot represents one event type (Accessed, Started, Completed, and Queried): See Figure 8 for event classifications.

A closer inspection of the engagement data shows that initiation of DMHI practice was substantially higher in the Ankor group, although the proportion of completed sessions did not rise at the same pace. This pattern does not necessarily reflect disengagement, as the DMHI platform classified sessions as "completed" only when the final second of audio had been reached. Users could therefore finish nearly the full session yet still be categorised as unfinished [13, 68]. Given the stronger physiological engagement and favourable psychological outcomes observed across the trial, it is plausible that the completion metric underestimated true adherence rather than signalling reduced persistence. Instead of implying a behavioural deficit, this highlights a measurement limitation and points to a future opportunity; more granular tracking of session trajectories may help distinguish brief withdrawal from sustained practice, and better capture how curiosity transitions into deeper engagement over time [88].

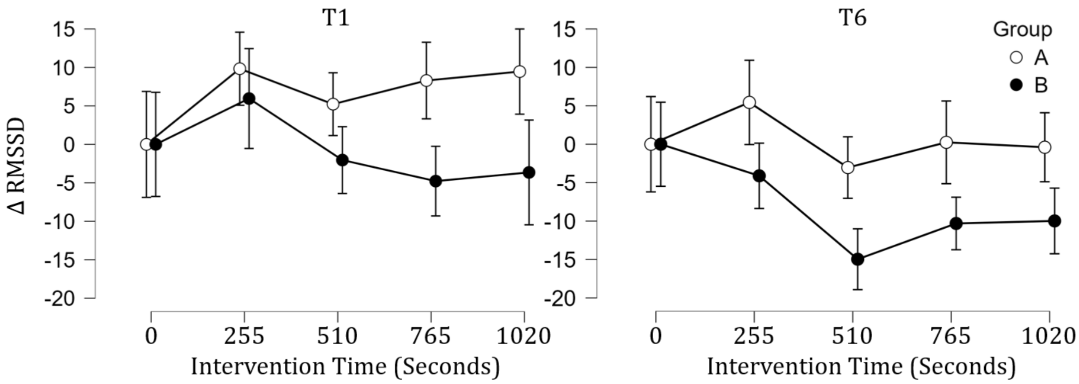


Figure 7: Elapsed intervention time of average ΔRMSSD across all T1 and T6 group participants during a in-lab mindfulness session.

Beyond raw usage metrics, the Ankor condition saw significant improvements in users' motivational state. Over the six-week period, this group showed an 18% reduction in *amotivation*, reflecting enhanced personal agency and willingness to engage. While no significant between-group differences emerged in other motivational dimensions (intrinsic motivation, identified regulation, or external regulation), the selective reduction in amotivation is noteworthy. Participants exposed to Ankor reported fewer feelings of helplessness or inefficacy. This suggests an increased initiative to practice, where users felt more capable to continue using the DMHI on their own beyond the structured weekly sessions. Thus, we posit that Ankor's tangible, real-time feedback, which simplified the core psychological technique of mindful breathing and enhancement of focus, helped overcome traditional barriers to engagement associated with amotivation, such as low expectations of benefit or perceived lack of competence [17, 47, 80].

Physiological evidence from the lab sessions further corroborates the Ankor device's engagement benefits. During T1 and T6, participants using Ankor exhibited significantly greater changes in HRV compared to controls. RMSSD is a vagally-mediated measure of parasympathetic nervous system activity and is sensitive to shifts in autonomic regulation. The Ankor group's higher ΔRMSSD during the mindfulness exercises suggests participants achieved a state of enhanced autonomic self-regulation and relaxation, indicative of deeper psychological engagement with the practice. Inferences from the HRV pattern (e.g., the inferred inhibition of sympathoexcitatory subcortical circuits associated with increased RMSSD [15, 100, 101]) imply that experimental participants experienced greater stress reduction and reduced physiological arousal during the sessions. While we caution that such neural inhibitory processes were not directly observed (only inferred from physiological proxies), this pattern aligns with prior studies of biofeedback-assisted engagement [26] and indicates a more profound meditative experience for Ankor users relative to the control group.

Hence, the convergence of behavioural and physiological evidence indicates that the shape-changing biofeedback physicalization made the mindfulness practice more salient and accessible. By providing a handheld, dynamic representation of the breath, Ankor lowered the effort required to engage with the exercises and strengthened users' sense of agency. These factors likely reduced amotivation and supported early habit formation [17, 80], explaining the substantially sustained DMHI usage observed outside the lab environment.

5.1.2 Implications. The findings reinforce and extend a growing body of work highlighting how biofeedback and haptic interaction can enhance user engagement. Our results resonate with prior evidence on the benefits of touch and biofeedback for learning [57, 86] and motivation [38, 60], and align with theories of embodied cognition [25, 74], inbodied interaction [77, 78], somaesthetics [36, 55], multisensory integration [22, 81], and operant conditioning [7, 86]. From these perspectives, Ankor's ability to render an internal process into a concrete, continuously responsive physical experience leverages embodied learning mechanisms and reward feedback loops that make the act of mindfulness more compelling and intuitive.

Beyond the laboratory, even a modest improvement in out-of-session adherence can affect clinical outcomes and the cost-effectiveness of mental health programs. For example, in 2021–2022 the NHS Talking Therapies program in the UK spent approximately £596.8 million to deliver 4.7 million therapy sessions, averaging roughly £127 per appointment [63]. Excluding dropouts, an eight-session course thus costs in the order of £1,016 per patient when completed, yet only about 50.2% of those who finish treatment achieve recovery by program criteria. There is strong evidence that homework adherence outside therapy sessions is positively associated with better therapeutic outcomes [16, 92]. Therefore, increasing patients' between-session engagement has a direct path to improving recovery rates. As such, if a device like Ankor can boost the proportion of patients who actively practice their homework from a low baseline of 5% in week 5 to a more substantial rate of 25%, the overall recovery rate might rise from 50.2% to approximately 60.9%[3]. In the context of the NHS, this translates

[3]Two-group mixture calculation. Let p be the proportion of completers who adhere to homework, $R(p)$ the overall recovery rate among completers, and r_H, r_N the recovery probabilities for adherent and non-adherent patients with $r_H = k\, r_N$. Using the homework advantage $k = 68/32$ from [92], $R(p) = r_N\ (p\,k + 1 - p)$. Calibrating to the observed baseline $R(0.05) = 0.502$ gives $r_N = 0.502/(0.05k + 0.95)$, or $R(0.25) \approx 0.607$ (60.9%)

to an estimated 72,600 more individuals recovering and around £64 million in annual savings due to improved efficiency of care[4].

Crucially, this engagement mechanism demonstrated here is not specific to any single therapeutic app or content. By translating the natural act of breathing into a salient, easily perceptible cue, Ankor reduces the cognitive and attentional load required to initiate and maintain mindfulness practice, thereby providing a reliable scaffold for habit formation. These accessibility and engagement benefits could be especially impactful for populations that typically face higher barriers to engagement, including children, older adults, individuals with neurodevelopmental conditions (e.g., ADHD), and those with sensory impairments such as hearing or vision loss [14, 16]. In such groups, even brief in-session exposure to a device like Ankor, combined with ongoing access to a mobile app, may significantly increase adherence and skill acquisition across a range of therapeutic activities, from breathing exercises and mindfulness meditation to homework practice in cognitive-behavioural therapy (CBT) programs. Since user engagement is a key determinant of treatment success across digital interventions, integrating shape-changing biofeedback physicalizations as adjuncts in various delivery models (stepped-care pathways, wait-list support programs, group therapy courses, community well-being workshops, etc.) holds promise.

5.2 Efficacy

5.2.1 Overview. To understand benefits beyond engagement, this study also examined the efficacy outcomes of adding Ankor to DMHI delivery. Using WEMWBS, the experimental group showed a 27.3% improvement from T1 to T6, outperforming the control group's 19.4% gain by 7.9%. However, in the DASS, both conditions showed significant within-group reductions from baseline, but between-group differences at T6 were not statistically significant. This result is consistent with a priori expectations that large between-group separation on symptom scales would be unlikely under six-week non-clinical conditions [31]. Nevertheless, the favourable observations in well-being for the experimental group suggest that the device *increased the effective dose* of training by boosting both the amount and quality of practice, which in turn led to greater improvements in certain outcomes. In other words, Ankor's contribution manifested not in statistically better symptom relief but in enhanced positive outcomes and skill gains that can be attributed to higher adherence and a deeper engagement with the mindfulness practice. This interpretation is supported by the pattern of secondary measures related to mindfulness skills, specifically the EMQ and the MAIA-2, where the Ankor group outperformed controls on several key subscales.

For example, the embodied skills that differentiated the groups closely map onto theorised mechanisms of change. On the EMQ, Ankor users showed greater gains in *awareness of the mind-body connection* and *acceptance of feelings and bodily sensations*, alongside reduced *disconnection from the body*. In the EMQ framework, these subscales index, respectively, the capacity to notice bidirectional associations between mental states and bodily cues, a non-avoidant stance toward internal sensations, and the inverse of bodily connection as an anchor for attention [44, 45]. On the MAIA-2, Ankor produced advantages in *attention regulation*, *body listening*, *emotional awareness*, *self-regulation*, and *not-distracting*. These dimensions capture the ability to sustain and control attention to interoceptive signals, actively heed bodily cues for insight, recognise links between sensations and emotions, regulate distress by attending to the body, and refrain from avoiding unpleasant sensations [59]. Together, these profiles indicate a shift toward more precise interoceptive attunement and a more accepting, skilful engagement with somatic experience.

However, it is important to consider why these higher engagement levels did not translate into consistently stronger outcomes across all clinical and well-being scales, particularly given prior evidence that homework adherence predicts better therapeutic response [16, 92]. Eligibility criteria restricted participants to a mild-to-moderate well-being range (WEMWBS < 44), introducing a ceiling effect that limited the amount of change observed on symptom scales in just 6 weeks. In our trial, both groups received an evidence-based mindfulness programme and showed meaningful within-group gains, and given the duration, non-clinical sample, and a design powered primarily for engagement and process measures rather than small symptom-level effects, limited scope remained for large between-group separation [31]. Under these conditions, increased adherence in the Ankor group is likely to have exerted its effects for underlying mechanisms rather than outcome, reinforcing embodied mindfulness and interoceptive regulatory skills without yet reaching the threshold required to produce substantial differential changes in broader well-being or symptom domains such as depression, anxiety, and stress. In line with stage models of psychological change [79, 94], our findings suggest that heightened engagement first manifests as improvements in skills and embodied processes, and that more intensive or prolonged deployment would likely be required for these gains to consolidate into robust, differential changes on clinical symptom scales.

For several reasons, this is theoretically coherent for a shape-changing biofeedback physicalization that continuously translates respiratory signals into graspable kinaesthetic and proprioceptive cues. First, Ankor lowers the attentional effort needed to locate and focus on the breath; participants did not have to rely solely on subtle internal sensations or memory to track their breathing, as the device provided an ever-present physical signal [60, 74]. This helped participants concentrate more easily and consistently, thereby strengthening their attention regulation skills and their ability to *listen* to bodily cues, as reflected in the attention regulation and body listening improvements. Second, Ankor provided immediate, unambiguous feedback when attention lapses (the device's movement changes if one's breathing pattern is disrupted by mind-wandering), gently nudging users back to the present moment [43, 83]. This consistent feedback loop can stabilize the focus on interoceptive targets and discourage distraction [15]; which aligns with the observed gains in the MAIA-2 not-distracting dimension. Third, by allowing participants to feel the natural ebb and flow of their breath in an amplified form, Ankor encourages a more curious and accepting mindset toward bodily sensations. Instead of perceiving bodily signals as faint or abstract, users are literally holding and feeling a physical embodiment of those signals [48]. This clearer

[4]Estimates omit adjustments for dropouts and downstream cost offsets; incorporating these factors would likely yield even greater savings and additional recoveries.

mapping between internal sensations and affective states heightens emotional awareness and gives users a concrete means to regulate arousal through the body [102].

Linking these mechanistic insights back to our outcome measures, the embodied skill enhancements seen with Ankor provide a pathway from device use to the improved engagement and outcomes we recorded. By increasing interoceptive awareness and fostering an open, non-avoidant attitude toward bodily sensations, Ankor likely reduced the perceived effort and uncertainty associated with mindfulness practice [8, 14]. This, in turn, reduced users' resistance and ambivalence toward practice (i.e., reduced motivation), encouraging them to practice more frequently on their own, consistent with the significant boost in outside-session app usage. At the same time, the richer interoceptive skills endowed Ankor users with tools that generalize beyond the lab setting, helping them manage stress and emotions in their daily lives. This explains why the Ankor group showed a larger improvement in WEMWBS. In essence, Ankor appears to have augmented the effectiveness of the mindfulness training by both increasing the quantity of practice (greater adherence) and enhancing the quality of learning (deeper skill acquisition), thereby providing a double benefit that supports better day-to-day emotional regulation [45, 59, 71].

5.2.2 Implications. In light of this, secondary outcomes indicate that Ankor can preferentially enhance positive mental health and embodied skill acquisition within a short, low-intensity programme. Taken together, the EMQ and MAIA-2 profiles indicate strengthened interoceptive clarity and a less avoidant stance toward somatic cues, equipping users to detect early physiological markers of stress and apply body-based strategies promptly during and beyond practice [66, 71, 102]. Such mechanisms provide a coherent route from device-supported training to greater day-to-day regulation and broader improvements in well-being under conservative trial conditions.

These effects are most relevant in contexts where positive valence and skill generalisation are valued outcomes. For example, clinical services deploying mindfulness or skills blocks could use these technologies to deepen embodied mechanisms that underwrite transfer to daily life, such as sustained attention tasks [101, 106] and non-reactive acceptance of sensations [70]. Therefore, these findings again further motivate targeting populations characterised by low interoceptive clarity or high sensation avoidance, including individuals who report difficulty locating the breath, those with pronounced cognitive load during practice, or users who struggle to translate in-session understanding into everyday regulation [8, 16, 66].

5.3 Generalizability

Though the present evaluation was confined to a single controlled setting with participants experiencing reduced well-being, the design principles and engagement mechanisms of Ankor appear broadly applicable. DMHIs support a wide range of mental-health and well-being conditions, and there is no strong reason to expect that the benefits of embodied, shape-changing biofeedback would be limited to our tested context. By providing dynamic, tangible feedback that engages the body directly, Ankor fosters self-awareness and motivation—skills that are foundational not only for individuals with diagnosable conditions but also for everyday practices of mental well-being. For instance, the well-established benefits of meditation [6, 103] closely align with the embodied mode of engagement that Ankor enables. This suggests considerable potential for Ankor to enhance engagement across a broad spectrum of interventions and user populations.

Our preference for a shape-changing embodied interface was theoretically motivated, where frameworks of embodied cognition and somaesthetic design argue that actively involving the body enhances attention, awareness, and motivation [36]. Consistent with these perspectives, our findings indicate that Ankor's benefits stem from its kinaesthetic, shape-changing qualities rather than its specific spherical morphology. Other tangible and kinaesthetic devices that employ similar handheld embodied dynamics could plausibly yield comparable outcomes, though further empirical validation will be required to substantiate this assumption.

5.4 Limitations

While our study was designed to emulate aspects of real-world therapy delivery, several limitations must be acknowledged when interpreting the results. Despite efforts to simulate a clinical format, the experiment was conducted in a controlled setting with a non-clinical university population. This relatively homogeneous sample may engage with digital mindfulness training differently than individuals seeking treatment for mental health conditions, but trial participation and non-contingent incentives may nonetheless inflate engagement levels compared to naturalistic use [10, 28]. Recruitment from the same institution introduced an additional limitation on blinding. Although participants were not informed of multiple conditions and were scheduled individually, informal discussions outside study sessions could not be fully controlled, thus complete maintenance of the single-blind design cannot be guaranteed. Additionally, the study was not pre-registered; while this was considered appropriate for an exploratory non-clinical design, future confirmatory research would benefit from pre-registration to enhance methodological transparency and mitigate the potential for selective reporting. In more complex clinical contexts, where users may present with a broader range of symptoms, comorbidities, or motivational challenges, additional adaptations or support mechanisms may be needed to achieve comparable levels of engagement and efficacy.

Further, the mechanisms driving the observed increases in engagement and outcomes remain ambiguous. Our data showed that adding Ankor led to higher engagement metrics, but it is not yet clear whether this reflects improved adherence to the mindfulness practices themselves or whether the device prompted more frequent app interactions that may or may not equate to deeper mindfulness practice. Similarly, where we found differences in secondary outcomes like interoceptive awareness and well-being, it is uncertain to what extent those arose because Ankor helped participants practice mindfulness more consistently versus making each instance of practice more effective (or both). The existing literature suggests that these factors likely act synergistically [16, 34, 39, 92], but our study was not explicitly designed to disentangle them. Moreover, our sample was predominantly young adult females, preventing stratified analysis of whether engagement or outcome patterns varied by gender or age, a potentially relevant consideration given evidence that demographics may adopt different motivational orientations in DMHI contexts [50]. Addressing this uncertainty will require more fine-grained research. Future studies should incorporate direct, objective measures of mindfulness practice quality and internal change. Such data would help clarify how a device like Ankor influences users' engagement behaviour and whether it fundamentally changes the nature of their mindfulness practice, beyond just increasing its frequency.

Another limitation concerns the extent to which the observed engagement effects can be cleanly attributed to the specific design properties of Ankor, as opposed to a novelty response to an additional artefact [87]. All participants received an evidence-based DMHI and attended structurally identical weekly laboratory sessions; the only systematic difference between conditions was the presence or absence of Ankor. Out-of-session engagement was measured over the remaining week, during which both groups had access only to the same smartphone app. The fact that the Ankor group showed higher DMHI use throughout the week, including greater rates of voluntary app access, track initiation, and exploratory query behaviour, suggests that the intervention operated primarily through carry-over mechanisms rather than through continuous exposure to a novel object in the home environment [87]. In other words, any novelty effect associated with handling a new artefact was temporally and spatially constrained to a small proportion of participants' week, yet the behavioural footprint of the intervention emerged in out-of-session practice windows where the artefact was absent, and only the psychological and bodily skills acquired in the lab could influence behaviour.

However, the study design cannot disentangle which specific components of Ankor are responsible for these benefits. The device simultaneously introduced multiple changes relative to the audio-only control, including an additional artefact, a handheld and tactile nature, shape-changing behaviour, and a contingent biofeedback link to respiration. Our results, therefore, speak to the effect of this composite system rather than isolating the incremental contribution of each design element. Accordingly, our claims are therefore framed at the level of integrated shape-changing biofeedback physicalizations as adjuncts to DMHIs.

Finally, we observed a notable divergence between some subjective self-report measures and the objective physiological and app metrics, which raises methodological considerations for future research. In our study, participants' self-reported perceptions of engagement did not always parallel the physiological signs of engagement and relaxation. There are a couple of potential explanations for this discrepancy. One is that the self-report instruments we used might not have fully captured the nuances of participants' experiences with Ankor. Another possibility is that participants' subjective sense of engagement simply differs from their physiological state. For instance, users might not consciously register the depth of their low-arousal states, or conversely, they might feel engaged even when their bodies indicate stress. This misalignment highlights the challenge of measuring experiential qualities in technology-assisted interventions. To improve the validity and reliability of evaluation in future work, researchers should examine these self-report vs. objective measurement gaps more closely.

5.5 Conclusion

Our findings illustrate that tangible artefacts are not only capable of improving adherence and skill uptake within DMHIs, but can do so by targeting a part of the therapeutic process that is frequently overlooked in technology design: how people sustain practice between structured sessions. Much of the existing work on novel interfaces and mental health technologies focuses on short-term in-lab experiences, proximal user satisfaction, or symptom outcomes, rather than on the ongoing cognitive and motivational demands of adhering to practice over time. By combining longitudinal app metrics, physiological indices, and validated self-report measures, this study demonstrates that a shape-changing biofeedback physicalization can shift both engagement patterns and embodied skills, with effects that persist beyond the immediate interaction with the device. In doing so, our work highlights the importance of designing technologies not only to deliver content or optimise interactions, but to scaffold the formation of durable, embodied habits of self-regulation. We argue that embedding this perspective into the design of new technologies and interfaces is essential if digital mental health tools are to move beyond novelty and aesthetics toward sustained, real-world impact.

Acknowledgments

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A Appendix

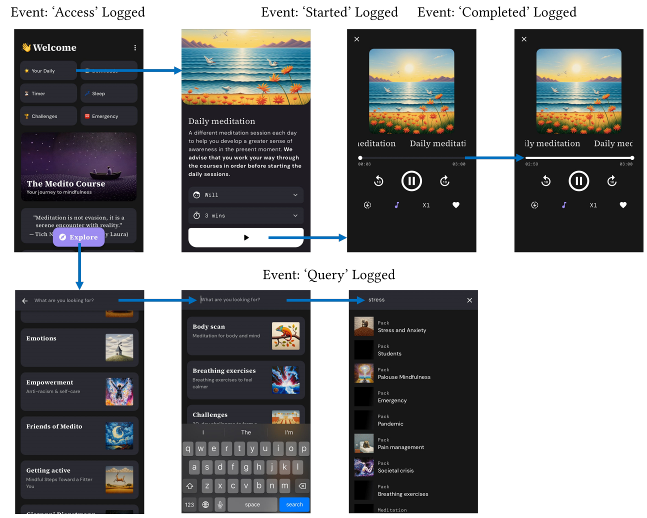

Figure 8: The DMHI Medito and its logged instances of digital metrics

		Baseline (T1)		6-week End-of-intervention (T6)			General Linear Model with Baseline Scores as Covariate					
							Group			Baseline		
		Exp Group A: M (SD)(SE)	Ctrl Group B: M (SD)(SE)	Exp Group A: M (SD)(SE)	Ctrl Group B: M (SD)(SE)	d (95% CI)	F(1,66)	Pr(>F)	η²p	F(1,66)	Pr(>F)	η²p
MAIA-2	Attention Regulation	2.319 (0.617)(0.106)	2.111 (0.849)(0.143)	2.992 (0.750)(0.129)	2.531 (0.808)(0.137)	0.591 [0.107, 1.071]	7.580	0.00761 **	0.064	18.280	6.28e-05 ***	0.217
	Body Listening	2.098 (0.967)(0.166)	2.001 (0.973)(0.164)	3.001 (0.861)(0.148)	2.429 (0.952)(0.161)	0.630 [0.144, 1.111]	8.417	0.005047 **	0.099	16.429	0.000136 ***	0.199
	Emotional Awarenes	3.159 (0.791)(0.136)	2.983 (0.803)(0.136)	3.865 (0.713)(0.122)	3.326 (0.785)(0.133)	0.718 [0.228, 1.203]	10.440	0.001922 **	0.107	12.670	0.000695 ***	0.161
	Not-Distracting	1.785 (0.873)(0.150)	1.681 (1.026)(0.173)	1.946 (0.792)(0.136)	1.658 (0.816)(0.138)	0.359 [-0.117, 0.834]	7.580	0.00761 **	0.034	18.280	6.28e-05 ***	0.383
	Not-Worrying	1.853 (0.774)(0.133)	1.754 (0.612)(0.103)	2.306 (0.780)(0.134)	2.006 (0.985)(0.167)	0.337 [-0.139, 0.811]	2.374	0.128	0.023	15.122	0.000237 ***	0.186
	Noticing	2.838 (0.723)(0.124)	2.757 (0.835)(0.141)	3.544 (0.608)(0.104)	3.314 (0.773)(0.131)	0.330 [-0.146, 0.804]	1.876	0.175	0.013	0.873	0.354	0.026
	Self-Regulation	2.257 (0.714)(0.122)	2.014 (0.809)(0.137)	3.243 (0.836)(0.143)	2.721 (0.837)(0.142)	0.623 [0.137, 1.104]	7.930	0.006405 **	0.068	13.390	0.000504 ***	0.169
	Trust	2.666 (0.848)(0.145)	2.533 (0.879)(0.149)	3.226 (0.823)(0.141)	3.095 (0.959)(0.162)	0.146 [-0.327, 0.618]	0.458	0.501	0.002	17.664	8.09e-05 ***	0.211
EMQ	Detachment from Automatic Thinking	1.724 (0.561)(0.096)	1.926 (0.511)(0.086)	2.212 (0.528)(0.091)	2.394 (0.735)(0.124)	0.285 [-0.190 , 0.759]	1.583	0.213	0.006	9.927	0.00245 **	0.131
	Attention and Awareness of Feelings and Bodily Sensations	3.453 (0.529)(0.091)	3.343 (0.607)(0.103)	3.535 (0.534)(0.092)	3.474 (0.742)(0.125)	0.094 [-0.378 , 0.566]	0.181	0.672	0.000	13.339	0.000515 ***	0.168
	Disconnection from the Body	2.747 (0.947)(0.162)	2.811 (0.959)(0.162)	2.100 (0.963)(0.165)	2.640 (1.001)(0.169)	0.550 [0.069 , 1.031]	7.047	0.00994 **	0.085	24.578	5.26e-06 ***	0.271
	Awareness of the Mind-Body Connection	3.816 (0.604)(0.104)	3.657 (0.673)(0.114)	4.316 (0.538)(0.092)	3.779 (0.571)(0.097)	0.969 [0.470 , 1.468]	22.380	1.22e-05 ***	0.199	26.640	2.44e-06 ***	0.288
	Acceptance of Feelings and Bodily Sensations	2.441 (0.616)(0.106)	2.280 (0.691)(0.117)	2.759 (0.705)(0.121)	2.371 (0.737)(0.125)	0.537 [0.057 , 1.017]	7.207	0.00917 **	0.056	31.113	4.9e-07 ***	0.320
	WEMWBS	38.353 (4.498)(0.771)	37.686 (7.020)(1.187)	48.824 (7.321)(1.256)	45.000 (8.619)(1.457)	0.478 [-0.001 , 0.956]	4.086	0.0473 *	0.052	3.606	0.062	0.052
DASS	DASS-D	16.059 (7.742)(1.328)	17.086 (9.460)(1.599)	10.706 (7.578)(1.300)	11.714 (8.584)(1.451)	0.124 [-0.348 , 0.597]	0.348	0.557	0.001	21.392	1.8e-05 ***	0.245
	DASS-A	16.588 (7.024)(1.205)	14.571 (7.678)(1.298)	9.235 (6.272)(1.076)	8.686 (6.077)(1.027)	0.089 [-0.383 , 0.561]	0.188	0.666	0.001	26.018	3.07e-06 ***	0.283
	DASS-S	20.794 (6.517)(1.118)	21.600 (7.968)(1.347)	13.647 (7.006)(1.202)	14.971 (7.168)(1.212)	0.187 [-0.286 , 0.660]	0.785	0.379	0.006	21.335	1.84e-05 ***	0.244
SIMS	Intrinsic Motivation	4.912 (0.959)(0.164)	5.107 (0.796)(0.135)	5.206 (1.054)(0.181)	5.100 (0.938)(0.159)	0.106 [-0.366 , 0.578]	0.291	0.592	0.021	34.088	1.76e-07 ***	0.341
	Identified Regulation	5.154 (0.973)(0.167)	5.450 (0.838)(0.142)	5.338 (1.031)(0.177)	5.257 (0.971)(0.164)	0.081 [-0.391 , 0.553]	0.208	0.650	0.041	57.369	1.53e-10 ***	0.465
	External Regulation	2.635 (1.122)(0.192)	2.471 (1.345)(0.227)	2.426 (1.033)(0.177)	2.521 (1.447)(0.245)	0.075 [-0.397 , 0.547]	0.164	0.687	0.011	46.005	3.94e-09 ***	0.411
	Amotivation	1.669 (0.639)(0.110)	1.821 (0.986)(0.167)	1.368 (0.527)(0.090)	1.657 (0.922)(0.156)	0.384 [-0.092 , 0.860]	4.044	0.0484 *	0.029	40.423	2.21e-08 ***	0.380
FSS	Autotelic Experience	3.632 (0.619)(0.106)	3.657 (0.616)(0.104)	4.164 (0.691)(0.119)	3.921 (0.757)(0.128)	0.335 [-0.141 , 0.810]	2.108	0.151	0.033	7.118	0.00959 **	0.097
	Unambiguous Feedback	3.044 (0.670)(0.115)	3.138 (0.689)(0.116)	3.691 (0.866)(0.149)	3.607 (0.689)(0.117)	0.108 [-0.365 , 0.580]	0.207	0.651	0.005	3.413	0.069	0.049
	Concentration on Task at Hand	2.551 (0.859)(0.147)	2.643 (1.013)(0.171)	3.228 (1.081)(0.185)	3.021 (1.012)(0.171)	0.197 [-0.276 , 0.670]	0.993	0.323	0.024	32.986	2.56e-07 ***	0.333
	Loss of Self-consciousness	3.206 (1.060)(0.182)	3.379 (0.850)(0.144)	4.044 (0.854)(0.146)	3.886 (0.924)(0.156)	0.178 [-0.295 , 0.651]	0.739	0.393	0.025	24.661	5.1e-06 ***	0.272
	Transformation of Time	3.235 (0.879)(0.151)	3.643 (0.832)(0.141)	3.713 (0.932)(0.160)	3.764 (0.959)(0.162)	0.054 [-0.418 , 0.526]	0.057	0.812	0.004	9.644	0.0028 **	0.127

Figure 9: Summary of Baseline and End-of-intervention Comparisons and GLM analyses. Baseline (T1) and week six (T6) scores for the experimental (Exp) group A and control (Ctrl) group B are presented as Mean (Standard Deviation) [SD] (Standard Error) [SE]. The effect sizes are reported as Cohen’s d with 95% confidence intervals [CI]. The GLM with Baseline scores as covariate provides F statistics, associated p-values (Pr(>F)), and partial eta squared (η_p^2) for ‘Group’ and ‘Baseline’ effects. ’Group’ indicates the significance of the intervention between groups at T6, while ’Baseline’ reflects the variance explained by baseline measures within the model. Asterisks denote levels of significance ($*p < .05, **p < .01, ***p < .001$), and partial η_p^2 values quantify the effect size for each factor, reflecting the proportion of variance accounted for by the respective variable in the model.

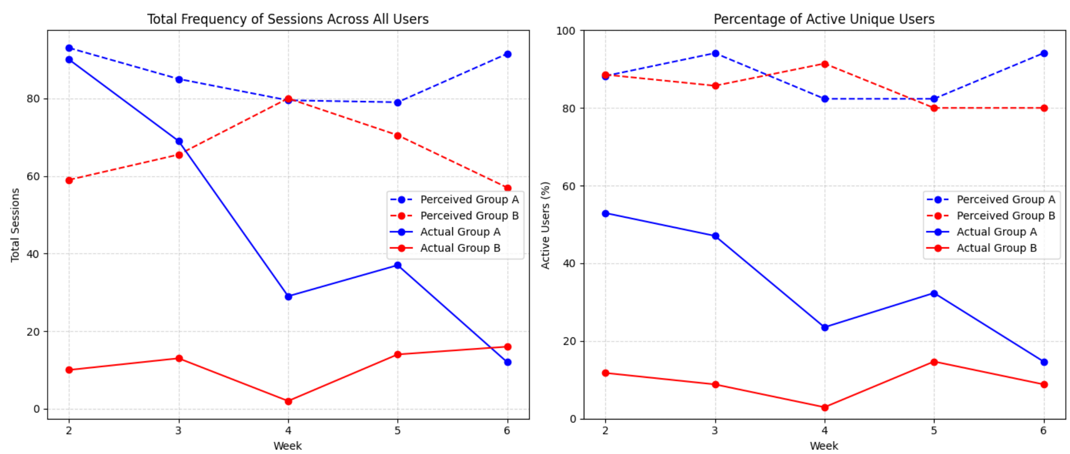

Figure 10: Comparison of total sessions started and percentage of active users based on self-reported and actual app usage over weeks 2–6. Perceived metrics were derived from survey responses by converting categorical practice frequencies into estimated session counts (0 for “Did not practice”, 1 for “Practised once”, 2.5 for “Practised 2–3 times”, 5 for “Practised 4–6 times, ”, and 7 for “Practised daily”) and by computing the percentage of respondents reporting any practice. Actual metrics were computed from app event logs, where total sessions represent the count of sessions started, and active user percentages are based on the weekly count of unique users. Dashed lines indicate perceived measures, while solid lines denote actual measures; blue and red represent groups A and B, respectively.