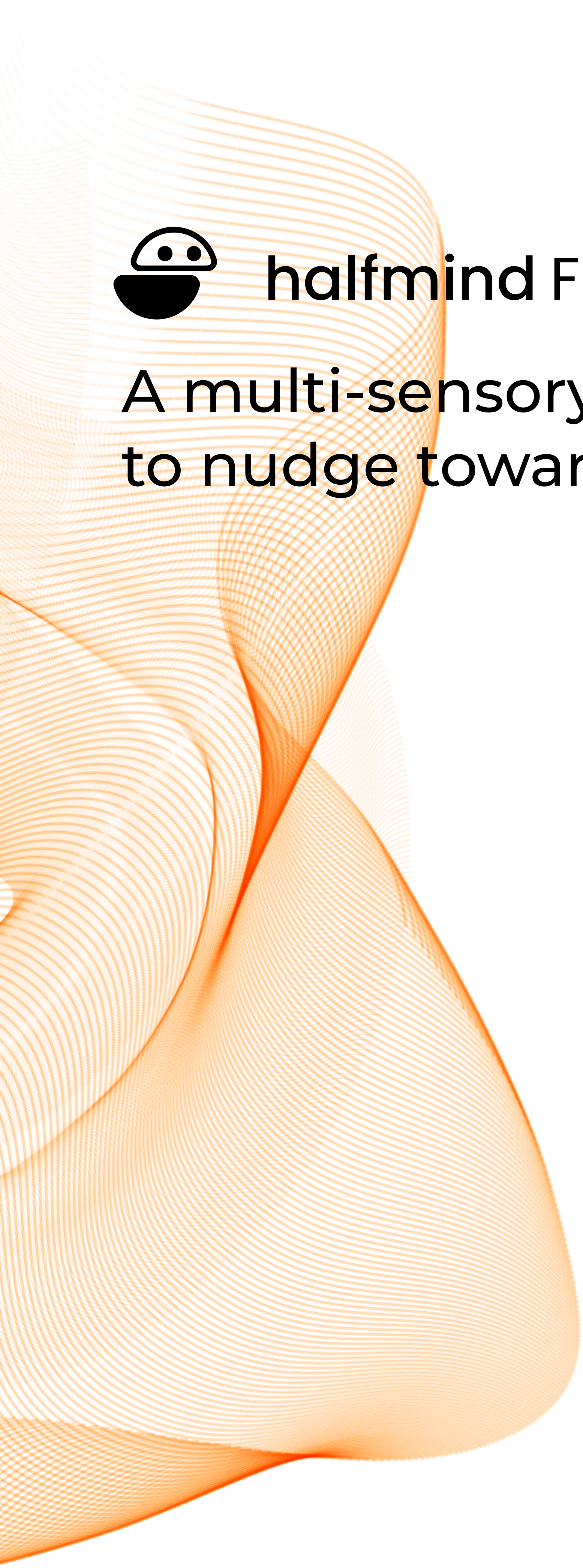

halfmind Flow

A multi-sensory intervention to nudge towards focus

Master thesis
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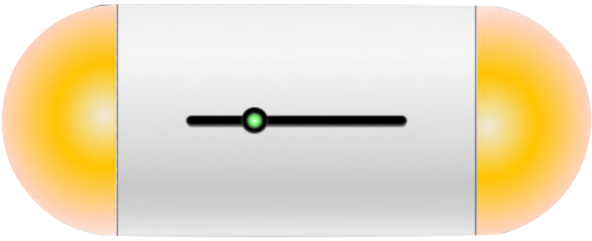


Executive Summary

In an era of cognitive overload and digital distraction, maintaining focused attention during work has become a critical yet under-supported challenge, particularly for individuals with ADHD and those navigating flexible, unstructured work environments. This thesis explores how a multisensory, sensor-driven system can assist users in overcoming task initiation inertia and sustaining deep focus through gentle, adaptive interventions at work-from-home scenarios.

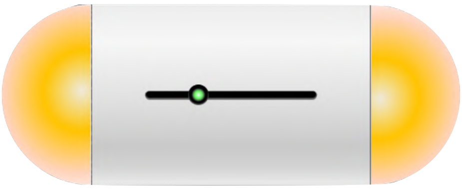
The project centers on the creation, prototyping and evaluation of Halfmind Flow, a contactless, radar-based ambient device that guides breathing and emotional readiness through synchronised auditory and visual cues. The system is built on trending applications in millimetre-wave (mm-wave) radar sensing, which enables unobtrusive tracking of micro-movements like respiration and fidgeting, allowing real-time inference of user attention states without physical contact.

Two complementary methodologies—Vision in Product Design (ViP) and Context4Change derived from participatory design—were employed to ground the intervention in real-world needs. A qualitative user study with four remote workers revealed nuanced behavioral and emotional patterns related to focus, particularly around the psychological threshold of "almost starting." From these insights, three metaphor-driven concept directions were explored. The final design, Energy Crystal, was selected for its emotional resonance, technical feasibility, and multisensory integration potential.

The system was prototyped using an Infineon 60 GHz radar sensor, an ESP32 microcontroller, and Max/MSP for generative audio. It operates automatically, adjusting music tempo and ambient lighting to reflect and subtly guide user physiology. A within-subject experiment (N = 17) compared baseline and intervention sessions using attention test, PreMo emotion ratings, and NASA-TLX workload scores.

Results showed non-significant changes in terms of response time, response time variability and focus sensitivity, while frustration level (NASA-TLX question 6) and valence showed significant improvement. Strong order effects from 2x2 ANOVA test suggested potential carryover bias in short-term crossover designs, highlighting the need for between-subject models in future work.

This research contributes to the fields of affective computing, attention-supportive design, and ambient interaction by demonstrating that subtle, personalised multisensory cues tuned to physiological and emotional rhythms can enhance focus-related experiences without demanding cognitive effort. Though preliminary in statistical strength, the system shows promise for broader applications in work-from-home well-being and ADHD-supportive tools.



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Glossary

This glossary defines the abbreviations and specialised terms used throughout the report. It is intended to ensure clarity and consistency for readers from different disciplinary backgrounds. Where an abbreviation is given, the corresponding full term appears alongside its definition. Terms are listed in alphabetical order for ease of reference.

Abbreviation	Definition
AB	Experiment sequence starting with baseline condition followed by intervention condition.
ACS	Attention Comparison Score; a composite metric combining multiple TOVA indicators, here defined as ACS = meanHitRT_LF + d′_HF + SDHitRT + 1.8
ADHD	Attention-Deficit/Hyperactivity Disorder; a neurodevelopmental condition characterised by persistent patterns of inattention and/or hyperactivity-impulsivity that interfere with functioning or development, relevant here for its impact on task initiation and sustained attention.
BGT60TR13C	A 60 GHz millimetre-wave radar sensor from Infineon, capable of detecting respiration and small body movements.
band-pass filter	A filter allowing only respiration-frequency (0.15–0.6 Hz) components to pass, removing noise outside the breathing band.
Blackman–Harris window	A window function used in signal processing to reduce spectral leakage in FFT results.
C4C	Context4Change; a participatory design methodology by Yu et. Al (2025) that uses context reflection, co-creation, and intervention validation to facilitate behaviour change in specific environments.
Cognitive Load	The mental effort required to process information, make decisions, and perform tasks, often discussed in contrast to perceptual load.
counterbalanced	A design method for ordering conditions so as to control for order effects across participants.
Design Group	A group of participants involved in co-creation sessions to generate and refine design concepts, distinct from evaluation participants.
d'	d prime, a measure from TOVA representing the sensitivity to distinguish signal from noise.
dprime_HF	Sensitivity index for high-frequency stimulus blocks in TOVA.
EEG	Electroencephalography; a method for recording electrical activity of the brain, mentioned here as a potential physiological measure.
effect size	A standardised measure of the magnitude of an effect, calculated from non-parametric tests, noted as r.
ESP32	A low-cost, low-power microcontroller with Wi-Fi and Bluetooth, used here for sensor interfacing and data transmission.
FFT	Fast Fourier Transform; an algorithm to compute the discrete Fourier transform efficiently, used here for range-domain transformation and frequency analysis of radar data.
Future Cone	A foresight design tool for exploring multiple possible, probable, and preferable future scenarios.
I/Q	In-phase and quadrature components of a complex signal, used in radar signal processing to extract phase and amplitude information.
LED	Light-emitting diode; here used in an array of seven units to visualise breathing depth and rhythm.
Max/MSP	A visual programming environment for audio and multimedia, used here for real-time sound generation and control.
meanHitRT_LF	Mean reaction time for correct responses during low-frequency stimulus blocks in TOVA.

mm-wave	Millimetre-wave; electromagnetic waves in the 30–300 GHz frequency range, used in this study for non-contact sensing of respiration.
Multi-sensory Design	Design approach that integrates multiple sensory modalities—such as visual, auditory, and tactile—to create more engaging and effective user experiences.
NASA-TLX	NASA Task Load Index; a subjective workload assessment tool that measures perceived workload across six dimensions.
Neurodiversity	The natural variation in cognitive functioning within the human population, encompassing conditions such as ADHD, autism, and dyslexia.
Participatory Design	An approach in which stakeholders actively contribute to the design process to ensure solutions meet their needs and values.
phase unwrapping	A process to correct for 2π discontinuities in phase data to obtain continuous displacement values.
PPG	Photoplethysmography, a non-invasive optical technique that measures blood volume changes in the microvascular bed of tissue using light absorption. Usually embedded in smart watches.
PrEmo	Product emotion measurement tool (Desmet, 2018); a non-verbal self-report tool that captures users' emotional responses along valence and arousal dimensions.
range bin	A discrete range interval in radar data after FFT processing, corresponding to a specific target distance.
RF	Radio Frequency; electromagnetic wave frequencies ranging from about 3 kHz to 300 GHz.
SDHitRT	Standard deviation of reaction time for correct responses in TOVA.
TOVA	Test of Variables of Attention; a continuous performance test that measures attention, response time, and consistency, used here as the main task in the evaluation phase.
UWB	Ultra-Wideband; a radio technology using frequencies between approximately 3.1 and 10.6 GHz, characterised by short pulses and high time resolution.
valence	The degree of pleasantness or unpleasantness associated with an emotion.
ViP	Vision in Product Design; a design method that starts from a desired future vision to guide concept generation and product definition.
washout	A rest period between conditions to reduce carryover effects.
Wilcoxon signed-rank test	A non-parametric statistical test used to compare two related samples.
within-subject	An experimental design where the same participants experience all conditions.
Yerkes–Dodson law	A principle describing an inverted-U relationship between arousal level and performance.

1. Introduction

1.1 Project goal and rationale

Challenges of focus in work

In modern work contexts, sustaining deep focus is an ongoing challenge shaped by cognitive overload, constant digital distractions, and mental fatigue. A typical work session naturally cycles through phases of initiation, immersion, and recovery, yet many existing tools treat attention as a constant resource to be maximised rather than a fluctuating state that requires sensitive support. As hybrid work environments and multitasking become the norm, the need for interventions that recognise and work with these natural attention rhythms is increasingly evident.

ADHD community

For individuals with Attention-Deficit/Hyperactivity Disorder (ADHD), difficulties in sustaining focus during work are especially pronounced. Common challenges include task initiation (also described as task paralysis), susceptibility to distractions, and maintaining engagement over time, where the latter two are also perceived as frequent task-switching. These factors can substantially affect both productivity and overall well-being. ADHD is one of the most common psychiatric conditions, affecting about 5.9% of youth and 2.5% of adults worldwide (Faraone et al., 2021). More recent global estimates suggest that in 2020, approximately 2.6% of adults met criteria for persistent ADHD, and up to 6.8% showed symptomatic ADHD, representing over 500 million affected individuals globally (Song et al., 2021). Such prevalence highlights ADHD as not only a childhood disorder but a lifelong condition with significant personal and societal impacts. Young adulthood (approximately ages 18 to 29) represents a particularly critical stage, as individuals are establishing routines, coping strategies, and professional identities. Understanding their experiences offers valuable insight into how ADHD interacts with daily habits and work practices. This, in turn, creates an opportunity to design adaptive systems that can respond intelligently to personal needs and diverse working styles.

Body-sensing technology

Recent advances in body-sensing technologies, particularly millimetre-wave (mm-wave) radar, are reshaping the landscape of smart and connected systems. Unlike traditional wearable devices, mm-wave radar can unobtrusively detect subtle physiological and behavioural cues without requiring direct skin contact (Ge et al., 2024). Its ability to capture fine-grained micro-movements enables the construction of a nuanced, real-time picture of attention and engagement.

Within the broader context of the Internet of Things (IoT), mm-wave radar is increasingly integrated into smart environments, from home automation and healthcare monitoring to workplace productivity tools. By embedding sensing capabilities into everyday objects and spaces, these systems can respond intelligently to users' states while preserving comfort and privacy. One interesting example is the alarm clock by Nintendo (Figure 1) that can guide the user to wake up with body-tracking games.

Personal motivation


Figure 1. Alarmo the mm-wave interactive clock, from Nintendo Store

My interest in this research comes from personal experience. In the past, I often relied on “ADHD Relief Music” to support concentration at work. While such tools were helpful, they remained generic—showing some efficacy but offering little adaptation to my changing states of focus or the demands of specific tasks. As I gained knowledge of radar sensing and grew more curious about how everyday electronic devices could be reimagined for well-being, I became motivated to explore how a personalised system might better support attention management. This motivation goes beyond convenience: it reflects my broader aspiration to design technologies that respond intelligently to human variability, balance personalisation with automation, reduce cognitive strain, and ultimately encourage working vitality.

1.2 Research questions

This project is guided by two central research aims that emerged from the challenges identified in the background and rationale. The first is to explore how a multi-sensory intervention can effectively nudge users to initiate tasks, addressing the common struggle of overcoming inertia or procrastination, particularly among individuals who experience fluctuating motivation and cognitive barriers to starting work. The second is to investigate how the same multi-sensory approach can support users in maintaining deep focus once engaged, by responding adaptively to subtle shifts in attention and embodied signals that indicate distraction or mental fatigue.

Initially, the research questions were framed broadly around the role of embodied cues — such as micro-movements detected via mm-wave radar — in signalling changes in cognitive state. As the project progressed through literature review, introspective studies, and early prototyping, the questions were iteratively refined to emphasise the practical balance between task initiation and sustained focus. This distinction recognises that these two phases of work require different kinds of support, both cognitively and experientially, and that a single intervention must adapt fluidly to the user’s shifting needs.

Therefore, the final guiding research questions are:

1. *How does a multi-sensory system detect and respond to embodied cues in order to nudge users to initiate tasks more effectively?*
2. *How can the same system sustain deep focus by adapting sensory feedback to real-time attention states in work contexts?*

These questions anchor the design process, ensuring that the resulting interventions respect individual cognitive rhythms while leveraging advanced sensing and interaction design to support meaningful productivity.

1.3 Design methodologies

This project employs two complementary design methodologies to guide its development: **Vision in Product Design (ViP)** and **Participatory Design**. Both approaches are chosen for their adaptability to innovative product research, their ability to structure insights from ambiguous contexts, and their suitability for reframing human–technology interaction in everyday work environments.

Vision in Product Design (ViP) method by Matthijs van Dijk and Paul Hekkert (2016) will guide the early stages of concept generation and ideation. ViP emphasises designing from a broader understanding of societal trends, user contexts, and future scenarios, providing a structured process for translating an abstract vision into concrete product concepts (Figure 2). This method is particularly relevant for this project, which seeks to reframe physiological data and micro-behaviours from mere distractions into valuable signals for adaptive interaction. Within this project, tools such as the Future Cone were employed to explore multiple potential trajectories for the final product, encouraging designers to speculate across different layers of possible, probable, and preferable futures.

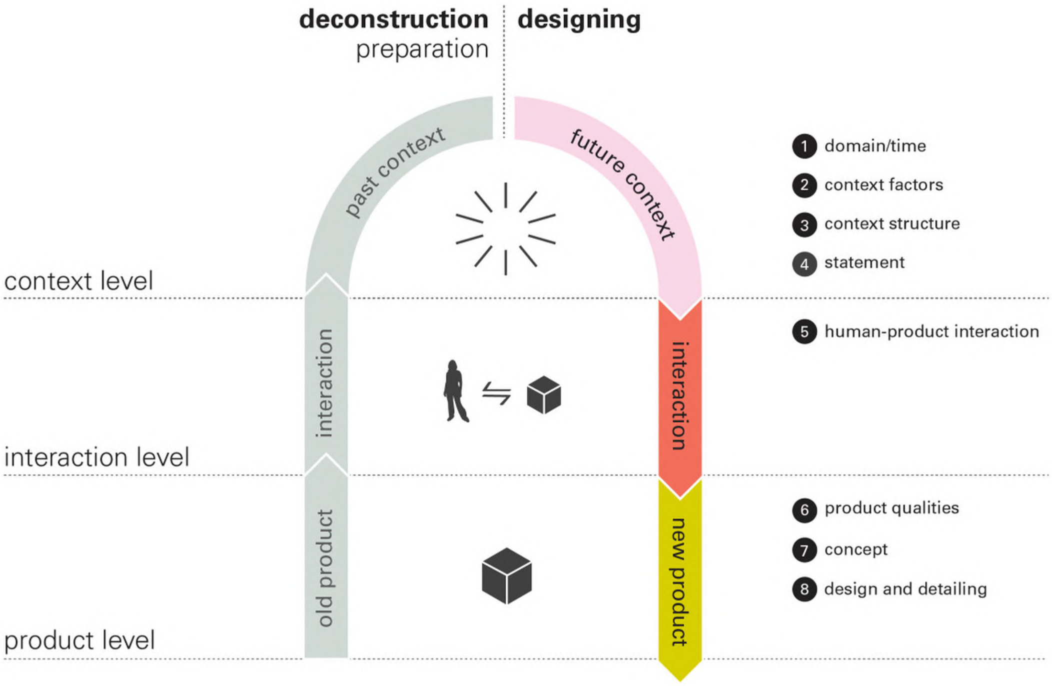


Figure 2. Steps of Vision in Product Design methodology (Hekkert & van Dijk, 2016)

Participatory Design has been selected to ensure that the perspectives, needs, and lived experiences of potential users are meaningfully integrated into the design process. By involving users and stakeholders directly (Muller & Kuhn, 1993), the project aims to co-create design opportunities that align with real contexts of work and attention regulation.

For example, a framework called Context4Change (Yu et al., 2025) demonstrates how participatory approaches can support the development of behavioural interventions that are context-driven and collaboratively validated, especially in office well-being and productivity domains.

By grounding the project in ViP’s structured and open-ended participatory design framework, the design process remains exploratory while ensuring conceptual coherence and alignment with the overarching vision of supporting sustainable focus at work.

2. Literature research

The overall goal of this chapter is to validate the adaptive multi-sensory design that can nudge for cognitive processes. This chapter reviews literature ranging from theories of attention in cognitive psychology to practical and experimental interventions designed to support cognitive activity. It begins by examining psychological models of focus and mind-wandering, followed by a discussion between typical individuals and those who experience more frequent difficulties with sustained attention. Emerging technologies are then reviewed to establish a foundation for later development. Finally, researches and design practices in multisensory interaction are presented to highlight their demonstrated efficacy in enhancing attention.

2.1 Cognitive background of attention

From the view in real life, desk work environments is a growing challenge due to constant distractions, cognitive overload, and mental fatigue (Lavie, 2005). Focus is not a static state but follows natural cycles, i.e. periods of intense concentration alternating with needed breaks, that vary by individual and context (Avila et al., 2019). Modern workflows and digital tools often disrupt these natural attention rhythms, making it harder to maintain productive focus (Mark et al., 2014). At the same time, individuals (especially those with attention deficits) struggle not only with staying on-task but also with initiating focus in the first place (Seli et al., 2015; Thomson et al., 2015; Barkley, 1997). To situate these challenges within a broader cognitive framework, it is necessary to examine how

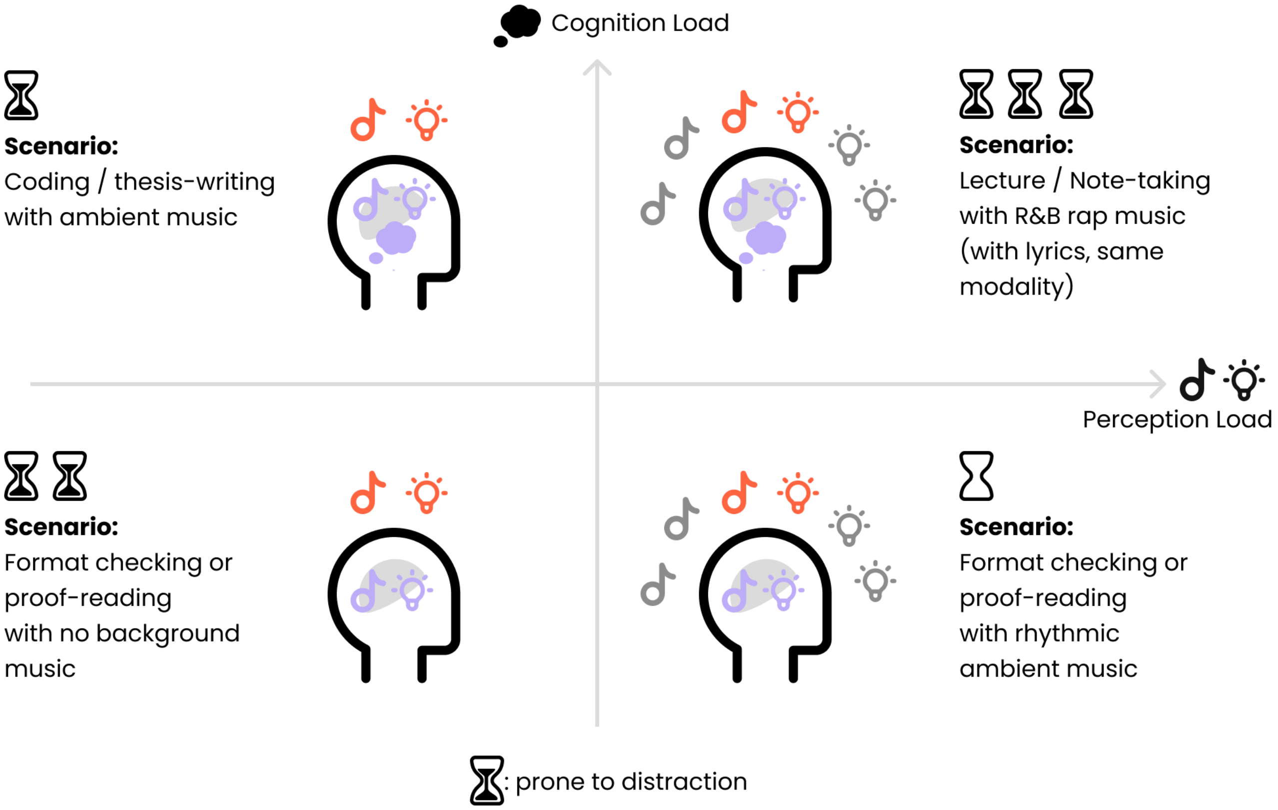


Figure 3. The vulnerability to distraction in different scenarios by Load Theory

attention is defined, the theoretical perspectives that inform its study, and the mechanisms by which cognitive load shapes the ability to sustain focus.

Definitions and theoretical perspectives

Focus can be defined as the selective concentration on task-relevant stimuli or information, while filtering out distractions (Logie, 2020). It is closely related to selective attention and relies on working memory and executive control to maintain goal-directed behaviour (Logie, 2020). Sustained attention (vigilance) refers to the ability to maintain focus over prolonged periods, which tends to wane as mental resources deplete (Logie, 2020). Executive function is the set of higher-order cognitive processes (planning, inhibitory control, task monitoring, and resistance to interference) that regulate attention and action (Barkley, 2001). According to cognitive load theory (Sweller et al., 2011; Lavie, 2010; Logie, 2020), human cognitive capacity is limited, and performance suffers when the mental workload exceeds those limits. Lavie's Load Theory refines the understanding by differentiating perceptual load (sensory complexity of the stimuli) and cognitive load (demands on working memory and control; Lavie et al., 2004; Lavie, 2010). A key finding from the theory is that high perceptual load can reduce distractibility by "using up" spare attentional capacity, whereas high cognitive load increases susceptibility to distraction by taxing executive control. In other words, when you are engaged in a very visually or sensorily rich task (high perceptual load), you are less likely to notice irrelevant distractions, but if your working memory is heavily burdened (high cognitive load), your mind's ability to suppress distractions is weakened (Figure 1-3). Subsequent research has qualified this theory by showing that the benefits of perceptual load only hold when cognitive load is low; under high cognitive strain, even a busy sensory environment won't prevent distraction (Logie, 2020). This interplay suggests that attention is governed by a limited shared resource, aligning with resource-control theories of sustained attention (Thomson et al., 2015). When that resource is drained (e.g. by difficult mental operations), attention drifts more easily, leading to lapses like mind-wandering (Thomson et al., 2015; Luna et al., 2022). This theoretical background informs my work by showing which cognitive mechanisms are most vulnerable to overload, thereby guiding how adaptive interventions, such as audio or lighting, can be designed to stabilize attention without adding to cognitive strain.

Cognitive mechanisms and load

Maintaining focus is also influenced by one's momentary cognitive state. Cognitive load (as described above) directly impacts attention: when working memory is overloaded, new information or even routine task steps cannot be processed properly, leading to errors or disengagement (Lavie, 2005). Interestingly, some design interventions leverage this relationship. For instance, adding mild sensory load (like background white noise or instrumental music) can occupy the part of perceptional attention that would otherwise wander, thereby keeping the person's main focus on track – but this only works if the secondary stimulus does not itself impose cognitive demands (e.g. lyrics or complex melodies might instead split attention; Logie, 2020). On the other hand, if one is already mentally fatigued or engaged in a heavy cognitive task, additional stimuli can become overloading and counterproductive (Logie, 2020). Thus, there is a delicate balance: an optimal level of arousal and stimulation can aid focus, but too much internal load or external distraction will tip the scales (as further explained in Figure 3). Therefore, any intervention must calibrate its sensory input to the user's cognitive context (we will revisit this point in multi-sensory design).

Procrastination, task avoidance, and related behaviours

Procrastination, the voluntary delay of intended tasks despite foreseeable negative consequences—is increasingly understood as a failure of self-regulation rooted in cognitive and emotional processes. A central contributor is mind-wandering, defined as the unintentional shift of attention from the task at hand to internally generated thoughts. While occasionally beneficial for creativity, mind-wandering is consistently associated with reduced performance on attention-demanding tasks (Randall et al., 2014). These lapses often arise from weakened executive control, allowing the brain's default mode network to override task-relevant goals (Smallwood & Schooler, 2013).

Mental fatigue is a state of diminished cognitive resources after prolonged effort exacerbating such lapses and leading to degraded sustained attention and increased susceptibility to distraction. Physiologically, fatigue is linked to reduced heart rate variability and impaired arousal regulation, compromising one's capacity to resist impulses and maintain task engagement.

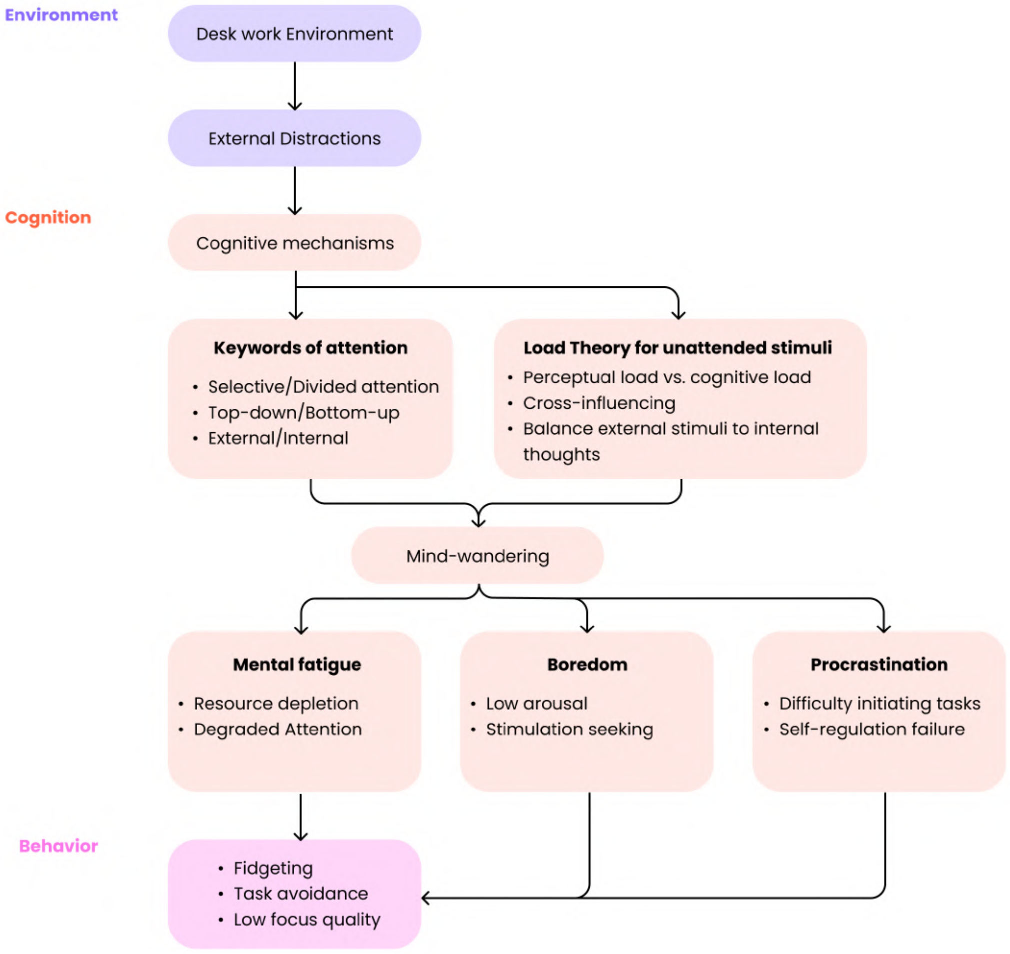


Figure 4. Graphical relationship of the attention-related concepts

Boredom similarly undermines focus. It is a low-arousal, aversive state marked by a drive to seek stimulation, often resulting in off-task behaviour (Danckert & Merrifield, 2018). Both boredom and fatigue can trigger fidgeting, which, rather than indicating distraction, may serve as a compensatory self-stimulation strategy. Small motor behaviours (e.g., pen tapping) may help maintain alertness in under-stimulating contexts (Carriere et al., 2013).

In contemporary digital work environments, external distractions compound these issues. Frequent notifications and multitasking demands fragment attention, producing "attention residue" and switch costs (Mark et al., 2014). Together, these internal and external factors create fertile ground for task avoidance, especially when tasks lack intrinsic interest or immediate reward. Figure 4 explains a graphical relationship of the concepts mentioned in this section.

2.2 ADHD

Attention Deficit/Hyperactivity Disorder (ADHD) is a neurodevelopmental condition typically characterised by patterns of inattention, hyperactivity (restlessness), and impulsivity that impair functioning across settings according to Diagnostic and Statistical Manual of Mental Disorders, 5th edition (DSM-5) by American Psychiatric Association (APA; 2013). Prevalence estimates vary by age and method, but childhood rates commonly fall in the 3–10% range and adult prevalence is commonly estimated around 4–6% in epidemiological studies (Patel et al., 2021). ADHD symptoms usually begin in childhood (before age 12 in DSM-5), and for many individuals symptoms persist into adolescence and adulthood; longitudinal work documents varied trajectories but substantial persistence for a sizable minority (Wender et al., 2001).

Clinically, ADHD has been described as consisting of three presentations: predominantly inattentive (ADHD-I), predominantly hyperactive-impulsive (ADHD-H), and combined presentation (ADHD-C; APA, 2013; Wender et al., 2001). Importantly, Barkley (1997) emphasised that what appears clinically as "inattention" often reflects failures of self-regulation and behavioral inhibition, which in turn produce secondary deficits in working memory, motivation/arousal regulation, internalized speech, and behavioral synthesis. In practice, many individuals with ADHD show context-dependent performance: periods of poor persistence on low-interest or delayed-reward tasks, and contrasting episodes of very strong focus (so-called hyperfocus) on stimulating, novel, or immediately rewarding activities (Barkley, 1997; Patel et al., 2021).

Behavioural challenges from executive dysfunction

Executive dysfunction is central: difficulties inhibiting distractions and impulses mean that even trivial cues (e.g., browser tabs, notifications) readily disrupt task engagement (Barkley, 2001). Tasks lacking immediate feedback or intrinsic interest are particularly challenging, often requiring external scaffolds such as body doubling or urgent deadlines. Adults may compensate with coping strategies, but this typically demands greater cognitive effort to sustain professional performance (Wender et al., 2001).

These impairments are closely linked to dysregulation of arousal, motivation, and affect, which underpin difficulties in sustaining effort for monotonous or delayed-reward tasks (Barkley, 1997; 2001). Individuals often resort to compensatory behaviours—fidgeting, novelty-seeking, or task-switching—as attempts to regulate arousal and maintain engagement (Sellier & Avnet, 2018). Such behaviours are not merely distractions but adaptive self-stimulation strategies that temporarily restore alertness. Research on boredom reinforces this interpretation: boredom, a low-arousal state common in ADHD, increases stimulation-seeking, with small repetitive actions (e.g., pen tapping, posture shifts) functioning as self-generated input that sustains alertness (Danckert & Merrifield, 2018; Carriere et al., 2013).

ADHD as a spectrum of attention regulation

An alternative framing views ADHD not as a single, unitary disorder but as a spectrum or set of dimensional markers of impairment in attention and/or impulsivity. The spectrum model emphasizes heterogeneity in symptom profiles, overlapping neurocognitive mechanisms, subthreshold presentations, and frequent comorbidity with other disorders; it therefore treats an index of attentional/impulsivity impairment as a marker that locates an individual on a broader continuum of related syndromes rather than as an endpoint label (Heidbreder, 2015).

This dimensional view has three practical consequences relevant to design and intervention. First, it explains why attentional capacity in ADHD is inconsistent rather than uniformly low: individuals show situational variability (poor persistence for boring/delayed tasks, intact or heightened focus for stimulating/novel tasks), which implicates regulation mechanisms more than a global attentional deficit (Barkley, 1997). Second, subclinical ADHD-like traits (e.g., spontaneous mind wandering, elevated response variability) are distributed across the general population, meaning that interventions tuned for ADHD can also benefit people who experience milder, situational attention failures (Seli et al., 2015). Third, the spectrum perspective foregrounds individualized profiling (which type of attentional/impulsivity difficulty is present and in which contexts), encouraging designers and clinicians to match support mechanisms (timing, salience, reward structure) to an individual's specific regulatory profile rather than only to a diagnostic label (Heidbreder, 2015).

Implications of spectrum view for design:

The spectrum-ADHD perspective emphasises behavior challenges rather than neural symptoms, which includes more scenarios even from normal people and daily life. It further argues for interventions that (a) detect when regulation fails (context- and state-sensitive sensing), (b) support momentary control through low-friction, timely nudges that respect variability in motivation and arousal, and (c) allow personalization so that support matches the user's regulatory profile (which tasks they find delay-averse, which reward structures engage them). In other words, sensor-driven, gentle nudges that adapt to momentary attention state are well aligned with a spectrum perspective because they work across severity levels and reflect the underlying regulation problem.

2.3 Contactless sensing for user state monitoring

Implementing real-time adaptive feedback requires the continuous monitoring of a user's cognitive or physiological state. In the context of workplace well-being interventions, this involves detecting indicators of distraction, restlessness, or fatigue without disrupting the user's activity. Contactless sensing technologies offer an unobtrusive means to achieve this, avoiding the compliance and comfort issues often associated with wearable sensors.

Rationale

Contactless techniques are particularly advantageous in scenarios where long-term, unobtrusive monitoring is required, such as office work. Compared to contact-based methods (e.g., chest straps, wristbands), contactless sensors avoid skin contact, reduce user burden, and can operate seamlessly in the background. As highlighted by Massaroni et al. (2021), contactless approaches are also preferred when privacy, hygiene, or minimal interference with task performance are priorities. They have been successfully deployed in healthcare, automotive, and occupational settings to detect physiological signals such as respiratory rate (fR), heart rate, and gross movement patterns (Massaroni et al., 2021).

Comparison of available contactless approaches

Several contactless sensing technologies are available for physiological and behavioural monitoring. Each technology differs in its sensing modality, environmental robustness, and privacy profile:

1. Optical methods (e.g., RGB cameras) can track subtle facial perfusion changes, but are sensitive to lighting conditions and raise privacy concerns due to image capture. It also requires computer vision capability to distinguish target zones, which is heavy-loaded for simple embedded systems.
2. Acoustic methods (e.g., microphones) can detect breathing patterns but are susceptible to environmental noise and speech interference.
3. Thermal cameras can detect air temperature variations between inhaling and exhaling, but tend to be expensive and require a stable thermal environment.
4. Radio-frequency (RF)-based methods, including Wi-Fi, ultra-wide band (UWB) radar, and mm-wave radar, offer robust sensing without direct contact or identifiable imagery. RF sensors are capable of penetrating clothing and operating in low-light or visually occluded conditions.

Methods	Deployment Requirements	Machine Learning for robust signal extraction	Privacy Concern (Risk of Unauthorised Access)
RGB Camera	Positioned facing user; adequate ambient lighting required	Convolutional Neural Networks (CNN)	High – captures personally identifiable information (PII)
Microphone	Placed in proximity to user	Support Vector Machine (SVM)	High – risk of eavesdropping and sensitive audio capture
Thermal camera	Oriented toward nasal or facial area	Optional	Medium – reveals physiological patterns (e.g., temperature)
RF-based radar	Positioned toward chest or torso region	Optional	Low – minimal risk; no identifiable image or audio data

Table 1. Comparison of Contactless Sensing Methods

Justification for mm-wave radar

RF stood out in the comparison with its counterparts as shown in Table 1. And among RF-based technologies, mm-wave radar is selected in this project because it offers a combination of spatial resolution, privacy protection, and robustness to environmental variation that aligns with the project's requirements.

Mm-wave radar operates at 24–300 GHz, enabling the detection of fine-grained physiological signals. The short wavelength allows for high-resolution measurement of micro-motions such as chest expansion during breathing and pulses per minute from heartbeats (Soumya et al., 2023). Unlike optical or acoustic sensors, mm-wave radar produces only Doppler or range profiles, which cannot reconstruct a person's identity or speech, which proves to be a privacy-preserving method (Dang et al., 2022).

From a usability perspective, mm-wave radar modules are compact and can be discreetly embedded in office equipment (e.g., monitor bezels, desk devices), supporting continuous monitoring without user awareness or active engagement. The technology functions in darkness, is unaffected by normal office clothing, and operates across variable environmental conditions.

Additionally, research has demonstrated the reliability of mm-wave radar for vital sign monitoring under realistic conditions. For example, van Loon et al. (2016) validated a Frequency-Modulated Continuous Wave (FMCW) radar for continuous respiratory monitoring in postoperative patients, showing close agreement with clinical reference instruments. Studies have also indicated that mm-wave radar can distinguish between presence, stillness, and fidgeting, enabling inference of attention or restlessness levels (Song et al., 2023; Dang et al., 2022; Wang et al., 2020; Imran et al., 2024). With machine learning models, it can also classify gestures or micro-movements, adding potential development touchpoint for interaction. The project Soli by Google presented a robust method to identify hand gestures like signs, actions, and symbolic movements using radar-based motion sensing (Lien et al., 2016). This result was also applied on Google's Pixel 4 phone.

Limitations

Despite these advantages, mm-wave radar also faces limitations compared to contact-based wearables. Wearables, like electro-encephalography (ECG), photoplethysmography (PPG), and accelerometry, continuously capture richer, multi-channel data streams while radar signals are more sensitive to noise and yield weaker robustness under complex movements. Accuracy often decreases when users move abruptly or leave the sensing zone, leading to invalid waveforms. Current research addresses this by combining radar with machine learning models to classify valid versus invalid signals and to compensate for noise (e.g., through neural-network-based filtering and recognition methods), but the challenge of achieving wearable-level reliability remains (Soumya et al., 2023; Dang et al., 2022). These limitations highlight the importance of designing filtering methods and adaptive algorithms in my work, so that radar-based monitoring remains practical even in naturalistic, movement-rich office environments.

2.4 Multi-sensory design

Human cognition is profoundly influenced by sensory input. Our brains continuously integrate sights, sounds, touch, and other sensory signals, which together shape our level of alertness, mood, and attention (Hecht et al., 2008). Multisensory design seeks to leverage this by engaging multiple senses in a coordinated way to achieve a particular cognitive or emotional effect (Spence, 2020). In the context of focus and attention modulation, multisensory interventions might include combinations of ambient lighting, soundscapes, and tactile feedback deliberately crafted to either heighten concentration or encourage timely breaks (Ranne, 2019). This section outlines the theoretical basis for multisensory effects and reviews how auditory, visual, and tactile stimuli have been used to influence attention.

BrightBeat (Ghandeharioun & Picard, 2017), a research prototype from MIT Media Lab, is designed to influence users' breathing rhythms through unobtrusive visual, auditory, and optional thermal feedback that mimics a calm breathing oscillation. In a randomized placebo-controlled trial (N = 32), BrightBeat significantly slowed breathing, improved self-reported calmness and focus, and was rated highly for future use. The interventions are tuned to the user's goal breathing rate (GBR), subtly nudging respiratory pace to shift users into a more regulated, engaged cognitive state without demanding conscious effort.

Endel is a digital soundscape platform that automatically generates adaptive music tailored to specific activities such as working, sleeping, or relaxing (Figure 5). Endel leverages the insights of preferred music: by allowing users to choose familiar, personally meaningful music, it supports intermediate arousal levels that are conducive to steady concentration, mirroring the psychological mechanism observed in the study.

As part of the research listed by Endel, Kiss and Linnell (2021) demonstrated that self-selected or preferred music significantly increases the proportion of task-focus states while reducing mind wandering during a sustained attention task, although it did not significantly change reaction times or external distraction states.

Aqara is a smart home appliance manufacturer and launched this human presence sensor (Figure 6) with mm-wave radar, capable of distinguishing 5 people maximum in room. This sensor could identify multiple home scenarios like presence or falling detection, and thus enabling automation over other actuators like lighting or alarms. However, it cannot provide realtime feedback of focus status with sensory cues.

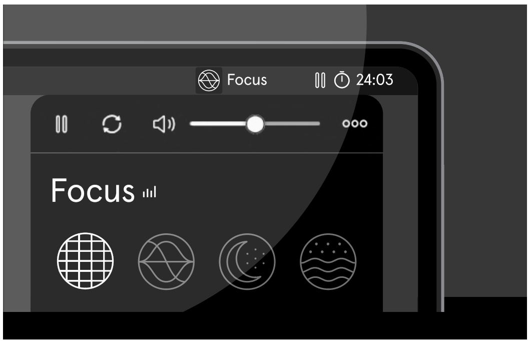


Figure 5. Endel App Demo from endel.io

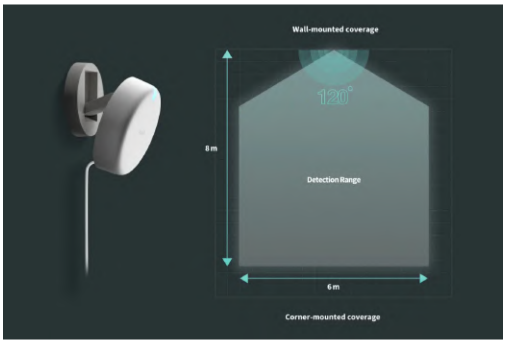


Figure 6. Aqara FP2 Presence Sensor from aqara.com

2.5 Synthesis and research gaps

Integrating insights from cognitive science, neurodiversity, sensing, and multisensory design points to intelligent workstations that adaptively scaffold focus. Such systems would infer attentional state and deliver proportionate cues—subtle sound, light, or haptics—to stabilize engagement. Yet the literature indicates key obstacles.

Chief among them is the scarcity of closed-loop implementations: most current tools are open-loop, offering static soundscapes or timers without real-time sensing and adaptation. Early demonstrations that couple physiological signals to feedback (e.g., radar-derived concentration indices or music modulated by breathing) remain proof-of-concept; rigorous, in-the-wild evaluations are needed to determine how much adaptivity improves focus without producing annoyance. Anecdotally, users tolerate gentle ambient shifts, but reject frequent or conspicuous prompts.

Privacy and social acceptance constitute a second constraint. Contactless radar reduces risks associated with imaging, yet continuous monitoring raises concerns about scope, access, and unintended use (e.g., managerial surveillance). Clear communication about data minimization and on-device processing, user control over sensing and interventions, and designs that localize cues to the individual are prerequisites for acceptance, particularly in shared offices. Practical issues—multi-user interference, conflicting interventions—also require empirical study; for example, two adjacent desks running concurrent systems may produce overlapping cues even when each is modest alone.

A third gap concerns efficacy. Evidence for multisensory nudges is suggestive but fragmented across domains (e.g., procrastination, mood, biofeedback). What is lacking are longitudinal field trials comparing adaptive multisensory systems with static or no-intervention baselines on objective outcomes (task completion, interruption rates) and subjective outcomes (perceived control, stress). Subgroup analyses are particularly important for users with ADHD, for whom short, frequent feedback and immediate reinforcement may be decisive. Additionally, robustness of sensing also challenges the industry in terms of signal processing and machine learning methods. False positives or negatives are inevitable especially in dynamic scenarios. This could be one of the reasons that future Google Pixel phones no longer equip mm-wave radar.

In response, this project will develop and iteratively evaluate a privacy-preserving, radar-informed prototype that delivers adaptive sensory feedback guided by psychological models and user preferences. The emphasis is on user agency, transparency, and everyday usability. The aim is not to eliminate mind-wandering or breaks—both are adaptive—but to scaffold self-regulation so attention aligns with goals and well-being. Anecdotally, such systems can function as a quiet environmental coach: easing task initiation, prompting restorative pauses, and ultimately supporting productive work with reduced strain.

3. Concept research

3.1 Introduction

The development of Halfmind Flow followed an integrated, research-driven design methodology that centres real user experiences, emotional behaviour patterns, and context-sensitive intervention opportunities. To ensure the concept was grounded in both lived realities and design rigour, the entire process was shaped by a participatory approach inspired by the Context4Change (C4C) framework (Yu et al., 2025), which emphasises contextual reflection, behavioural insight, collaborative ideation and prototyping throughout the design process (Figure 7). The complete record of C4C workshop was logged in Appendix B.

Four people, referred to as the Designer Group (Figure 8, right), played key roles throughout the research and development process. The facilitator (also the author of C4C) was responsible for guiding discussions and synthesising outcomes across all phases. Two designers (the author and a peer designer) were responsible for translating research insights into core content, speculative directions, and interface concepts. The fourth team

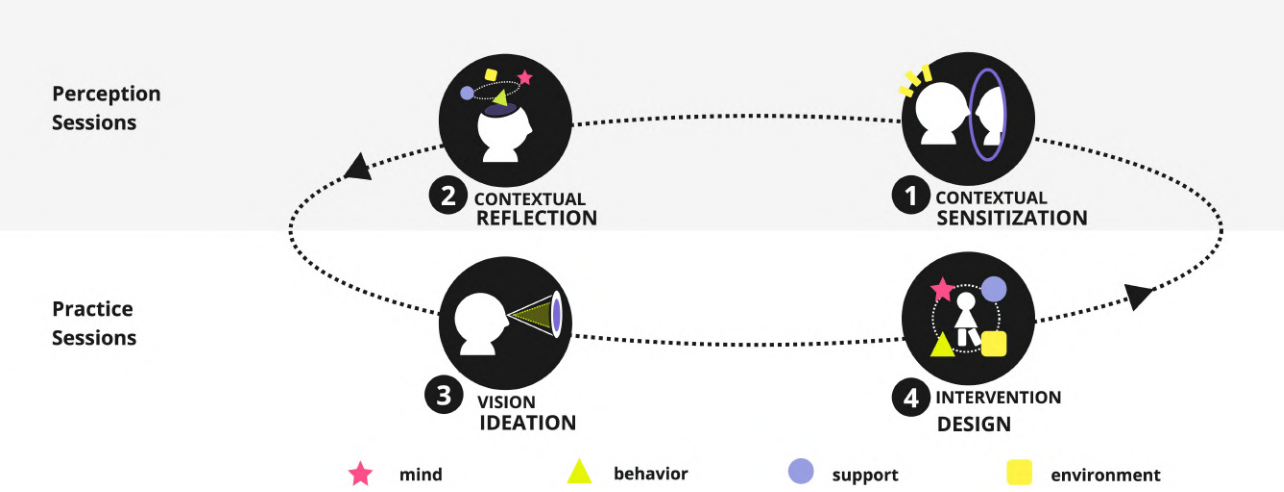
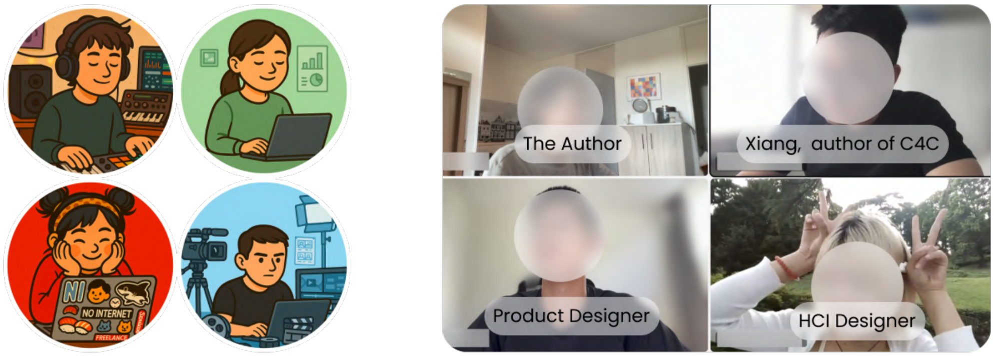


Figure 7. Four sessions of Context4Change (C4C) framework (Yu et al., 2025)



Participants of Perception Sessions (various occupations)

Participants of Practice Sessions (Designer Group)

Figure 8. Participants from Perception Sessions were potential users from various occupations, while the Designer Group were skilled in design.

member was a co-designer, a master's student in interaction design who also represented a potential user. Positioned between participant and contributor, the co-designer played a vital role in grounding concept development through lived experience, offering critiques, validating ideas, and generating alternatives.

The process began with the Perception Sessions, which focused on understanding users' everyday struggles with task initiation and focus within freelance and flexible work contexts. Semi-structured interviews were conducted to examine how emotional readiness, environmental cues, and motivational patterns affect work behaviours. Based on the qualitative data, we developed a two-axis classification framework to synthesise recurring patterns. This framework clarified the diverse frictions users experience at the threshold of starting tasks and informed subsequent design strategies.

The Practice phase followed, consisting of participatory design sessions involving the Design Group. Rather than running as a singular workshop, this phase unfolded as an iterative and collaborative progression. Drawing on the user typology developed earlier, the team engaged in contextual storytelling, future cone visioning, and early prototyping exercises. These sessions were guided by emotionally resonant "intervention moments" identified during the user study, where participants expressed being mentally prepared but unable to act. Through reflective dialogue and scenario co-creation, the team envisioned speculative interventions designed to gently support users through that fragile threshold between intention and engagement.

This chapter details the evolution of Halfmind Flow from contextual understanding to concept realisation. The following sections will describe each phase of the process, highlight the collaborative dynamics among the four team members, and illustrate how behavioural and emotional complexity was translated into design interventions.

3.2 User scenario

The user study investigates the emotional and behavioural challenges faced by emerging adults navigating freelance and remote work environments. Through in-depth interviews with 4 participants across creative and analytical fields, we explored how individuals initiate tasks, maintain focus, and construct personalised routines in the absence of formal (office) structure.

We developed a two-axis framework from observation of users that classifies them based on motivational orientation (efficiency-driven vs. quality-driven), and operational mode (self-initiated vs. externally structured). This framework was inspired by the co-designer's observation and the scheduling habits revealed by Sellier & Avnet (2019). It revealed key frictions unique to each quadrant, from emotional inertia and spatial instability to over-scheduling and lack of feedback. Regardless of background, all participants described a persistent need for emotional readiness, embodied cues, and non-intrusive support to help them begin tasks.

Research objective and methodology

To ground the design of Halfmind Flow in real user needs, the author conducted a qualitative user study focused on understanding how emerging adults navigate flexible or self-directed work modes, particularly in relation to task initiation and attention regulation. The core objective was to explore how individuals construct their own work rhythms in the absence of external structure, and to identify the psychological frictions that occur at the threshold between intention and action - what we define as the moment of “almost starting.”

The study recruited four participants aged between 24 and 30, all of whom currently operate in freelance, remote, or project-based work settings. We selected participants who varied in professional domain, level of autonomy, and emotional relationship to their work, in order to capture a broad spectrum of self-established routines and motivational patterns. All interviews were conducted remotely using a semi-structured format, followed by visual mapping and persona construction to synthesise insights. During the sessions, participants were encouraged to reflect on their typical workdays, challenges with focus and motivation, workspace setups, emotional states, and personal coping strategies. After the interviews, data were thematically coded in Miro, and participant narratives were compared and analysed using a two-axis classification framework, detailed below.

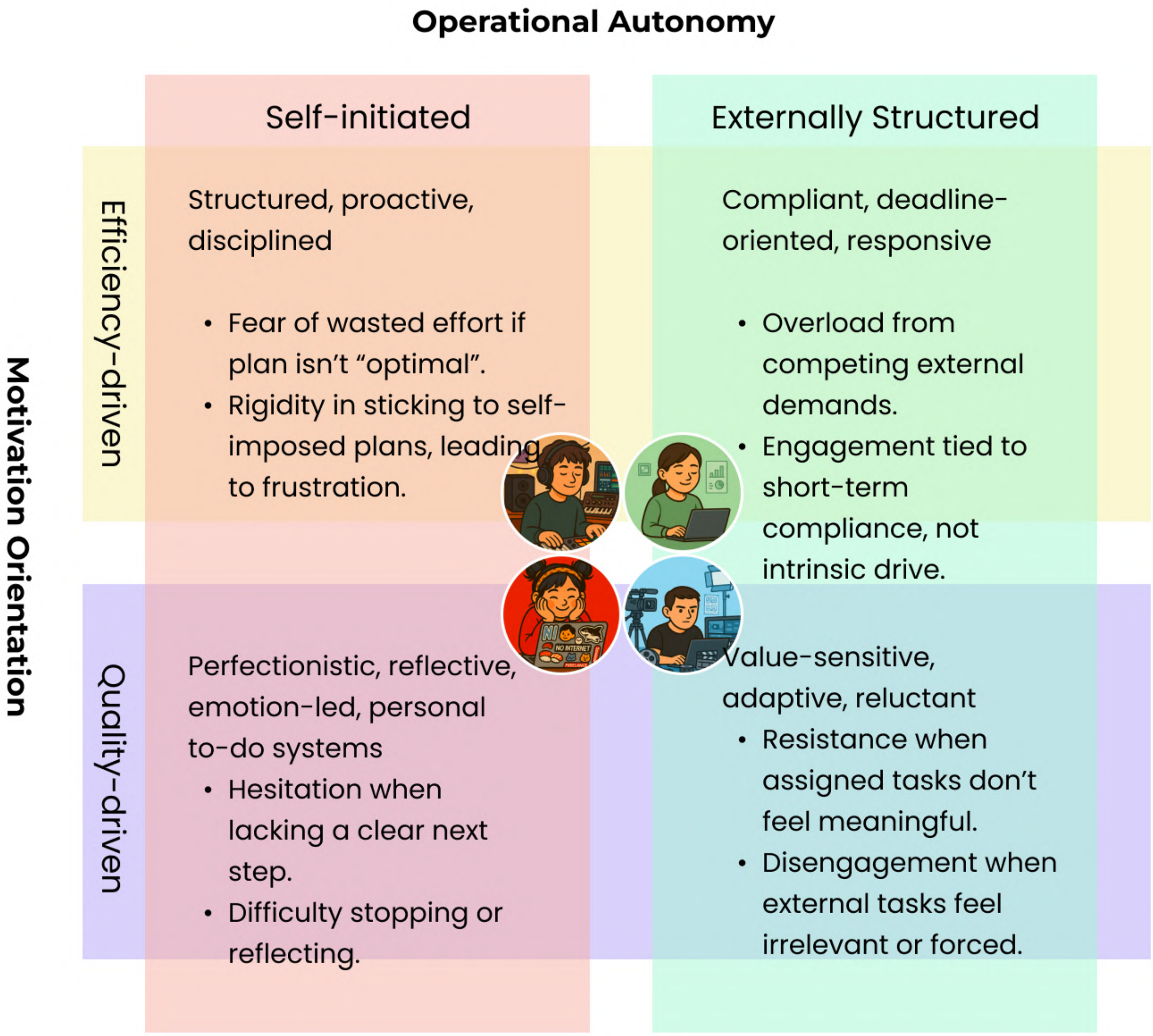
Two-Axis framework for behavioural mapping

Following the user interviews, it became clear that participants’ task initiation challenges were not solely dependent on their profession or environment but rather stemmed from the interplay between two behavioural dimensions: motivational orientation and operational autonomy. While analysing early narratives, the co-designer noted recurring tensions that appeared to cluster along these two axes. Drawing from their own experience and the observed participant behaviours, they informally proposed an initial two-dimensional typology to distinguish between quality-driven vs. efficiency-driven motivations and self-initiated vs. externally structured modes of operation (Figure 9).

This proposition was critically reflected upon during synthesis and later substantiated through patterns observed in the broader interview data. To further validate its relevance, we aligned this emergent framework with existing research on scheduling styles and self-regulation strategies, particularly the distinctions outlined by Sellier and Avnet (2018). Their work demonstrates that people approach time and task management through either event-time (internally driven, flexible) or clock-time (externally imposed, structured) scheduling lenses, each corresponding to distinct motivational schemas and regulatory modes. This alignment strengthened the theoretical validity of the framework and helped to map participant behaviours within an established psychological model.

In our adaptation, the first axis, motivational orientation, ranges from quality-driven to efficiency-driven. This axis describes whether individuals are primarily guided by efficiency (progress and deliverables) or by quality (emotional alignment and meaningful output). Efficiency-driven participants prioritise deadlines, deliverables, and structured progress, often pushing through regardless of emotional readiness. In contrast, quality-driven individuals emphasise emotional alignment, meaning-making, and inspiration. They tended to delay task initiation until internal conditions felt “right.”

The second axis, operational mode, describes the degree to which participants initiated and structured their work routines independently. On one end, self-initiated individuals designed personalised workflows and environments, frequently experimenting with strategies to optimise engagement. On the other, externally structured individuals operated within constraints set by employers, clients, or shared environments, often reacting to external demands rather than proactively shaping their routines.



Structured, proactive, disciplined

- Fear of wasted effort if plan isn’t “optimal”.
- Rigidity in sticking to self-imposed plans, leading to frustration.

Compliant, deadline-oriented, responsive

- Overload from competing external demands.
- Engagement tied to short-term compliance, not intrinsic drive.

Perfectionistic, reflective, emotion-led, personal to-do systems

- Hesitation when lacking a clear next step.
- Difficulty stopping or reflecting.

Value-sensitive, adaptive, reluctant

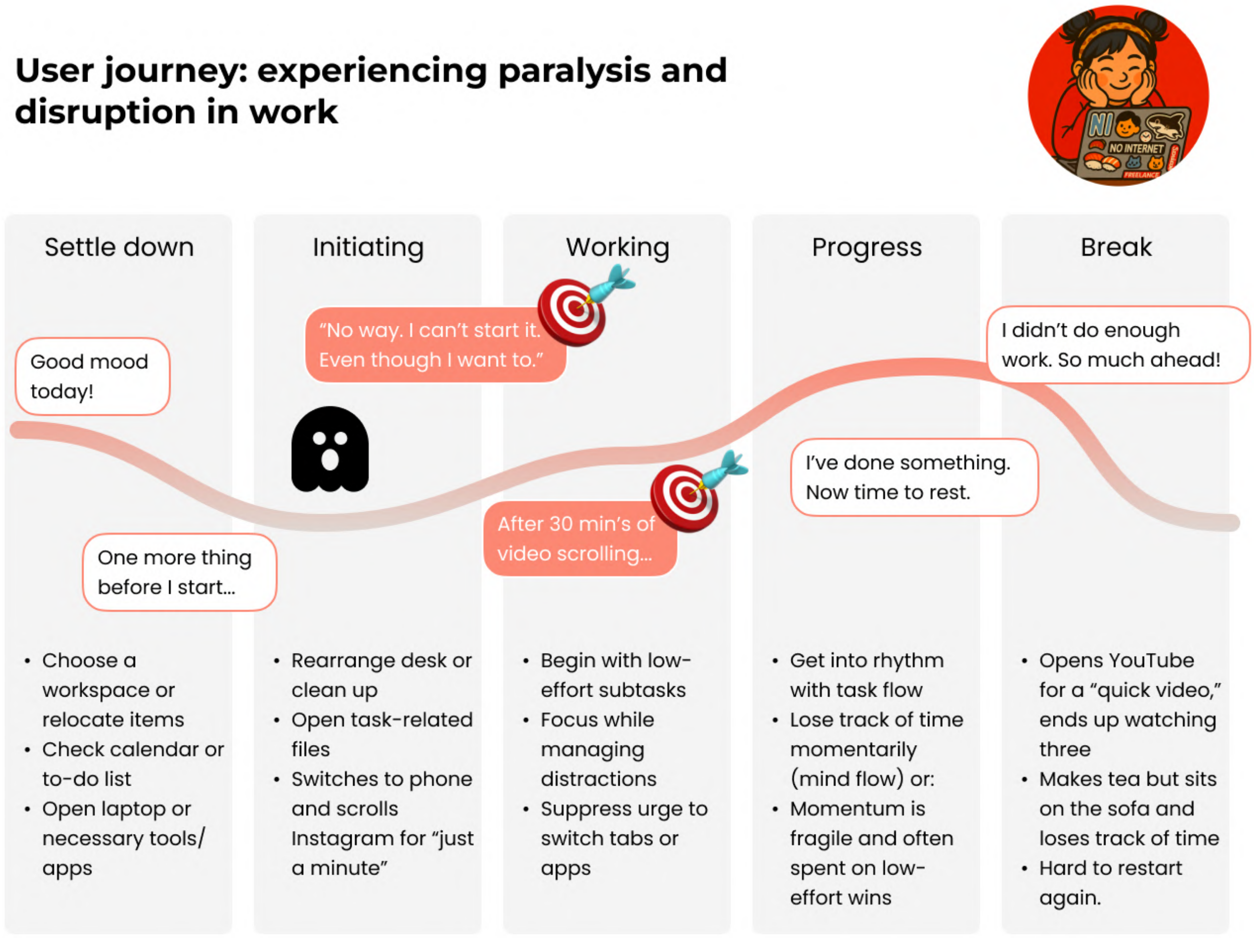
- Resistance when assigned tasks don’t feel meaningful.
- Disengagement when external tasks feel irrelevant or forced.

Figure 9. Two-Axis Framework for Behavioural Mapping, showing persona traits and challenges in task initiation and focus in work.

Participant narratives and insights

The participants represented a diverse range of motivational orientations and operational modes within freelance or remote work environments. This diversity allowed the research team to map emerging behavioural patterns across the two-axis framework described earlier. While each participant provided valuable insight into how individuals navigate the emotional and cognitive demands of self-structured work, Ricky’s case was selected for further focus due to the recurring overlap between her behavioural patterns and those commonly associated with adults diagnosed with ADHD.

Ricky, a 29-year-old media freelancer, emerged as a key representative of those who are quality-driven yet internally structured. Although passionate about creative work such as copywriting, video editing, and podcasting, she frequently found herself stalled by emotional inertia and environmental instability. With ADHD and having challenges to work on a fixed desk, she experimented with various makeshift workstations, but struggled to sustain focus. Her challenges were compounded by an internal demand for emotional alignment before initiating tasks. Ricky described entire mornings lost to mental paralysis,



Settle down
- Choose a workspace or relocate items
- Check calendar or to-do list
- Open laptop or necessary tools/apps

Initiating
- Rearrange desk or clean up
- Open task-related files
- Switches to phone and scrolls Instagram for "just a minute"

Working
- Begin with low-effort subtasks
- Focus while managing distractions
- Suppress urge to switch tabs or apps

Progress
- Get into rhythm with task flow
- Lose track of time momentarily (mind flow) or:
- Momentum is fragile and often spent on low-effort wins

Break
- Opens YouTube for a "quick video," ends up watching three
- Makes tea but sits on the sofa and loses track of time
- Hard to restart again.

Figure 10. Pain points embodied on user journey map.

despite the approaching of an explicit deadline. She expressed a desire for tools that could gently shift her emotional state or provide non-intrusive cues to help her enter the working mindset.

LimLim, a 28-year-old music producer, exemplified the efficiency-driven and self-initiated quadrant. Her creative process depended on mood, energy, and inspiration, and she intentionally avoided rigid scheduling in order to protect her artistic spontaneity. However, this approach left her vulnerable to irregular sleep patterns, inconsistent momentum, and periods of avoidance. She reported that emotional buildup often prevented her from starting projects, and she experimented with spatial adjustments, ambient music, and creative rituals as coping strategies.

Dave, a 30-year-old freelance film director, was situated in the quality-driven and externally-structured quadrant. Navigating among multiple large-scale projects, he had developed a structured but flexible system for managing fluctuating workloads. He emphasized the importance of outcome orientation and deliverables, and while he faced similar interruptions in workflow, his systems for accountability and progress tracking helped buffer against major delays.

Nicole, a 27-year-old remote data analyst, belonged to the efficiency-driven and externally structured quadrant. Working for an international company with fixed hours, she benefitted from stability but experienced exhaustion from continuous screen exposure and the absence of in-person social cues. Despite clear expectations, she noted a gradual erosion of motivation over time, especially in the absence of embodied breaks or varied stimuli in her daily routine.

Across these diverse cases, common patterns began to emerge (Figure 10). All participants experienced varying degrees of emotional fatigue, difficulty transitioning into focused states, and a lack of consistent environmental or social anchors. For those without fixed schedules, the moment between intention and execution—the cognitive limbo where tasks are acknowledged but not begun—was often the most psychologically taxing. Many attempted self-regulation strategies, including space-switching, environmental redesign, music-based mood regulation, and accountability journaling. Yet few found a sustainable solution that worked across all contexts.

Implications for design

Ricky's narrative illustrates how the struggle often begins at the threshold of work: the moment of initiation. Her motivation and emotion dropped most when she realized little could be done to break her paralysed state, and with only trivial progress she tended to seek premature breaks, later regretted. Similar themes were echoed across other participants, albeit in different forms.

Taken together, the user study suggests that for many participants the core challenge was not a lack of skill or time, but the difficulty of transitioning from intention to action. This was most acute during emotionally low or unstructured periods, when conventional time management tools proved insufficient. Participants frequently described resistance that felt emotional rather than logical—expressed as being 'off,' 'not in the mood,' or 'stuck in a fog' (Ricky, LimLim). Rather than tighter schedules or more rigid systems, what they sought were gentle, adaptive forms of support that could align with emotional readiness, signal rhythm, and reframe the first step of work as engagement rather than performance.

3.3 Multi-sensory concept exploration

The product concept of multi-sensory experience was proposed as the second phase, Practice Sessions in C4C.

In the Vision Ideation session, Future Cone, a method developed and refined by Hancock & Bezold (2020) was used to speculate future possibilities of user's ultimate experience of focus in work, as shown in Figure 11. Then, a brainstorming session among the Designer Group was conducted by the concept rotation method, where designers extend the idea from previous one to generate new concepts, and pass it on to the next participant. The form of the product and therefore the multi-sensory experience were hence proposed and prototyped to try out the user's preference. Generative artificial intelligence (Gen AI) was used to facilitate participants to diversify and visualise ideas.

Three concepts of metaphor were selected among proposed possibilities from the observed needs of persona during work: the Energy Crystal, the Rhythm Hitchhiker, and the Flow Portal.

The Energy Crystal embodies the idea that personal energy is a valuable and limited resource, much like a precious gem. In modern work-from-home environments, invisible fatigue often builds unnoticed due to the absence of immediate physical signals, social cues, or dedicated rest spaces. The Energy Crystal visualises the user's well-being energy

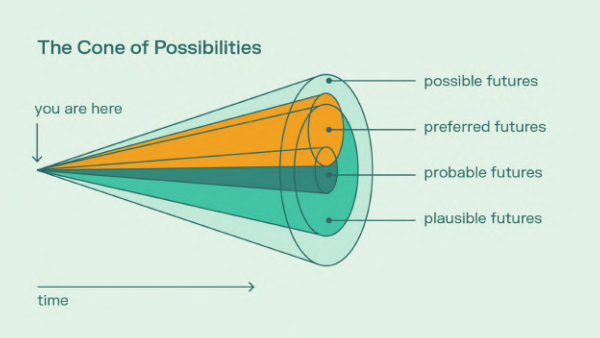


Figure 11. Future Cone explains future outcomes as possible, preferred, probable and plausible futures (Hancock & Bezold, 2020).

in real time, creating a gentle, ambient reminder to pause, recharge, and protect one's health. Placed in a dedicated "third space" within the home, and supported by multisensory feedback (light, texture, biofeedback), it serves as both a symbolic and functional anchor for energy self-awareness, encouraging sustainable focus without hidden over-exertion.

Its multi-sensory expression could include gradual changes in on-device lighting intensity and colour temperature: cool white when energy is high, soft amber as it drops. In the dedicated "third space" where it is placed, the Energy Crystal might pair light cues with a sonic palette of calm textures (soft harmonic pads, gentle bell-like tones) that evolve slowly over time, creating an atmosphere conducive to restoration. Tactile cues, such as a rug or surface that responds subtly to touch or weight, can further anchor the user's attention back to their body, enhancing self-awareness and prompting restorative action.

Due to limitations in radar recognition accuracy, the sensor must be positioned in a fixed location above the computer screen to reliably capture user presence and physiological signals. This placement constrains opportunities for direct tactile interaction. As a result, the initial concept of integrating texture-based haptic feedback was removed from the current iteration. However, the approach remains technically feasible and could be reintroduced in future versions by pairing the system with a remotely controlled switch, allowing texture changes to be actuated independently of the radar's fixed position.

The Rhythm Hitchhiker concept draws on the metaphor of merging into a highway stream: joining a collective rhythm helps individuals accelerate into and sustain productive pace. In this envisioned future scenario, the user connects to a community or environment where a shared working rhythm is promoted—much like syncing to the energy of a music festival or a shared brainstorm session. This shared rhythm functions as both a motivational driver and a structural scaffold for maintaining momentum, allowing individuals to "hitchhike" on the collective pace rather than relying solely on personal discipline.

Its multi-sensory form could be realised through dynamic lighting pulses—low to moderate brightness that subtly "breathes" in sync with the shared tempo—alongside an auditory layer that reflects the group's collective pace. Upbeat but non-distracting music genres (e.g., lo-fi beats, minimal house, or polyrhythmic percussion) could sustain momentum, with tempo gently increasing during ramp-up phases and settling into a stable groove during sustained focus. Scenario setups could involve virtual co-working environments or shared playlists that reinforce the sense of being “in the flow” together, even when working apart. A generative drum-beat system was developed to simulate a highway-tempo.

The Flow Portal creates a smooth passage between different mental states, allowing the user to move effortlessly from one mode of work to another. Whether shifting from high-energy collaboration to quiet creative immersion, or from structured thinking to restorative pause, the transition feels intuitive and fluid.

Crossing the “portal” could be accompanied by a gradual shift in environmental cues: lighting smoothly changes hue and intensity to match the desired mental mode—brighter, cooler tones for active collaboration; softer, warmer tones for reflective work. Sound design can reinforce the passage: an ambient transition soundscape, such as a rising pad or dissolving harmonic layer, signals departure from one mode, while the arrival space is characterised by music or environmental sound tailored to the new activity. Scenario setups might include a dedicated work zone that transforms visually and sonically with each transition, making the act of passing through the “portal” a distinct sensory ritual that prepares the mind for its next phase.

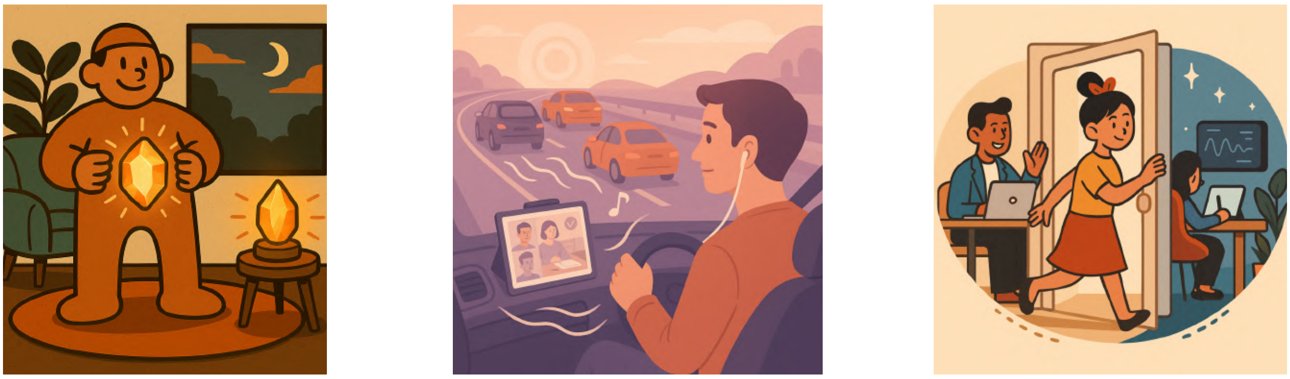


Figure 12. Illustration of Energy Crystal, Rhythm Hitchhiker & Flow Portal, by ChatGPT

Concept selection

The concept development process culminated in the evaluation of three metaphor-based design directions—Energy Crystal, Rhythm Hitchhiker, and Flow Portal (Figure 12)—each responding to a shared psychological threshold identified in the user study: the liminal state of “almost starting”, in which users recognised the need to begin a task but struggled to transition into action. While all three concepts addressed this moment of inertia, they did so through distinct interpretive lenses: Energy Crystal emphasised inner emotional awareness, Rhythm Hitchhiker foregrounded social momentum and synchrony, and Flow Portal focused on cognitive transitions between modes of work.

The selection was guided by a set of criteria as explored above. Specifically, the concepts were assessed for:

1. Emotional resonance, particularly in relation to users’ self-described emotional states during task initiation;
2. Compatibility with radar-based contactless sensing, a central constraint and opportunity within the proposed system;

3. Multi-sensory integration potential, supporting embodied interaction through visual, auditory, or tactile feedback;
4. Adaptability across behavioural profiles, as defined by the two-axis motivational–structural framework developed during user synthesis.

Among the three, the Energy Crystal emerged as the most integrative and versatile concept. Its central metaphor, treating personal well-being as a visible, finite energy resource, offered both symbolic clarity and functional relevance. Participants such as Ricky and LimLim, who exhibited quality-driven but emotionally variable work patterns, often described feeling unable to begin tasks until a subjective sense of emotional readiness was achieved. The Energy Crystal directly addressed this condition by externalising internal states through ambient, non-intrusive feedback. In doing so, it helped reframe readiness not as a binary condition, but as a gradually shifting state that could be acknowledged and gently influenced without demanding active engagement from the user.

From a technical standpoint, the Energy Crystal aligns well with the affordances and constraints of contactless radar sensing. Given the sensor's fixed position above the screen and its limited capacity for precise touch-based interaction, concepts that relied on embodied proximity or spatial movement (e.g., Flow Portal) were less feasible. The Energy Crystal, by contrast, capitalised on passive sensing and conveyed feedback through gradual transformations in light and sound, both of which could be perceived peripherally and tailored to the user's state. The symbolic form of a "crystal" further lent itself to multi-sensory augmentation, with potential for subtle shifts in colour temperature, harmonic audio textures, and, in future iterations, surface tactility.

While Rhythm Hitchhiker presented a compelling model for co-regulated motivation, particularly resonant with the concept of body doubling often observed in ADHD communities, its dependence on synchronous social rhythms limited its generalisability. Participants in the study frequently lacked stable social work structures, making such forms of coordination difficult to sustain. Similarly, Flow Portal introduced a valuable notion of facilitating mental mode transitions, especially between active and restorative states. However, it implied a degree of spatial segmentation and cognitive intentionality that did not consistently align with the fragmented and mobile work routines reported by participants.

In summary, the Energy Crystal was selected not only for its symbolic and emotional coherence but also for its ecological validity, its technical viability, and its interpretive flexibility across diverse user profiles. It provides a means of re-engaging focus without enforcing productivity, acknowledging the complex affective landscape of remote and freelance work while offering a tangible interface to support sustained attention. It stands as a promising foundation for developing a multi-sensory system attuned to the emotional rhythms of independent workers navigating the threshold between intention and action.

4. Concept presentation

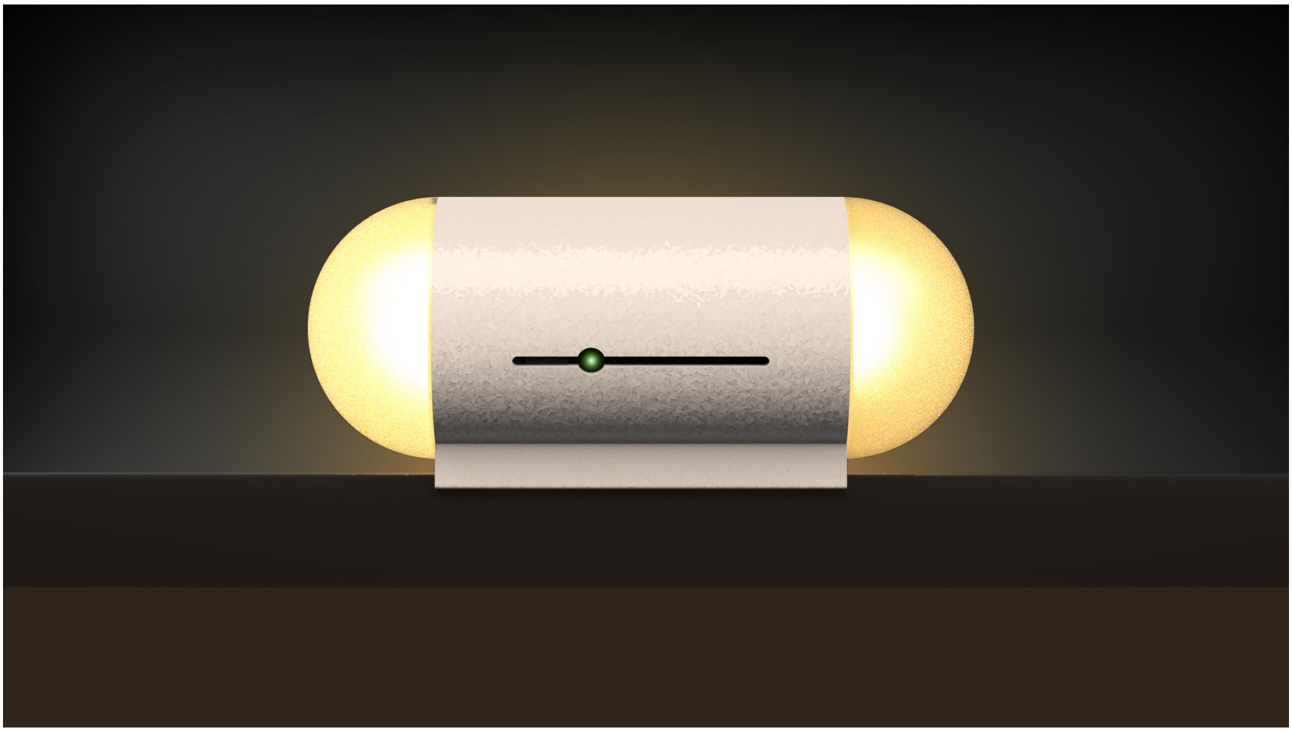


Figure 13. Rendered image of the Halfmind Flow concept

Halfmind Flow

Halfmind Flow (Figure 13) is a focus initiator designed for immersive work-from-home contexts. Utilising a contactless sensor, it assists users in regulating stress, guiding breathing, and engaging in personalised rituals that facilitate a smooth transition into deep focus. Mounted on top of the monitor display, it functions as an unobtrusive companion throughout the work session. Figure 14 concludes the workflow.

Key features

1. **Welcome and leave rituals.** The system automatically activates a welcome sequence when the user engages with the desk and transitions into an idle or farewell state when the user disengages. These rituals help establish consistent psychological cues for starting and ending focused work periods.
2. **Breathing guidance through multi-sensory experience.** Without requiring conscious effort, users are subtly guided to slow their breathing rate through synchronized visual and auditory cues. Music and ambient lighting patterns are designed to operate in the periphery of awareness, aligning subconsciously with the user's breathing rhythm and occupy perceptional resources to limit mind-wandering.
3. **Gentle interventions for elevated activity.** When the contactless sensor detects potential indicators of stress or restlessness, i.e. heightened physical movement, fidgeting, or increased breathing rate, the music changes in pattern and chords to help gain awareness and restore focus.

4. **Customisable & randomised music patterns.** To address ADHD users' preference for novelty and variety, the system generates diverse melodies and tonal textures. These can be customised or left in randomised mode, ensuring each focus session presents a fresh auditory experience.

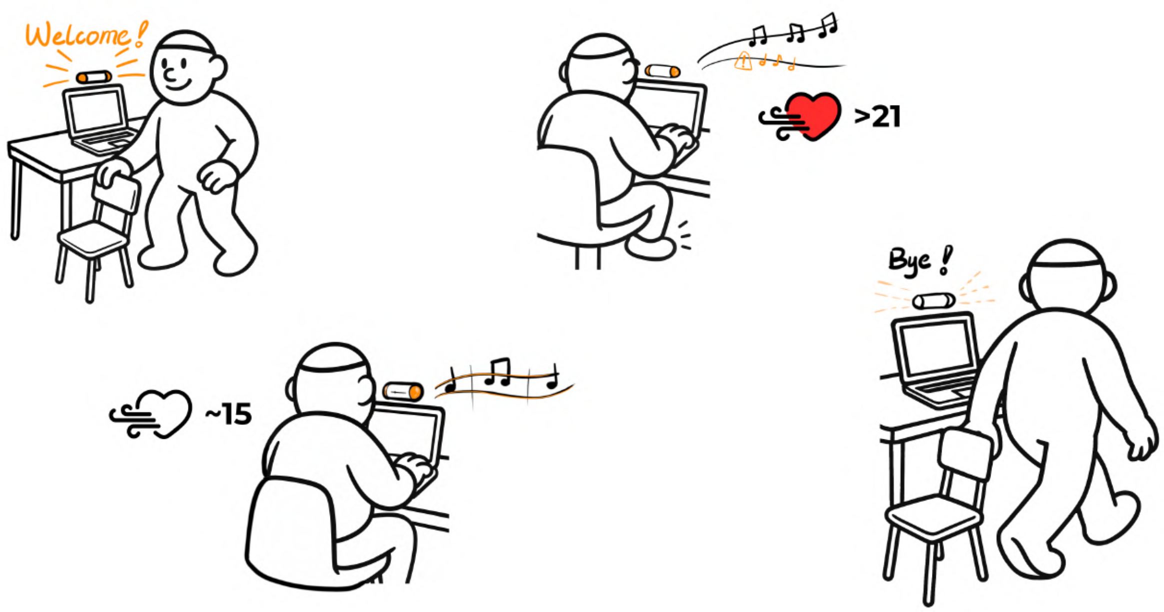


Figure 14. User experience walkthrough. Users are welcomed upon seating; enjoy personalised music from their breathing rate; are alerted by different melodic layer upon high breathing rate; and an end-of-work ritual when they leave.

5. Prototype development

5.1 Form

Halfmind Flow adopted the pill concept, similar in size and form of an “energy crystal”, to stay on top of the monitor display. When properly installed, the radar sensor is oriented toward the user’s body. This placement within the office environment minimizes the risk of obstruction by other objects on the desk. A comparable reference in positioning is the display lamp (e.g. ScreenBar by BenQ). Figure 15 is a photo of the working state of the prototype.

The shell is 3D-printed in two pieces and bolted by a screw. They jointly housed the radar board and ESP32. This structure considers the future adaption for injection moulding, tube metal extrusion or CNC manufacturing.

Figure 15. Prototype of Halfmind Flow on the laptop screen

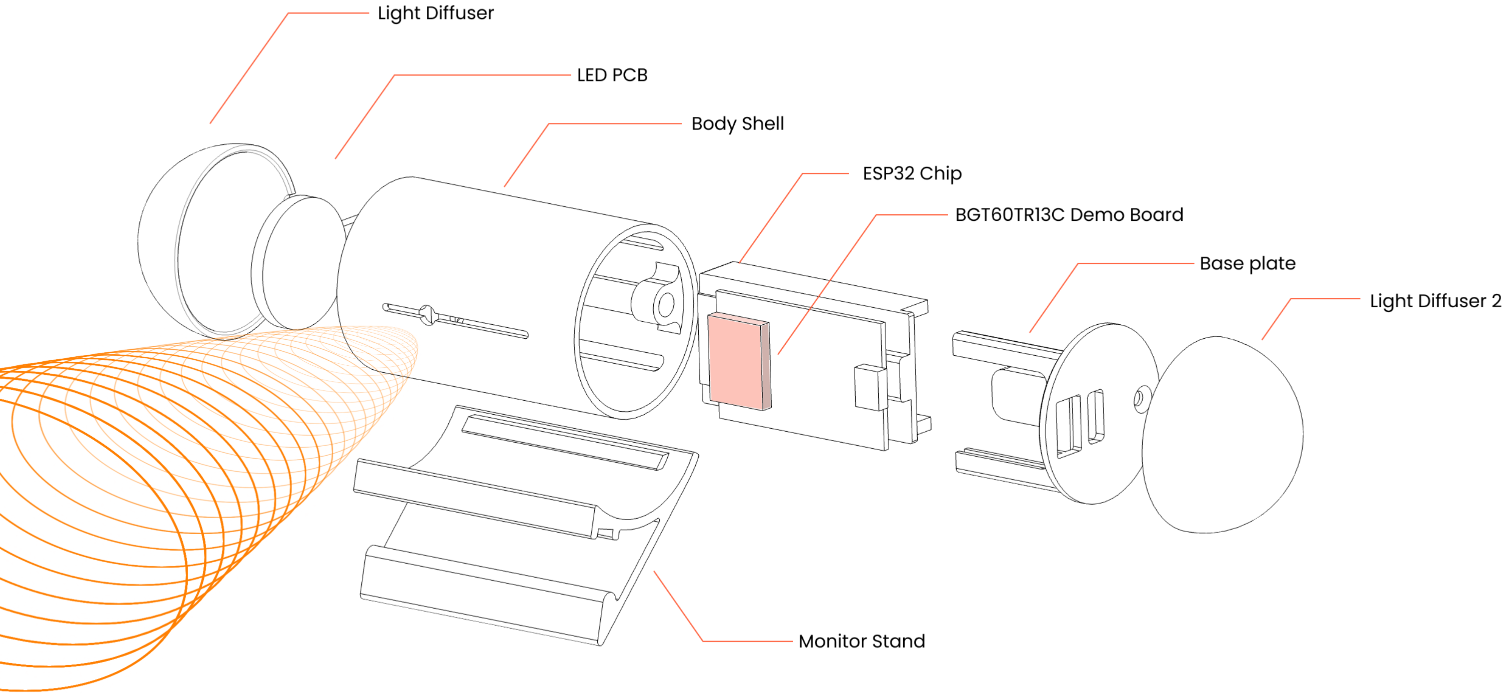


Figure 16. Exploded view of Halfmind Flow prototype.

LEDs were installed in the transparent hood printed in transparent PLA. The hoods were glued to the shell body. Different from the concept and limited by the direction of PCB boards, the lighting on one side was removed for cable connection. Figure 16 shows the internal structure of the Halfmind Flow prototype.

5.2 Technology

System architecture

Halfmind Flow consists of a 60 GHz mm-wave radar evaluation board (Infineon BGT60TR13C), an ESP32 microcontroller from Espressif, a custom PCB with seven surface-mounted LEDs, and a 3D-printed housing. The system captures respiratory

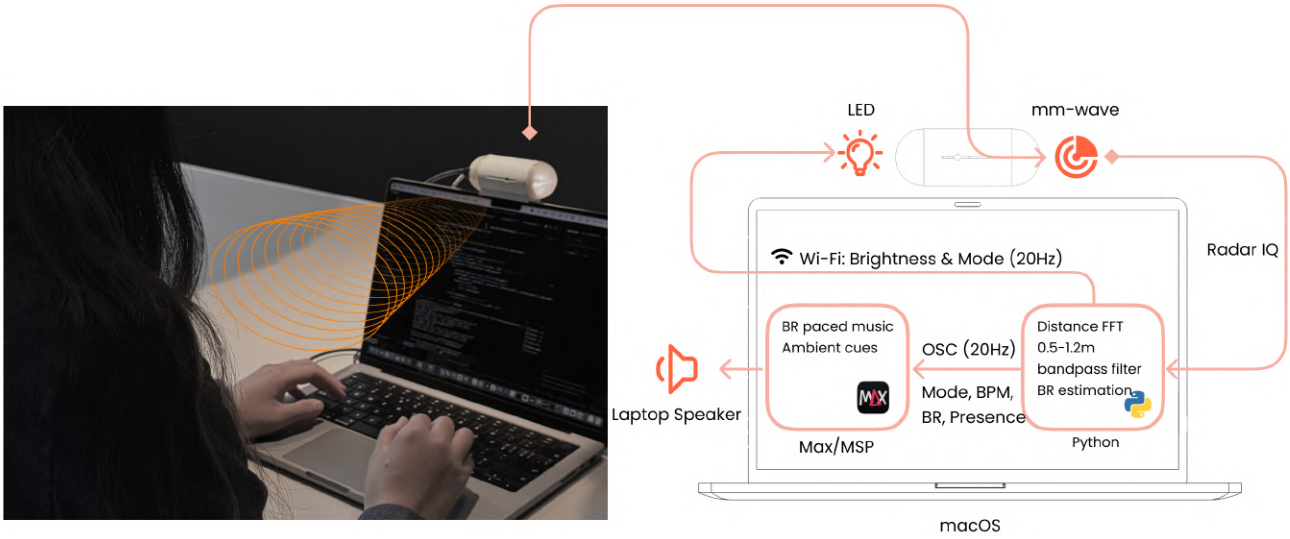


Figure 17. From installation of Halfmind Flow to processing logic.

signals via radar sensing, processes them through embedded signal pipelines, and generates sound in real time using a Max/MSP patch running on a laptop computer (Figure 17).

Radar sensing

The estimation of breathing rate and real-time breathing depth from radar signals relies on analysing the raw In-phase and Quadrature (IQ) data, which encodes the phase and amplitude information of the reflected electromagnetic waves, from a 60 GHz radar evaluation board from Infineon, with integrated BGT60TR13C radar chip. The periodic movement of the chest wall during respiration modulates the phase of the received signal, enabling the extraction of respiratory parameters through advanced signal processing techniques. Figure 18 juxtaposes the breathing-sensing in time and frequency domain.

Signal preprocessing

Let $I(t)$ and $Q(t)$ denote the in-phase and quadrature components of the radar signal at time t. The complex baseband signal is constructed as $S(t) = I(t) + jQ(t)$ where $j = \sqrt{-1}$. To enhance the signal quality, pre-processing steps such as DC removal and windowing (e.g., Blackman-Harris window) are applied. The signal is then zero-padded and transformed into the range domain using the Fast Fourier Transform (FFT), allowing the selection of the range bin corresponding to the subject's position.

Phase extraction and unwrapping

The phase of the selected range bin, which is sensitive to minute chest wall displacements, is computed as

$$\phi(t) = \arg(S(t)) = \arctan 2(Q(t), I(t))$$

Due to the 2π periodicity, the phase signal is unwrapped to obtain a continuous representation of displacement:

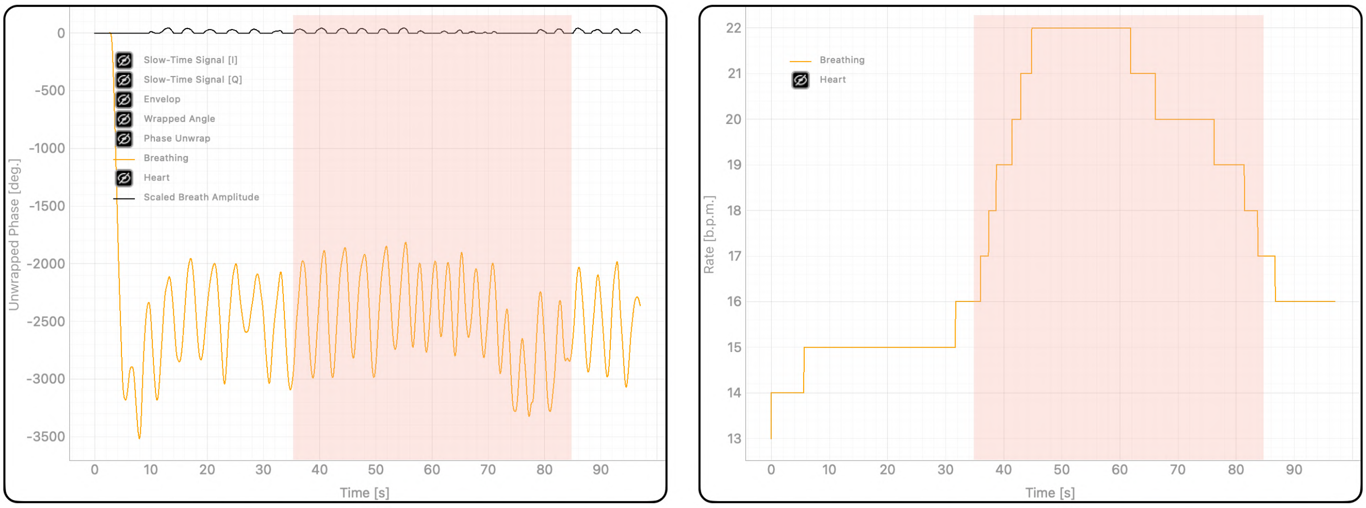


Figure 18. Time-domain (left, orange) breathing pattern and frequency-domain (right) breathing rate from the same session. The coloured area represents an increase in breathing rate.

$$\phi_{\text{unwrapped}}(t) = \text{unwrap}(\phi(t))$$

This unwrapped phase is directly proportional to the physical displacement of the chest wall.

Respiratory Signal Isolation

To isolate the respiratory component, the unwrapped phase signal is filtered using a bandpass filter with cutoff frequencies corresponding to the typical human breathing range (e.g., 0.15–0.6 Hz):

$$\phi\ \text{breath}(t) = \text{BandpassFilter}(\phi_{\text{unwrapped}}(t))$$

This yields a signal in which the dominant oscillatory component is due to respiration. Those extracted information are transmitted via the ESP32 and parsed by Max/MSP to influence musical parameters dynamically.

Resistance to noise

The system demonstrates robustness against minor micro-movements such as leg fidgeting, keyboard typing, or switching between keyboard and mouse (Figure 19). Although these behaviors produce distinct patterns in the signal graphs, they do not compromise measurement accuracy. In contrast, more intensive body movements like moving chairs or leaning back can substantially distort breathing rate extraction. This limitation could be addressed in future work through neural network–based recognition. Additionally, contaminated data frames may be filtered to prevent false alarms regarding irregular breathing patterns.

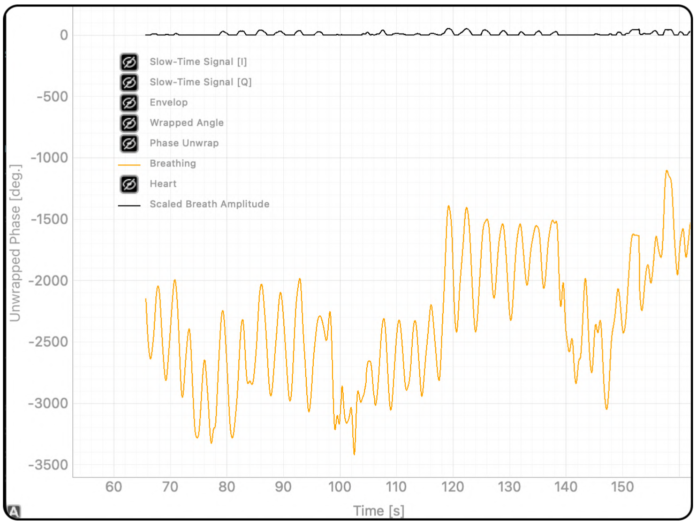


Figure 19. Time-domain breathing data against keyboard-typing activities is usable for breathing pattern extraction and breathing rate calculation.

Generation of multi-sensory cues

The music generation system was implemented in Max/MSP, selected for its robust real-time audio processing capabilities and flexibility in integrating algorithmic composition with external sensor inputs. The program operates on a laptop running macOS, which also serves as the primary interface for user testing. Sound is generated in real time and output through the laptop's built-in speakers during evaluation sessions.

Musical structures are defined algorithmically within Max/MSP using a rule-based system that determines pitch sequences, rhythmic patterns, and timing intervals. This approach allows the system to adapt musical output dynamically to changes in user state without requiring manual control.

Open Sound Control (OSC) is implemented to facilitate communication between the computer and external hardware components. OSC enables data exchange from the 60 GHz radar sensor and the ESP32 LED microcontroller to Max/MSP. The radar sensor captures physiological or behavioural cues, while the ESP32 triggers corresponding visual responses, ensuring that auditory and visual elements remain synchronised.

This architecture provides a scalable framework in which musical parameters can be expanded or refined. Additional instruments, generative algorithms, or sensory feedback mechanisms can be integrated by adding more devices that parse OSC messages, supporting iterative development for future versions.

5.3 Interaction

The core functions are designed for zero-touch interaction, eliminating the need for physical or manual input. Presence and physiological signals are detected using short-range radar (0.5 - 1.2 m), allowing the device to activate automatically without imposing cognitive load.

User interaction is divided into three phases based on radar data: absence, focused work, and unfocused state. When no user is present, music is turned off and the lights remain dim. Upon detecting a seated user, the system initiates music playback and increases light intensity. The radar tracks breathing in real time, and the music tempo is set slightly

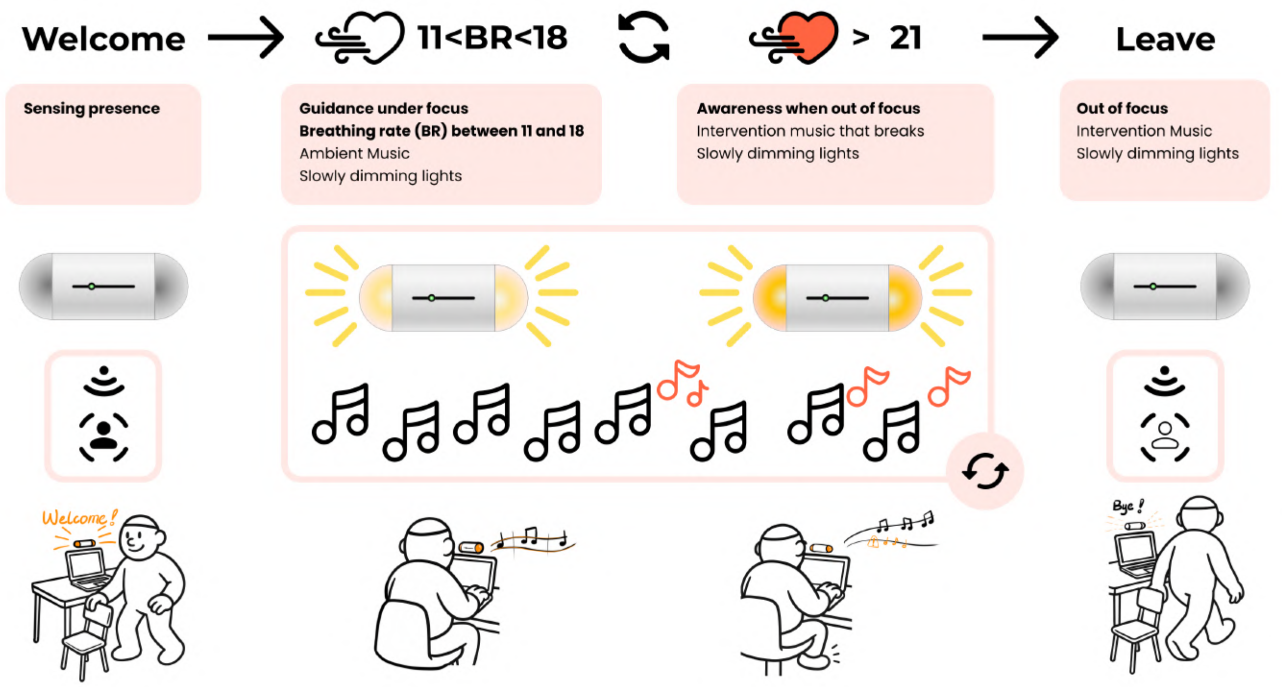


Figure 20. Visualisation of the interaction flow in a 4-step feedback loop.

below the estimated breathing rate to encourage a calm physiological state. Light brightness reflects breathing depth, gradually pulsing with inhalation and exhalation.

When the system detects increased fidgeting or rapid breathing, it shifts to an unfocused phase. In this state, the music tempo is fixed below the user's baseline breathing rate, and a secondary layer of syncopated rhythm is added to subtly disrupt the ambient pattern and prompt self-awareness.

The auditory feedback is based on a modified generative composition originally developed in Max/MSP by Undulae. The tempo, layering, and rhythmic structure are dynamically adjusted to be slightly lower than user's breathing rate. Visual feedback is provided through LEDs that respond to breath depth, offering ambient, non-intrusive biofeedback.

All transitions are automatic, requiring no user initiation. The system maintains a continuous loop of sensing and feedback, promoting focused yet relaxed engagement through ambient cues, without diverting attention from the user's primary tasks. However, it is advisable in the future to incorporate additional control options such as a remote or physical dial to adjust volume or music genre without compromising the system's low-effort design.

The interaction is further visualised in Figure 20. Figure 21 is an imaginary effect of the music engaging the user.

Figure 21. Visualised multi-sensory experience

6. Evaluation

To evaluate the effectiveness of the multisensory intervention on sustained attention and emotional regulation, a controlled within-subject experiment was conducted (N = 17). This data-centric, exploratory study addressed the following research questions:

- Can Halfmind Flow enhance attention, regulate emotions, or reduce perceived task load significantly?

An additional question—whether Halfmind Flow could shorten task initiation time—was originally considered but ultimately excluded, as it would have introduced uncontrolled conditions into the experiment.

6.1 Methods

Participants

Seventeen participants (8 males; mean age = 24.71, SD = 1.48) took part in the study. They were provided informed consent prior to participation. Demographic information such as age and gender was collected for data analysis. Limited by the algorithm of TOVA, the gender only had two options: male or female. Participants were screened for stable mood fluctuations, sufficient sleep, normal stress levels, and absence of energy drink intake before each session.

Stimuli and Procedure

The experiment was conducted in a studio room in Delft, intentionally decorated to resemble a home office. Each participant completed two sessions on consecutive days: one under baseline conditions and one under the intervention condition. Participants were randomly assigned to either a standard order (baseline first, then intervention) or a counterbalanced order (intervention first, then baseline), with 9 participants in each subgroup.

The intervention system delivered multisensory cues during the test, including breathing-paced ambient music and subtle visual animations of breathing. When participants' breathing exceeded 21 breaths per minute, syncopated melodic tones were introduced to encourage a calmer rhythm.

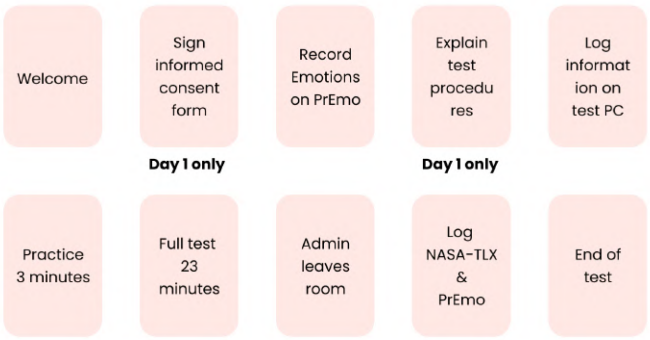


Figure 22. Test procedure on both days.

Figure 23. Participants in TOVA test

Attention performance was measured using the Test of Variables of Attention (TOVA), a 23-minute Continuous Performance Test in which participants differentiated between target and non-target stimuli at an interval of 2000ms (Figure 22). A 3-minute practice preceded the test. Subjective workload and emotional states were assessed using the NASA Task Load Index (NASA-TLX) and PrEmo questionnaires before and after each test session.

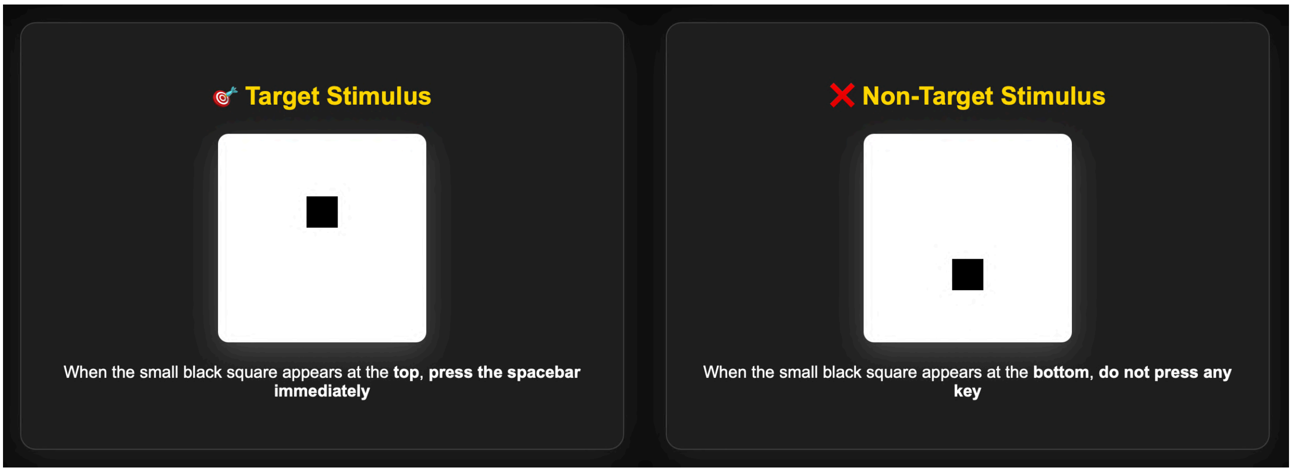
Both sessions followed the same structure: initial emotion rating (PrEmo), practice trial, 23-minute TOVA, and post-test questionnaires. On Day 1, participants additionally provided consent and received a test introduction; these steps were omitted on Day 2. Experimental conditions such as lighting and ambient noise were kept constant across sessions. Figure 22 and 23 provide the timeline and real scenario during test.

6.2 Data analysis

Three main aspects were examined: attention performance (TOVA), perceived workload (NASA-TLX), and emotional experience (PrEmo). The analysis was designed to evaluate both objective cognitive performance and subjective self-reports under baseline and intervention conditions. Statistical significance was set at $p < 0.05$ unless otherwise specified. Paired two-tailed t-tests were applied for within-subject comparisons.

Attention Performance (TOVA)

TOVA data were processed according to the official guidelines. Three dependent variables were analysed: D′ (dprime), an index of perceptual sensitivity that reflects the ability to discriminate targets from non-targets (see Appendix F for calculation); Mean Response Time (meanHitRT) under low target-frequency, indicating response efficiency; and Response Time Standard Deviation (SDHitRT), representing intra-individual response consistency. Each variable was computed per participant for both sessions, and within-subject comparisons were carried out using paired-sample t-tests and 2x2 ANOVA test to examine the order effect. The Shapiro-Wilk test did not show a significant departure from normality for all three variables. Outliers were screened based on rules proposed in TOVA manual, though all data were valid for further analysis.



When the small black square appears at the **top, press the spacebar immediately**

When the small black square appears at the **bottom, do not press any key**

Figure 24. Participants need to press space key upon target stimulus (left) and remain still for non-target (right) at 2000ms intervals during a TOVA test.

Emotional Experience (PrEmo)

Emotions were measured with the PrEmo tool at three points in each session: before, during, and after the TOVA task. Participants selected any number of emotions from a predefined list and rated their intensity on a 5-point scale (1 = very weak, 5 = strong). For analysis, ratings were aggregated into higher-order dimensions of valence and arousal using principal component analysis (Desmet, 2018), and mean scores were compared across baseline and intervention sessions. The order effect was tested by ANOVAs and Shapiro-Wilk test was performed to determine data normality.

Workload Assessment (NASA-TLX)

Workload was assessed on six subscales—Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration—each rated on a 100-point continuous scale. Raw scores were analysed independently without weighting. Paired-sample t-tests compared baseline and intervention ratings, with Cohen's d reported as effect sizes. T order effect was tested by ANOVAs and Shapiro-Wilk test was performed to determine data normality.

6.3 Results

TOVA

To examine the effects of intervention and sequence order on TOVA performance, a two-way mixed ANOVA was conducted with Experiment Order (EO, standard vs. counterbalanced) as a between-subject factor and Intervention vs. Control (IC) as a within-subject factor. Analyses were performed on four dependent measures: mean hit reaction time (z_meanHitRT_LF), sensitivity index (z_dprime_HF), reaction time variability (z_SDHitRT), and a composite z-score. Paired-samples t-tests were also conducted on the within-subject change in z-scores (N = 17).

For z_meanHitRT_LF, there were no significant main effects of experiment order, F(1, 15) = 1.38, p = .258, or test_type, F(1, 15) = 0.003, p = .960. However, the experiment order × test_type interaction was significant, F(1, 15) = 4.66, p = .047. A paired-samples t-test indicated that the change between intervention and control conditions was not significant, t(16) = 0.96, p = .35.

For z_dprime_HF, no significant main effects of experiment order, F(1, 15) = 0.76, p = .396, or test_type, F(1, 15) = 1.61, p = .224, were found. The interaction was significant, F(1, 15) = 5.97, p = .027. The paired-samples t-test was not significant, t(16) = 0.28, p = .78.

For z_SDHitRT, no significant main effects of experiment order, F(1, 15) = 2.55, p = .131, or test_type, F(1, 15) = 0.19, p = .672, were observed. The experiment order × test_type interaction was significant, F(1, 15) = 9.97, p = .006. The paired-samples t-test did not reach significance, t(16) = 0.73, p = .47.

Finally, for the composite z-score of ACS, there were no significant main effects of experiment order, F(1, 15) = 1.68, p = .214, or test_type, F(1, 15) = 0.36, p = .555. A significant interaction emerged, F(1, 15) = 12.87, p = .003. The paired-samples t-test was not significant, t(16) = 0.65, p = .52.

Differences of three independent variables from TOVA (noted as diff_variable) were verified for normal distribution with Shapiro-Wilk test. The results did not show a significant departure from normality, while the mean hit response time showed an edge case with p = .057. For diff_meanHitRT_LF, W(17) = .9, p = .057; for diff_SDHitRT, W(17) = .93, p = .197; and for diff_dprime_HF, W(17) = .96, p = .654.

In summary, across all four TOVA measures, no significant main effects of experiment order or test_type were found. However, significant experiment order × test_type interactions were observed for each measure, indicating that the effect of intervention was dependent on test sequence. Paired t-tests on within-subject change scores did not reveal significant overall differences between intervention and control conditions. Table 2 further visualises the results.

Measure (z scores)	**Effect**	**F(1, 15)**	**p**	**t(16)**	**p (t-test)**
z_meanHitRT_LF Mean response time of low-frequency half	EO	1.38	0.258		
	IC	0	0.96		
	EO × IC	4.66	0.047*	0.96	0.35
z_dprime_HF D Prime of high-frequency half	EO	0.76	0.396		
	IC	1.61	0.224		
	EO × IC	5.97	0.027*	0.28	0.78
z_SDHitRT Standard deviation of response time.	EO	2.55	0.131		
	IC	0.19	0.672		
	EO × IC	9.97	0.006**	0.73	0.47
ACS Attention Comparison Score (for diagnosing ADHD clinically)	EO	1.68	0.214		
	IC	0.36	0.555		
	EO × IC	12.87	0.003**	0.65	0.52

Table 2. F-statistics and T statistics of TOVA variables ($p < 0.05$*, $p < 0.01$**)

PrEmo

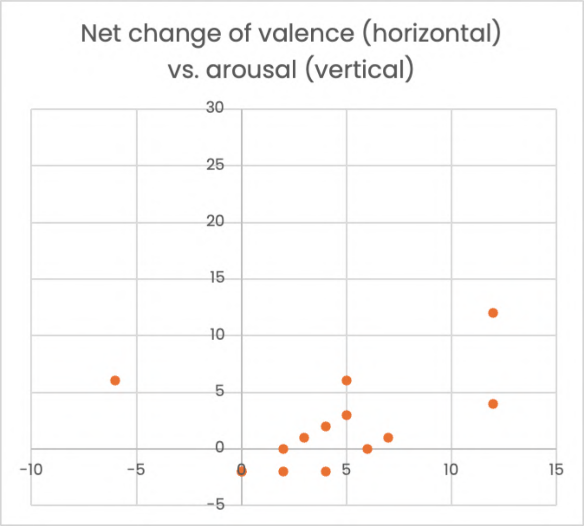


Figure 25. Most data points fall in the first quadrant, indicating that net changes in both valence (p = .0013**) and arousal (p = .020) are predominantly positive, suggesting an overall improvement in emotional state.

After accounting for data quality issues, analysis of the PrEmo ratings (N = 16) revealed a mean net increase in valence of 4.88 points and a net increase in arousal of 1.56 points following the intervention. Paired-samples t-tests indicated that the increase in valence was strongly significant (p = .0013**), while the increase in arousal did not reach conventional significance levels (p = .20).

Effect size analyses further contextualize these findings. The valence change corresponded to a very large effect (Cohen's d = .98), suggesting that the intervention robustly enhanced participants' positive emotional states. The arousal change was associated with a medium effect (Cohen's d = .34), pointing to a moderate tendency toward higher activation, although the statistical evidence was weaker. Taken together, these results indicate that the intervention exerted a substantial influence on emotional valence and a potential, though less reliable, effect on arousal.

To examine whether the counterbalancing order introduced any systematic differences in emotional ratings, separate one-way ANOVAs were conducted on valence and arousal scores. For valence, the analysis revealed no significant order effect, F(1, 14) = 0.01, p = .92. For arousal, the analysis also indicated no significant order effect, F(1, 14) = 0.83, p = .38.

These results suggest that the counterbalancing procedure was effective: the order of conditions did not influence participants' reported emotional states, thereby eliminating potential confounds related to sequence effects.

During data inspection, participant 003 displayed unusually extreme scores in the self-reported PrEmo ratings across the two sessions. Qualitative evidence from the participant's feedback notes suggests that this discrepancy stemmed from applying inconsistent evaluation standards when logging emotions rather than reflecting genuine emotional change. Given this response shift, the participant's self-reported data were treated as invalid and excluded from PrEmo analysis. Importantly, other measures from TOVA and NASA-TLX were unaffected and were retained in the analysis. This approach ensured both the integrity of the statistical analysis and the transparency of data handling.

NASA-TLX

Analysis of workload ratings across the six NASA-TLX subscales revealed mixed patterns of change following the intervention. Paired-samples t-tests with Cohen's d effect sizes were conducted. For the mental and physical demand subscale, the Shapiro–Wilk test indicated a deviation from normality; thus, its t-test result should be interpreted with caution. The other four subscales did not show significant departures from normality. Table 3 presents average change, standard deviation (STDEV), effect size, Shapiro-Wilk test together. Table 4 shows the ANOVA test results of order effect for each subscale.

1. Mental Demand decreased by –9.76 points, corresponding to a small negative effect (d = –.38), though this difference was not statistically significant (p = .292). The Shapiro–Wilk test showed a significant departure from normality, W(17) = .89, p = .039.
2. Physical Demand increased by 2.76 points, with a negligible positive effect (d = .10), but did not reach significance (p = .175). The Shapiro–Wilk test showed a significant departure from normality, W(17) = .89, p = .049.
3. Temporal Demand decreased by –11.35 points, reflecting a small-to-medium negative effect (d = –.39), which was not significant (p = .348). The Shapiro–Wilk test did not show a significant departure from normality, W(17) = .96, p = .686.
4. Performance ratings changed by –4.41 points (where lower scores indicate better perceived performance), with a small negative effect (d = –.20) and a non-significant result (p = .670). The Shapiro–Wilk test did not show a significant departure from normality, W(17) = .94, p = .302.
5. Effort decreased by –11.00 points, showing a small-to-medium negative effect (d = –.46), approaching significance (p = .130). The Shapiro–Wilk test did not show a significant departure from normality, W(17) = .93, p = .197.
6. Frustration demonstrated the strongest change, with a reduction of –13.06 points and a medium-to-large negative effect (d = –.62), which reached statistical significance (p = .014). The Shapiro–Wilk test did not show a significant departure from normality, W(17) = .97, p = .891. A one-way ANOVA on the difference scores revealed a significant order effect for this subscale, F(1,15) = 5.98, p = .027, whereas no significant order effects were observed for the other five subscales.

Taken together, these results suggest that the intervention most strongly reduced **Frustration**, with evidence of a large and statistically significant effect. For the other dimensions the observed mean differences were small in magnitude, with effect sizes ranging from –.11 to .42, and none reached statistical significance (p values between .130 and .670).

Subscale	Average change	STDEV	Effect size (d)	Shapiro-Wilk W	Shapiro-Wilk p	Significance (p)
Mental demand	-9.76	25.37	-0.38	0.89	0.039	0.292
Physical demand	2.76	27.3	0.1	0.89	0.049	0.175
Temporal demand	-11.35	29.32	-0.39	0.96	0.686	0.348
Performance	-4.41	22.13	-0.2	0.94	0.302	0.67
Effort	-11	23.81	-0.46	0.93	0.197	0.13
Frustration	-13.06	21.2	-0.62	0.97	0.891	0.014

Table 3. Statistics of NASA-TLX results from TOVA. Frustration shows most decrease while significantly influenced by the order effect.

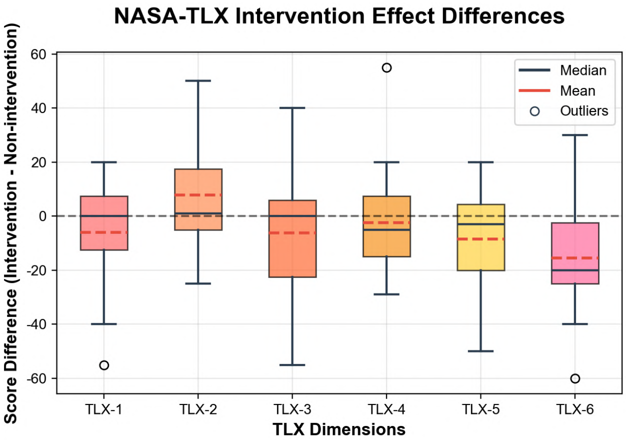


Figure 26. Frustration showed significant change among all index, while influenced by order effect.

ANOVA for NASA-TLX order effect

Subscale	F	p-value
Mental demand	0.1015	0.7545
Physical demand	0.1588	0.6959
Temporal demand	2.6402	0.1250
Performance	0.6789	0.4229
Effort	4.0448	0.0626
Frustration	5.9824	0.0273

Table 4. Results of one-way ANOVAs testing order effects for each NASA-TLX subscale. Each analysis was conducted with df(1,15). Only Frustration (TLX-6; F = 5.98, p = .027) showed a significant order effect, while the other subscales did not reach significance.

7. Discussion

7.1 Revisiting the research questions

This thesis set out to investigate two main research questions.

RQ1: How does a multi-sensory system detect and respond to embodied cues in order to nudge users to initiate tasks more effectively?

The prototype explored the use of radar-based sensing to capture embodied signals such as breathing, which was then mapped to auditory and visual feedback (guidance). While the study design did not directly measure task initiation behavior in an ecological setting, the system nevertheless demonstrated that such embodied cues can be harnessed in real time to modulate feedback. Participants reported that the sensory prompts felt subtle rather than intrusive, aligning with earlier work on nudging and environmental scaffolds for task initiation (Thaler & Sunstein, 2008; Chu et al., 2021). The study therefore suggests that multi-sensory, contactless feedback systems hold potential for addressing pre-task inertia, especially in populations such as adults with ADHD, where starting tasks is often a greater challenge than sustaining them.

RQ2: How can the same system sustain deep focus by adapting sensory feedback to real-time attention states in work contexts?

The within-subject experiment compared baseline and intervention conditions during sustained attention tasks. Although objective measures of performance, such as reaction time in the TOVA test, showed limited improvement, participants reported feeling calmer and less frustrated under the intervention condition. This resonates with findings by Kiss and Linnell (2021), who argue that subjective experience and affective support can be as critical as performance metrics when evaluating attention-support systems. In this study, the multi-sensory feedback seemed to promote an emotionally supportive environment, suggesting that its value may lie more in reducing cognitive strain and enhancing users' sense of control rather than directly boosting task performance. This highlights the importance of considering experiential outcomes alongside statistical measures when evaluating attention-support technologies.

7.2 Design Reflections and Implications

This research aligns with the goals of adapting to dynamic cognitive load under different working conditions. The prototype demonstrates a form of **zero-touch interaction**, in which users' physiological signals seamlessly trigger adaptive feedback for a easy start and continuously filling the gap of perception and cognition load. Unlike wearable devices that require continuous physical contact, the radar-based approach enables a more ambient mode of interaction, where feedback emerges from the background of daily work practices. This research offers a pathway for designing technologies that flexibly respond to users' cognitive states without demanding explicit input.

Second, the study revealed subtle order effects, as participants' responses varied depending on whether they encountered the intervention before or after the baseline condition. From a design perspective, this suggests that novelty and contrast may influence how users perceive and benefit from multi-sensory feedback. Designers should therefore consider how such systems might evolve over longer-term use, and how to maintain a sense of freshness and personal relevance in the sensory cues.

Finally, the qualitative feedback highlighted a strong preference for customizable and non-repetitive sensory patterns. Several participants emphasized that music, in particular, should feel dynamic rather than predictable, which aligns with prior research on auditory stimulation for focus (Haake, 2011). In a prior study, I employed rhythmically strong music as the stimulus. While this engaged some participants, others reported that the pronounced rhythm created pressure and heightened anxiety. Due to time constraints in the current project, only one type of music—ambient—was implemented to avoid these adverse effects. Nevertheless, the findings suggest that the most effective solution would not be a fixed musical style but rather offering users the ability to choose from different auditory options, thereby accommodating individual preferences and sensitivities.

Taken together, these reflections suggest that the contribution of the prototype lies less in statistical improvements in attention scores and more in shaping new interaction paradigms for supporting focus through subtle, embodied, and adaptive feedback.

7.3 Connecting the Literatures

Reviewed from theoretical approach, this project mainly draws on Lavie’s Load Theory, which proposes that perceptual load determines the extent to which irrelevant distractors are processed, while cognitive control mechanisms govern attentional focus when perceptual load is low. By deliberately navigating between perceptual and cognitive load, the design introduces a layer of multi-sensory experience that fills the attentional “gap” left under low-load conditions. In doing so, it aims to shield users from external distractions while supporting a more sustained focus, offering a conceptual bridge to studies on background music and subtle sensory interventions.

Comparison with Kiss and Linnell (2021)

Kiss and Linnell (2021) investigated the influence of self-selected background music on sustained attention during a low-demand psychomotor vigilance task. Using a within-subjects design with 40 university students, they compared performance under silence and preferred-music conditions. Results showed that preferred music increased reports of task focus and reduced mind-wandering, while reaction time and variability remained unaffected. No significant order effects emerged in their study.

The present results align with their performance findings: objective speed and variability did not change reliably. This similarity supports the interpretation that music can enhance the internal attentional state without necessarily producing faster or more stable task performance in a standardised measure such as TOVA. The current study extends their work by highlighting affective outcomes and workload changes; although task-focus was not directly assessed, the preservation of positive valence and reduction in Frustration are consistent with the attentional benefits reported by Kiss and Linnell. A key difference lies in the observed order effects, absent in Kiss and Linnell’s study. Given the strong practice component of the TOVA, the shorter washout period employed here, and the documented increase in commission errors on second administrations, carryover effects remain a likely explanation. Future studies should consider between-subject designs or extended washout intervals.

Comparison with BrightBeat

Ghandeharioun and Picard's (2017) BrightBeat system modulated screen brightness and headphone volume to guide breathing toward personalised targets. In a randomized placebo-controlled between-group trial with 32 university affiliates, participants assigned to the intervention group (n=19) achieved their goal breathing rate significantly more often than the control group (n=13), reported greater calmness and focus, and showed no detriment in quiz performance during concurrent reading tasks.

The current findings converge with BrightBeat's affective outcomes: the intervention preserved a more positive affective state under cognitive load and reduced frustration without impairing task performance. This supports the broader view that subtle, background sensory interventions can promote calmness and focus during ongoing work. Differences should also be noted: BrightBeat verified a physiological mechanism by measuring breathing patterns, whereas no physiological data were collected in the present study, leaving the underlying mechanism unconfirmed. Additionally, BrightBeat reported no sequence-related effects, while the current findings showed strong order sensitivity.

7.4 Summary of experiment findings

Across the objective TOVA measures, the music intervention yielded only minor, non-significant improvements, suggesting that it was insufficient to produce a substantial reduction in response time variability or to meaningfully alter attentional performance. A notable order effect was observed: when participants experienced the normal sequence (non-intervention first), three of four measures reached significance, whereas none were significant in the counterbalanced group (intervention first). Given established short-interval TOVA test–retest patterns showing significant reliability in terms of mean response time and variation, the reversed sequence may have been disadvantaged by second-session error increases, potentially masking intervention benefits. Subjective workload analysis indicated that Frustration decreased most prominently under the intervention, showing a large effect size ($r = 0.55$) and a significant 17.3% reduction ($p = .003$). Overall workload decreased but not significantly. Affective data from PreMo demonstrated that net valence dropped to negative values during TOVA in the control condition (–1.72) but remained positive in the intervention condition (0.49), suggesting that the intervention may have buffered against negative affect under task demand.

Order Effect in NASA-TLX

Among the six NASA-TLX subscales, only Frustration showed a significant order effect, $F(1,15) = 5.98$, $p = .027$, whereas no such effect was observed for the other five subscales. Specifically, participants who completed the baseline condition first reported a reduction in frustration following the intervention, while those who received the intervention first exhibited an opposite trend. This indicates that the apparent effect of the music intervention on frustration was contingent on presentation order.

The presence of an order effect exclusively in the frustration subscale suggests that this dimension is particularly sensitive to contextual influences. A plausible interpretation is that frustration is shaped by relative comparisons: when the intervention followed the baseline, participants may have experienced it as relieving, whereas when it appeared first, its perceived benefit diminished or even reversed. This pattern highlights that the intervention's influence on frustration may not reflect a stable, intrinsic effect, but rather one that emerges through contrast with the preceding condition.

This raises an important question for future research: is the reduction of frustration attributable to the intervention itself, or does it primarily arise from its sequential positioning relative to the baseline? Addressing this issue will require designs with stricter counterbalancing, larger samples, or alternative approaches capable of disentangling genuine intervention effects from order-related biases.

7.5 Limitations and implications

This study faces several limitations at both the system and experimental level. From a system perspective, while radar-based sensing successfully captured embodied cues, it lacks validation against gold-standard physiological measures such as EEG or fMRI, which could provide stronger evidence for the underlying cognitive and neural mechanisms. The robustness of the prototype also remains limited, as movement artifacts and hardware constraints reduce reliability in dynamic contexts, particularly when users shift on wheeled office chairs. Currently, no filtering mechanism compensates for such movements, which restricts ecological validity.

At the participant level, the study did not include individuals across the full ADHD spectrum. Prior research has shown that stimulating music can have differential effects depending on the severity of attentional difficulties (Woods et al., 2021), suggesting that the absence of clinically diverse participants limits the generalizability of the findings.

Methodologically, sequence effects combined with the known retest patterns of the TOVA highlight the need for alternative designs such as between-subject allocation or longer washout periods. The strong order sensitivity observed indicates that baseline drift and measurement interaction can meaningfully alter outcomes, which should be carefully considered in the design of future nudging interventions. In addition, due to time constraints, the generative music module adopted only one ambient style, whereas exploring more varied genres may yield richer insights into how auditory patterns influence attention.

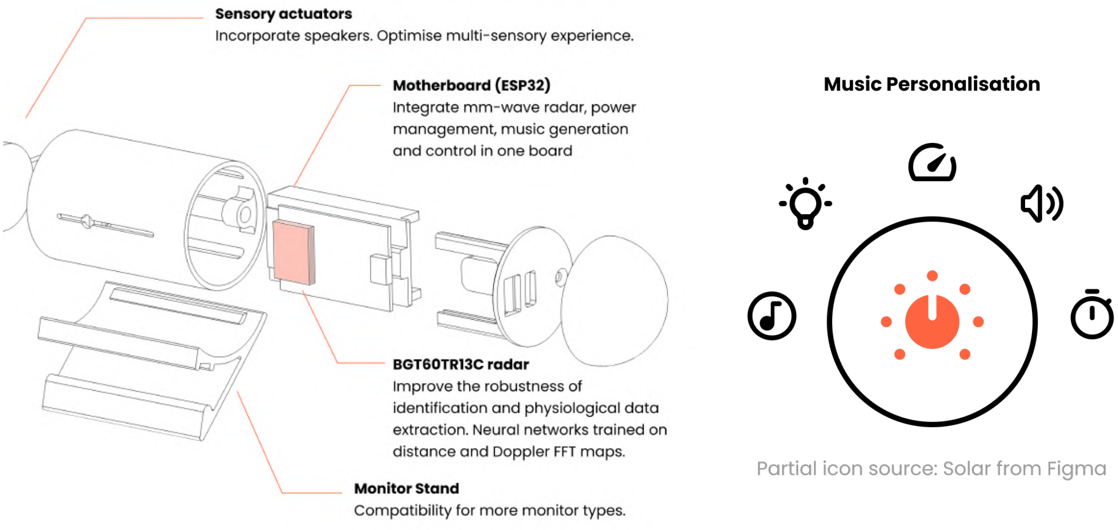
Together, these limitations suggest that while the present study provides promising indications for multisensory, zero-touch feedback systems, future work should both diversify participant groups and strengthen system robustness in real-world environments.

7.6 Future Work and Experiment Optimisation

Derived from the previous section, this project points to two complementary future directions: advancing system development toward a deployable multi-sensory companion and improving experimental design for validation. Figure 27 provides an illustration of those directions.

System development

On the technical side, the next stage will focus on refining the prototype toward an integrated and production-ready form factor. This includes developing customisable music generation with a physical control dial, allowing users to directly adjust tempo, genre, and intensity to match their personal preferences. Further integrate radar module, power regulation, music generation, and speaker driving into one custom PCB, so as to reduce the system's footprint while maintaining sensing quality. Robust detection of user states will be achieved by implementing neural networks trained on distance and Doppler FFT maps, enabling the system to distinguish between calm breathing, fidgeting, or absence with fewer false alarms. Lastly, feedback will expand from simple on/off cues to dynamic intensity control: breathing variability and fidget frequency will be translated into gradual adjustments of sound layering, tempo, and light brightness, ensuring that interventions feel organic and ambient rather than abrupt.



Partial icon source: Solar from Figma

Figure 27. Visualised takeaways for future system development. Left: engineering specifications. Right: a dial for music personalisation.

Experimental optimisation

Future studies should adopt designs that minimise carryover effects (e.g., between-group experiments) and include physiological monitoring to directly probe underlying mechanisms of attention and emotion. Using standardised TOVA equipment would strengthen data validity and comparability across participant groups. Music testing can be extended beyond the current selection by parameterising additional genres—including "ADHD Relief Music", a previous experiment done in similar way that can significantly improve attention performance score in a standard order (see Appendix G)—and systematically assessing their effects on attentional performance. To synthesise findings across genres, a holistic framework for comparing musical styles should be developed. Finally, adaptive multisensory interventions should be evaluated against non-adaptive baselines to substantiate the unique benefits of physiological adaptation.

8. Conclusions

This project applied holistic product innovation methodology (ViP) to probe a new concept product that helps users seamlessly integrate a multi-sensory device into a home working scenario. C4C and ViP methodologies were applied to elicit the form of design from user needs and cognitive science, guiding both the conceptual framing and the intervention's sensory composition. The resulting prototype was evaluated through a within-subject attention study with simple counterbalancing using TOVA, alongside affective PreMo and NASA-TLX workload measures.

The evaluation of Halfmind Flow revealed a nuanced picture: while the intervention produced non-significant results towards improved attentional performance, from a cognitive resource theory perspective, the intervention appeared lower in perceived task demands, most notably through a reduction in Frustration in NASA-TLX scores. Such affective modulation could support attentional maintenance, even if immediate performance gains are not consistently observed.

The design follows the principle of ambient cues in behavioural design—subtle, low-friction nudges that operate in the background without interfering with primary task execution. By sustaining a more positive affective state and lowering frustration, the intervention may help tackle task initiation challenges, delay emotional decline during extended tasks, and align with affective regulation strategies for enhancing focus.

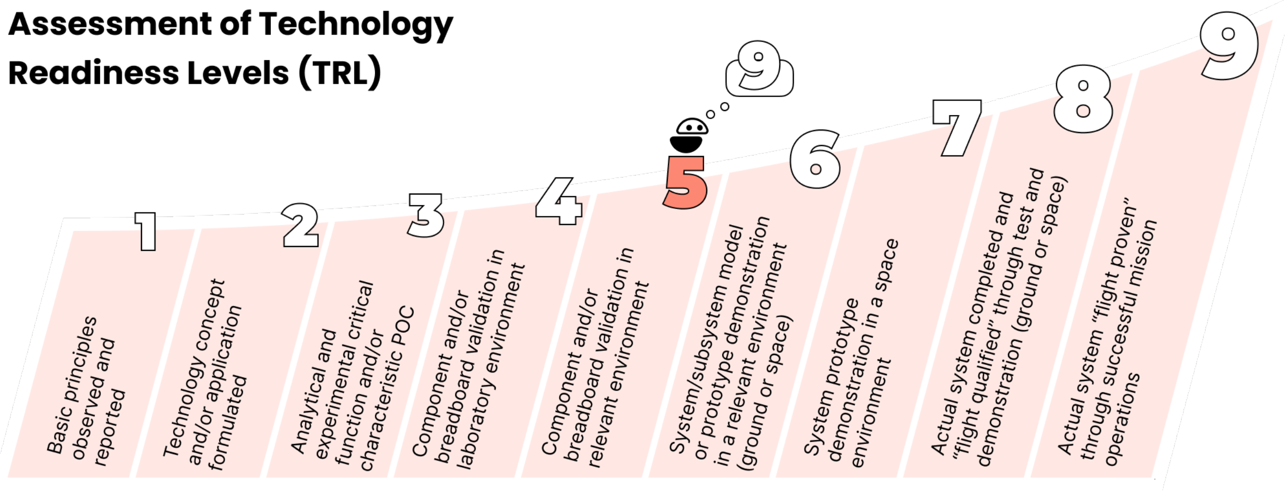


Figure 28. Halfmind Flow reached level 5 in TRL assessment, while we ultimately aim for 9.

Overall Conclusion

While the present study stops short of demonstrating strong statistical effects on attentional performance, it provides converging evidence that Halfmind Flow can positively influence the emotional climate of focused work, particularly in reducing frustration and preserving positive affect during sustained cognitive effort. The intervention's subtle, non-intrusive nature may be key to long-term adoption, even if its immediate measurable effects are modest. Future work should scale the participant pool, diversify contexts, and refine adaptive algorithms to more dynamically respond to user state, ultimately aiming to bridge the gap between supportive ambience and demonstrable cognitive enhancement. From the criteria in Technology Readiness Level (TRL), I reckoned that the breadboard prototype was validated in relevant environment, and thus reaching level 5 (Figure 28).

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Appendix

A. Project brief

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title A multi-sensory intervention to nudge towards focus

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

A typical work session involves multiple cognitive processes, including initiation (decision-making and emotions) and task execution (focus and emotional regulation). Sustained attention plays a key role in maintaining performance but is frequently disrupted by external distractions, cognitive overload, and mental fatigue. However, focus does not operate as a constant state—it follows natural cycles that vary based on individual cognitive styles, work environments, and task demands. Some people thrive in deep work sessions with extended focus periods, while others perform better with frequent breaks or dynamic task switching. Digital tools, multitasking, and hybrid work environments often interfere with these natural rhythms, making it increasingly difficult to sustain focus effectively. This highlights the need for interventions that not only reduce distractions but also support individual attention patterns and cognitive transitions.
Many existing products attempt to address these cognitive obstacles using sensory interventions such as soundscapes and ambient lighting, but these solutions are typically static and non-adaptive to the user's real-time focus state. For example, soundscape applications like Endel claim to enhance concentration through personalized music generation, while Neurable's EEG-embedded headphones can track focus levels. However, these tools still rely on manual activation rather than real-time automation based on user needs. A logical next step would be to integrate sensing technology to automate interventions—for instance, playing focus-enhancing music when a system detects the user struggling to begin a task. This would require a practical method to remotely measure user's attention.
Beyond the technological challenges, another critical barrier to attention-tracking systems is privacy concerns. While community-driven solutions in smart home forums demonstrate interest in such automation, commercial implementation poses ethical and legal risks. With AI-driven emotion detection classified as high-risk under the EU AI Act, developing a privacy-protective and ethically sound approach is essential for broader acceptance of the product with sensing technologies.

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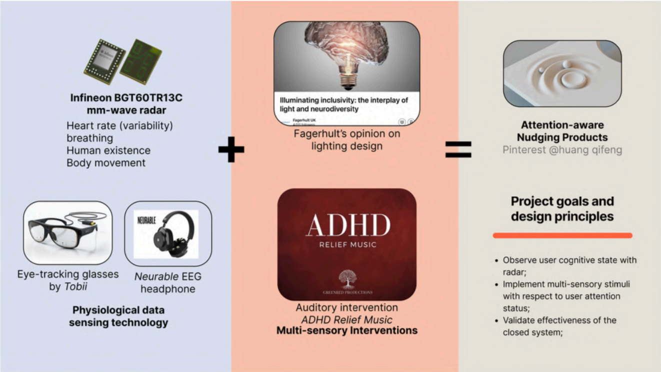


Project goals and design principles

- Observe user cognitive state with radar;
- Implement multi-sensory stimuli with respect to user attention status;
- Validate effectiveness of the closed system;

Design Outcome

- Explore various methodologies for effective nudging design practices;
- A sensing method that helps user to understand their attention;
- A desktop gadget with integrated visual, auditory and haptic feedback, based on mm-wave radar sensor.

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

In digital and hybrid work environments, sustaining focus is increasingly difficult due to distractions, cognitive overload, and mental fatigue. Existing sensory interventions, such as soundscapes and ambient lighting, remain static and non-adaptive, requiring manual activation and failing to support natural focus cycles, which vary across individuals and tasks.
A key challenge is helping users transition into and maintain focus without intrusive or rigid interventions. Both initiation (overcoming the inertia of starting work) and sustained attention (managing distractions and fatigue) play a role, yet many struggle with the initial hurdle of engagement, even when motivated. Structured rituals—such as adjusting lighting or playing specific sounds—can aid this process, but their effectiveness depends on adaptability to real-time cognitive states rather than pre-set routines.
At the same time, attention-tracking and adaptive interventions raise privacy and ethical concerns, particularly under the EU AI Act, which classifies AI-driven emotion detection as high-risk. Ensuring privacy protection and regulatory compliance is essential when designing interventions that influence cognitive states.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a multisensory intervention aligned with attention sensing technology that enables a natural focus cycle for professionals and students in desktop scenario.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

This graduation project follows a research-through-design approach, integrating psychological models of cognition, physiological sensing technologies, and iterative prototyping. By leveraging established attention models and current ethical guidelines, the design will recognize shifts in focus and respond through a multi-sensory intervention, creating personalized feedback loops to enhance concentration and allow gaps to rest.
I will use rapid prototyping to explore nudging mechanisms such as soundscapes, ambient lighting, and haptic feedback. In addition to intervention designs, a sensing method involving millimeter-wave radar (mm-wave radar) with respect to cardiac activity will be developed and tested to evaluate the attention status of the user working on desktop.
The project will adhere to existing ethical guidelines, including the AI Act, for implementing nudging techniques and physiological sensing. The outcome will be a validated prototype for attention-enhancing interventions and a comprehensive report on research process and applied design principles.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the f
chart format to show the different phases of your project, deliverables you have in m
Keep in mind that all activities should fit within the given run time of 100 working day
meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation cerem
activities and/or periods of not spending time on your graduation project, if any (for
course activities).

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting 11 March, 2025

Mid-term evaluation 5 May, 2025

Green light meeting 30 June, 2025

Graduation ceremony 28 July, 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

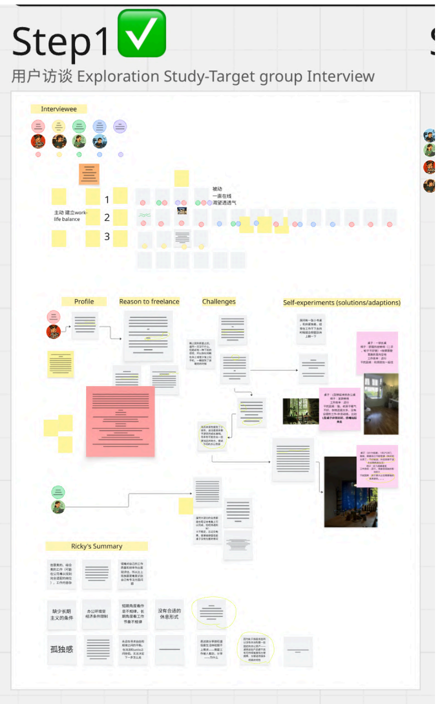
Motivation and personal ambitions

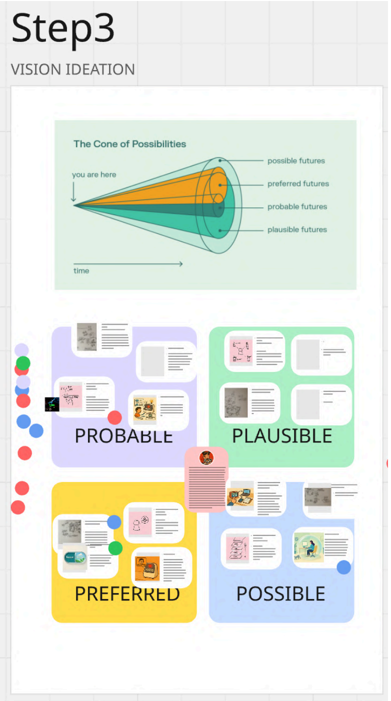
Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

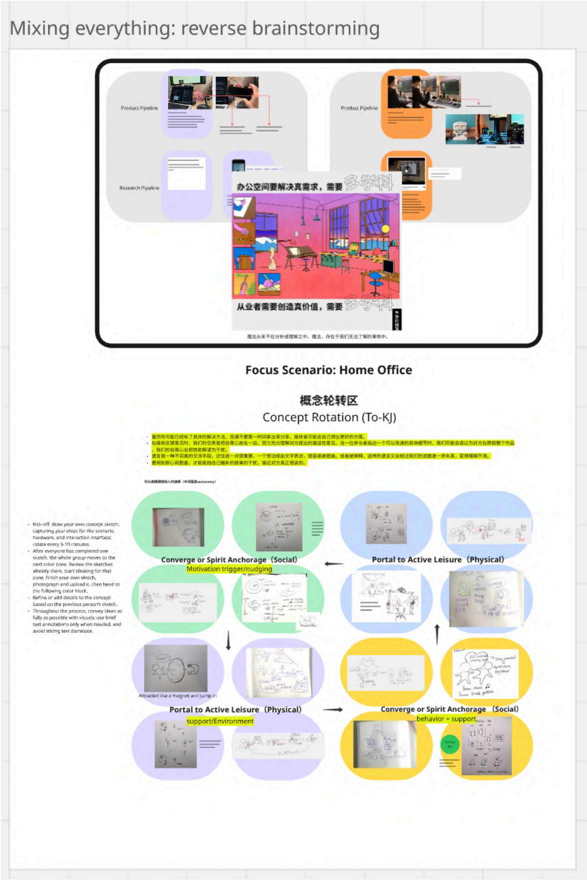
Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My motivation for this project stems from my deep interest in designing intelligent interfaces that enhance human cognition through multi-sensory interactions. As someone who has experienced challenges with focus, I see this as an opportunity to explore how sensing technologies and psychological models can create adaptive interventions that support sustained attention—particularly in the context of ADHD.
Through this project, I aim to develop expertise across design, technology, and business, ensuring a holistic approach. In design, I will refine my skills in human-centered interaction, multi-sensory feedback, and cognitive-aware interfaces to create an engaging and effective user experience. In technology, I will deepen my understanding of physiological sensing, radar-based attention tracking, and AI-driven nudging systems to build a robust, adaptive solution. Finally, in business, I will explore market opportunities, user adoption strategies, and commercialization models, laying the foundation for launching a company around this concept.

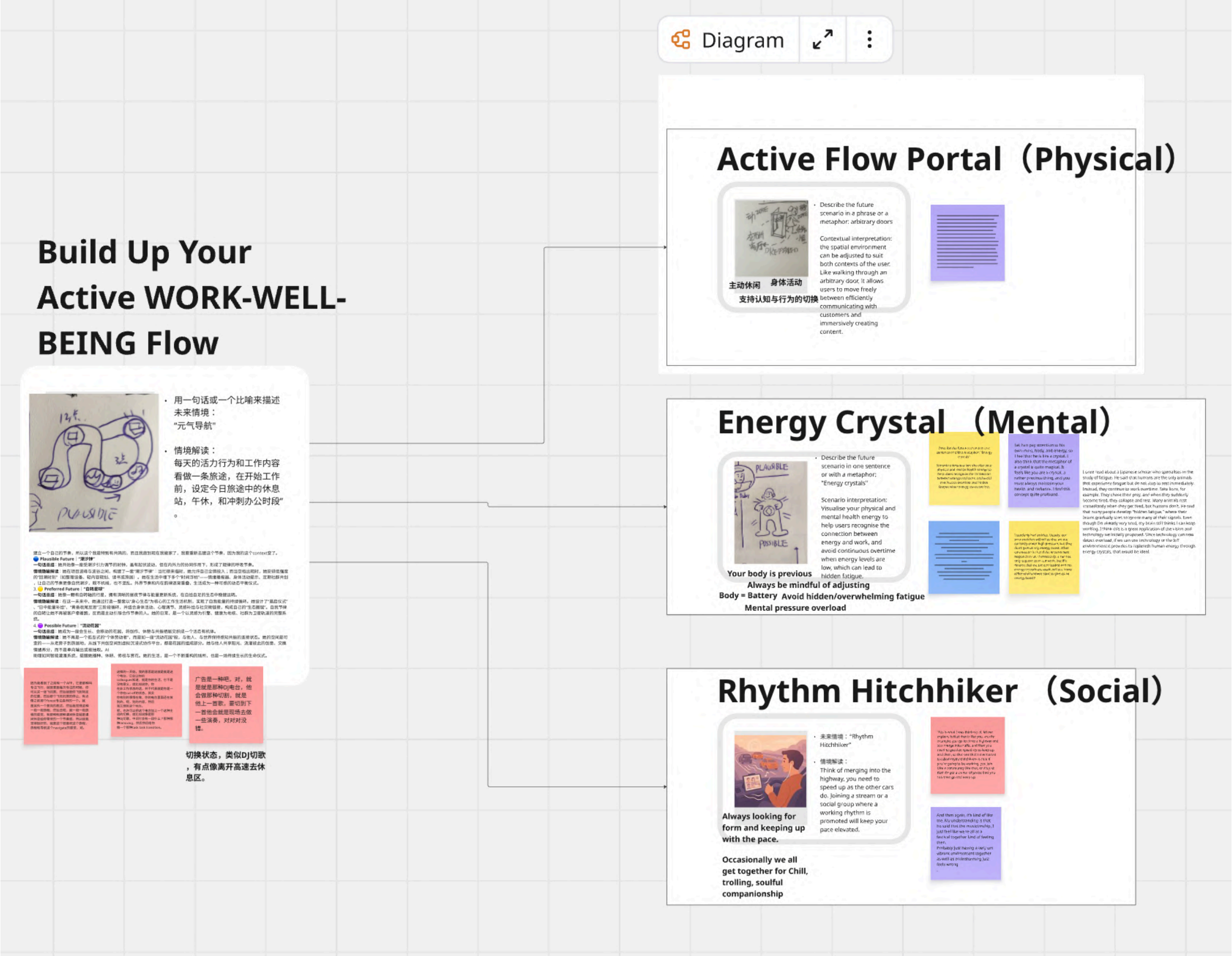
B. C4C Workshop Records







The final concepts were brainstormed based on design & research backgrounds, taking into account behavioural cues, technology, and possible future scenarios in C4C.



Build Up Your Active WORK-WELL-BEING Flow

- 用一句话或一个比喻来描述未来情境：
“元气导航”
- 情境解读：
每天的活力行为和工作内容看做一条旅途，在开始工作前，设定今日旅途中的休息站，午休，和冲刺办公时段”。

广告是一种吧，对，就是就是那种DJ电台，他会做那种切割，就是他上一首歌，要切到下一首他会就是现场去做一些演奏，对对对没错。

切换状态，类似DJ切歌，有点像离开高速去休息区。

Active Flow Portal（Physical）

支持认知与行为的切换

- Describe the future scenario in a phrase or a metaphor: arbitrary doors

Contextual interpretation: the spatial environment can be adjusted to suit both contexts of the user. Like walking through an arbitrary door, it allows users to move freely between efficiently communicating with customers and immersively creating content.

Energy Crystal （Mental）

- Describe the future scenario in one sentence or with a metaphor: "Energy crystals"

Scenario interpretation: Visualise your physical and mental health energy to help users recognise the connection between energy and work, and avoid continuous overtime when energy levels are low, which can lead to hidden fatigue.

Your body is previous
Always be mindful of adjusting
Body = Battery Avoid hidden/overwhelming fatigue
Mental pressure overload

Rhythm Hitchhiker （Social）

- 未来情境：“Rhythm Hitchhiker”
- 情境解读：
Think of merging into the highway, you need to speed up as the other cars do. Joining a stream or a social group where a working rhythm is promoted will keep your pace elevated.

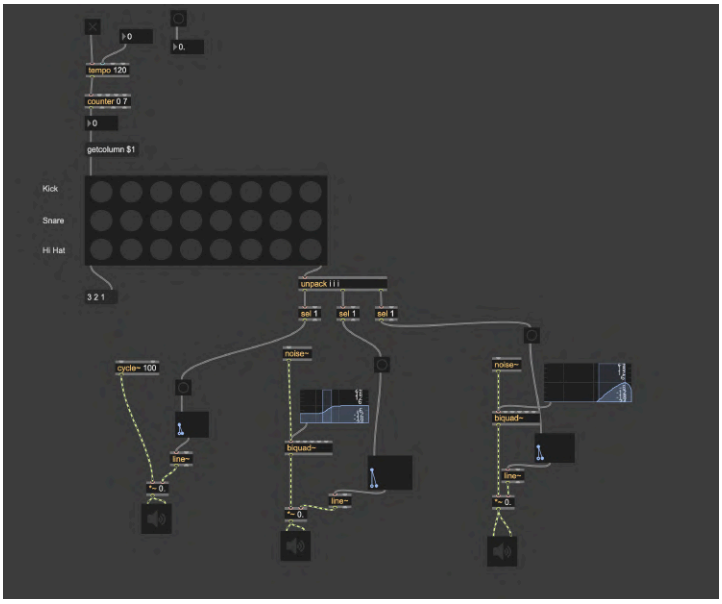
Always looking for form and keeping up with the pace.

Occasionally we all get together for Chill, trolling, soulful companionship

C. Max/MSP Music Patch

Learning tutorial: a kick, snare, and hat drum system

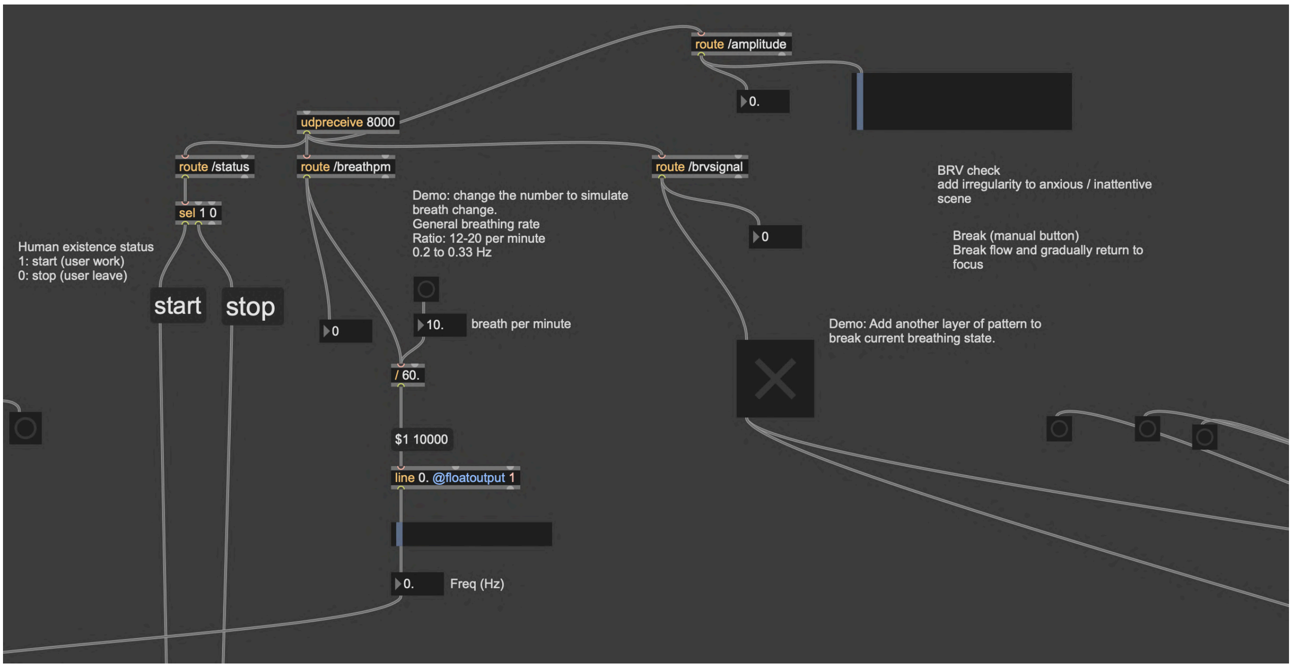
Reference: https://www.youtube.com/watch?v=j1ySd99uXkM



Learning outcome of basic MAX/MSP control.

Original generative ambient demo by Undulae:

Reference: https://www.youtube.com/watch?v=nQhsYv9w-z0



Human existence status
1: start (user work)
0: stop (user leave)

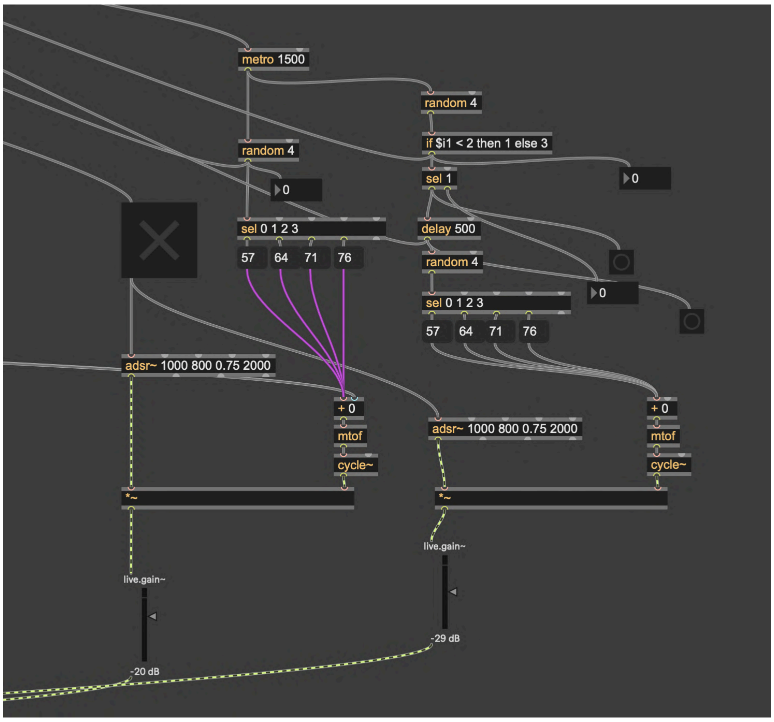
Demo: change the number to simulate breath change.
General breathing rate
Ratio: 12-20 per minute
0.2 to 0.33 Hz

BRV check
add irregularity to anxious / inattentive scene

Break (manual button)
Break flow and gradually return to focus

Demo: Add another layer of pattern to break current breathing state.

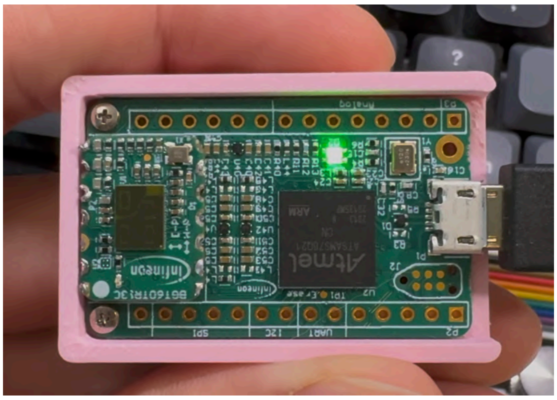
Control part of the generative ambient in MAX/Msp. It receives signal from OSC stream.



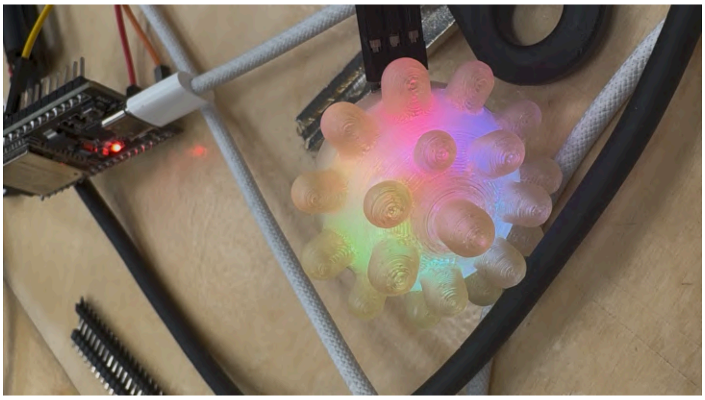
Fidgeting layer music generation in MAX/MSP

D. Prototype Iteration

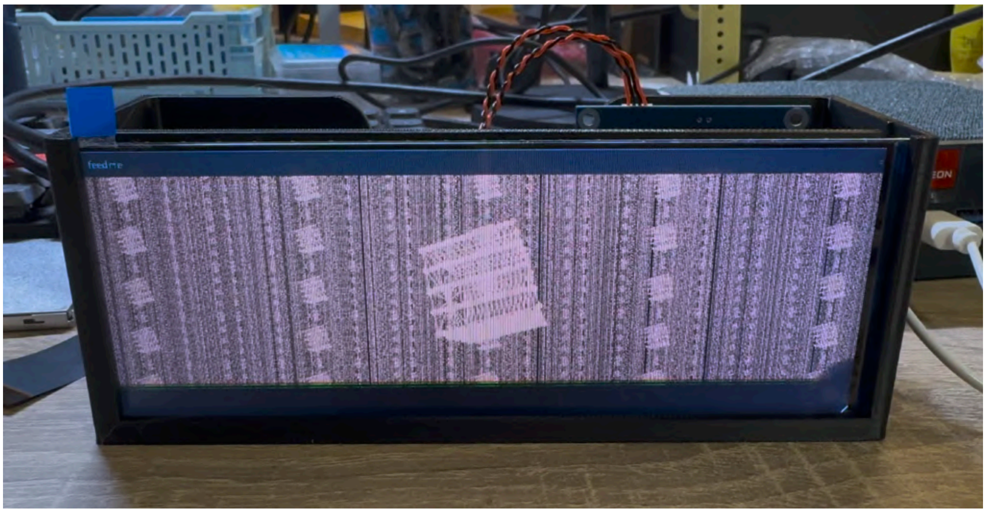
Evolution of the capsule body design



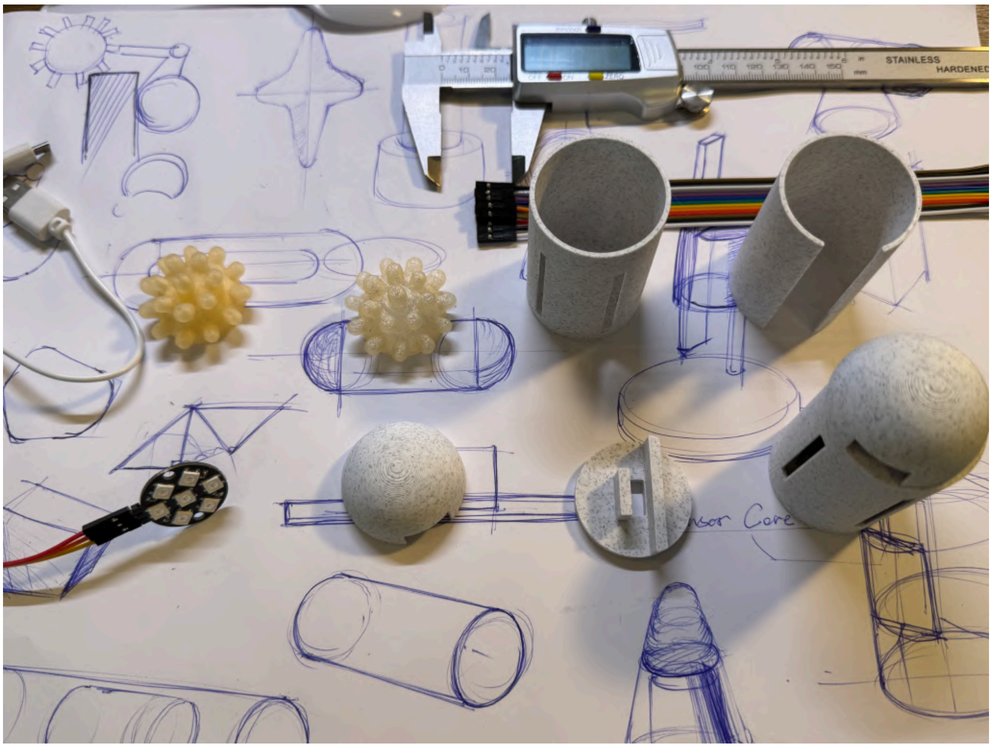
Mm-wave radar board



Early testing of rainbow color effect



A discarded screen prototype due to significant distractions as a visual stimulus



A collage of parts with sketching as background

E. User testing: detailed procedure and setup

This is a check list to prepare for the testing.

Experimental Setup

Location: The study was conducted in a studio room in Delft. The room was intentionally decorated to resemble a home office to evoke a familiar and informal working atmosphere.

Environment Control: Lighting and ambient noise levels were kept constant across all sessions. Participants were allowed to indicate preferred light and sound levels during the practice session; these were maintained for the remainder of their sessions. The researcher left the room after the practice phase to eliminate social facilitation effects, ensuring the workspace resembled a quiet, distraction-free environment.

Participant Scheduling and Pre-test Screening

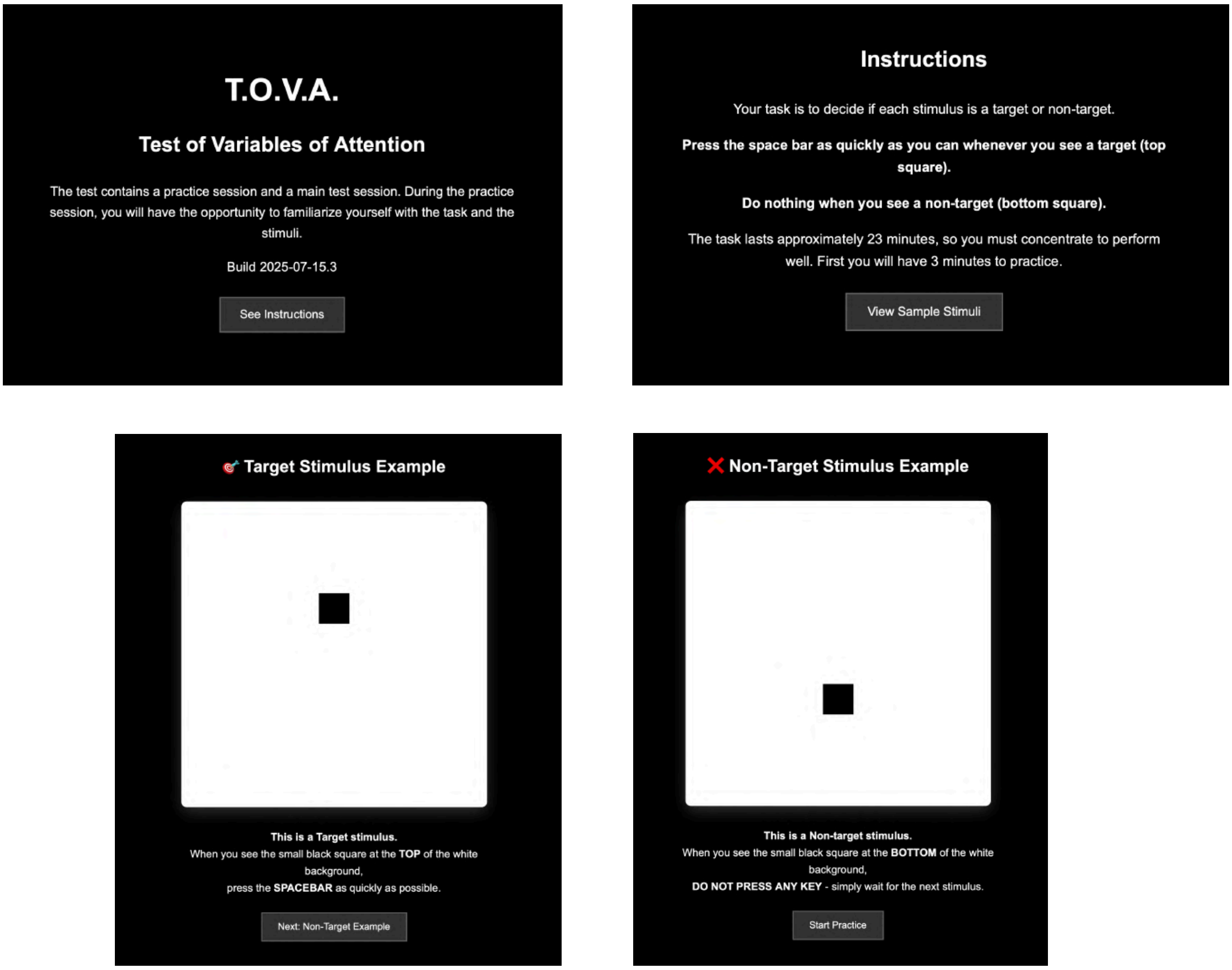
- Session Timing: Each participant completed two sessions on consecutive days. Sessions were scheduled at approximately the same time of day to minimize circadian influences on attention and mood.
- Pre-test Screening: Before each session, participants were required to confirm:
- Stable mood without extreme fluctuations.
- No intake of energy drinks.
- Adequate sleep the night before.
- Normal stress level.

Study Design and Condition Order

- Design: Within-subjects, two sessions per participant: baseline and intervention.
- Order Counterbalancing:
  - Standard (S) group: Day 1 = baseline, Day 2 = intervention.
  - Counterbalanced (C) group: Day 1 = intervention, Day 2 = baseline.
  - Random Assignment: Participants were randomly assigned to the S or C group, resulting in 9 participants in each subgroup.

Experimental Tasks

1. **Intervention System**
   - Activated automatically when participants sat down at the test station.
   - Delivered auditory and visual cues:
   - Breathing-paced ambient music.
   - Subtle visual animations synchronized with breathing rhythms.
   - When breathing rate exceeded 21 breaths per minute, syncopated melodic tones were introduced to guide participants back to a calmer rhythm.
2. **Attention Test (TOVA)**



T.O.V.A.

Test of Variables of Attention

The test contains a practice session and a main test session. During the practice session, you will have the opportunity to familiarize yourself with the task and the stimuli.

Build 2025-07-15.3

Instructions

Your task is to decide if each stimulus is a target or non-target.

Press the space bar as quickly as you can whenever you see a target (top square).

Do nothing when you see a non-target (bottom square).

The task lasts approximately 23 minutes, so you must concentrate to perform well. First you will have 3 minutes to practice.

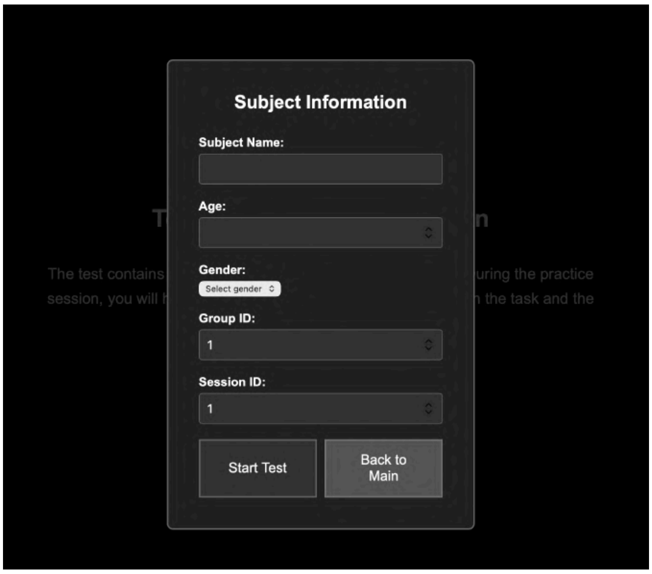
🎯 Target Stimulus Example

This is a Target stimulus.
When you see the small black square at the **TOP** of the white background,
press the **SPACEBAR** as quickly as possible.

❌ Non-Target Stimulus Example

This is a Non-target stimulus.
When you see the small black square at the **BOTTOM** of the white background,
DO NOT PRESS ANY KEY - simply wait for the next stimulus.

Interface of TOVA test, including the welcome page and instructions



Subject Information

Subject Name:

Age:

Gender: Select gender

Group ID: 1

Session ID: 1

Information Logging interface

- A 23-minute Continuous Performance Test requiring participants to differentiate between target and non-target stimuli on screen.

  - A 3-minute practice preceded the test. Practice data were not recorded.
  - Behavioural performance was logged automatically, including [blank] (e.g., commission errors, reaction times).

3. **Questionnaires**
  - PrEmo: administered pre-test (initial emotional state) and post-test (emotional response).
  - NASA-TLX: administered post-test only, to measure subjective workload.

Session Flow

Day 1

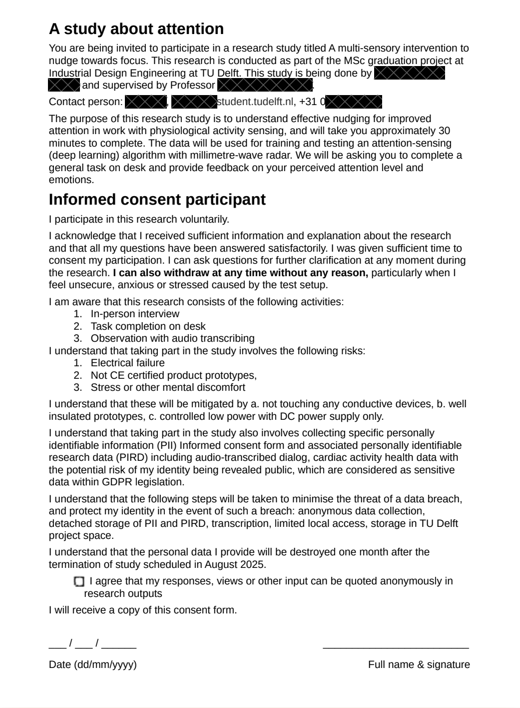
1. Welcome and informed consent.
2. Pre-test PrEmo emotional rating.
3. Collection of demographic information (age, gender).
4. Researcher introduction to TOVA, including interactive demo.
5. 3-minute practice trial (lighting/noise adjusted as preferred).
6. Researcher exits room.
7. 23-minute full TOVA test.
8. Researcher re-enters when participant opens the door.
9. Post-test NASA-TLX and PrEmo completed.

Day 2

1. Pre-test PrEmo emotional rating.
2. Confirmation of demographic information.
3. 3-minute practice trial.
4. Researcher exits room.
5. 23-minute full TOVA test (baseline or intervention, depending on order).
6. Researcher re-enters when participant opens the door.
7. Post-test NASA-TLX and PrEmo completed.

Notes on Excluded Research Question

Originally, the study intended to examine whether the intervention could reduce task initiation time. This was excluded because including task initiation measures would have introduced uncontrolled variables and compromised experimental validity.



A study about attention

You are being invited to participate in a research study titled A multi-sensory intervention to nudge towards focus. This research is conducted as part of the MSc graduation project at Industrial Design Engineering at TU Delft. This study is being done by [redacted] and supervised by Professor [redacted].

Contact person: [redacted], [redacted]student.tudelft.nl, +31 0[redacted]

The purpose of this research study is to understand effective nudging for improved attention in work with physiological activity sensing, and will take you approximately 30 minutes to complete. The data will be used for training and testing an attention-sensing (deep learning) algorithm with millimetre-wave radar. We will be asking you to complete a general task on desk and provide feedback on your perceived attention level and emotions.

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research. **I can also withdraw at any time without any reason,** particularly when I feel unsecure, anxious or stressed caused by the test setup.

I am aware that this research consists of the following activities:
1. In-person interview
2. Task completion on desk
3. Observation with audio transcribing

I understand that taking part in the study involves the following risks:
1. Electrical failure
2. Not CE certified product prototypes,
3. Stress or other mental discomfort

I understand that these will be mitigated by a. not touching any conductive devices, b. well insulated prototypes, c. controlled low power with DC power supply only.

I understand that taking part in the study also involves collecting specific personally identifiable information (PII) Informed consent form and associated personally identifiable research data (PIRD) including audio-transcribed dialog, cardiac activity health data with the potential risk of my identity being revealed public, which are considered as sensitive data within GDPR legislation.

I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: anonymous data collection, detached storage of PII and PIRD, transcription, limited local access, storage in TU Delft project space.

I understand that the personal data I provide will be destroyed one month after the termination of study scheduled in August 2025.

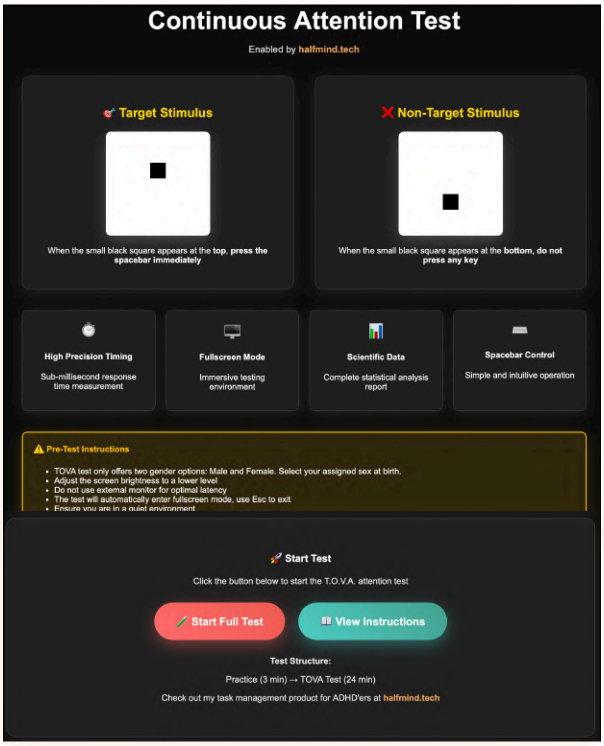
☐ I agree that my responses, views or other input can be quoted anonymously in research outputs

I will receive a copy of this consent form.

___ / ___ / ______ ____________________________

Date (dd/mm/yyyy) Full name & signature

Informed consent form



Continuous Attention Test

Enabled by halfmind.tech

Target Stimulus

When the small black square appears at the **top, press the spacebar immediately**

Non-Target Stimulus

When the small black square appears at the **bottom, do not press any key**

High Precision Timing

Sub-millisecond response time measurement

Fullscreen Mode

Immersive testing environment

Scientific Data

Complete statistical analysis report

Spacebar Control

Simple and intuitive operation

⚠ Pre-Test Instructions

- TOVA test only offers two gender options: Male and Female. Select your assigned sex at birth.
- Adjust the screen brightness to a lower level
- Do not use external monitor for optimal latency
- The test will automatically enter fullscreen mode, use Esc to exit
- Ensure you are in a quiet environment

Start Test

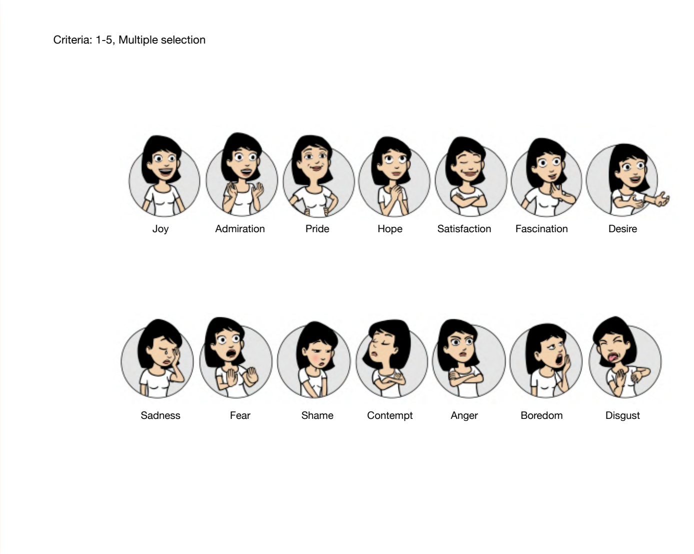
Click the button below to start the T.O.V.A. attention test

Test Structure:

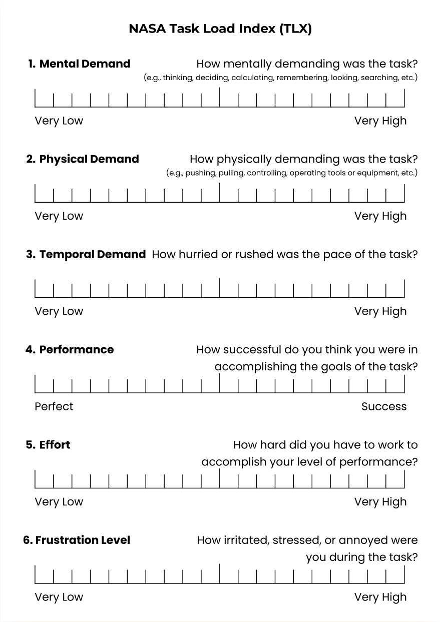
Practice (3 min) → TOVA Test (24 min)

Check out my task management product for ADHD'ers at halfmind.tech

Screenshot of TOVA test landing page



Criteria: 1-5, Multiple selection



NASA Task Load Index (TLX)

1. Mental Demand How mentally demanding was the task?
(e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)

Very Low Very High

2. Physical Demand How physically demanding was the task?
(e.g., pushing, pulling, controlling, operating tools or equipment, etc.)

Very Low Very High

3. Temporal Demand How hurried or rushed was the pace of the task?

Very Low Very High

4. Performance How successful do you think you were in accomplishing the goals of the task?

Perfect Success

5. Effort How hard did you have to work to accomplish your level of performance?

Very Low Very High

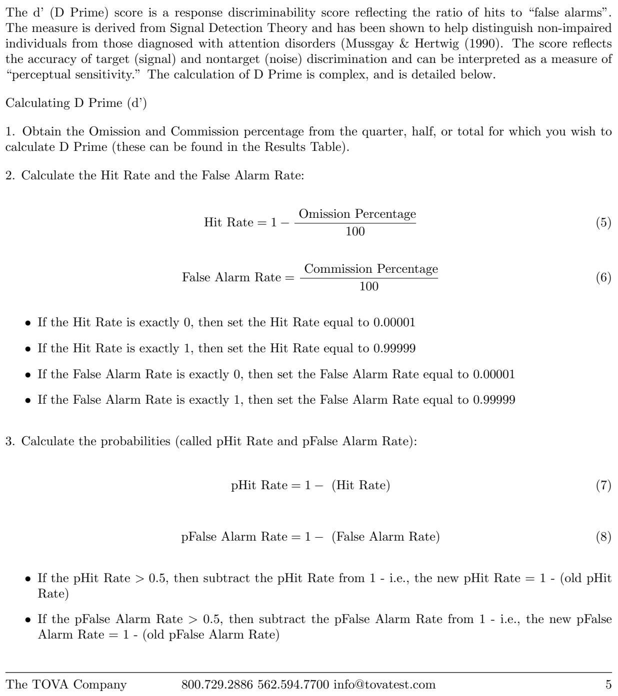
6. Frustration Level How irritated, stressed, or annoyed were you during the task?

Very Low Very High

Feedback form of PrEmo and NASA-TLX

F. Calculating D Prime

This part is excerpted from TOVA manual, to properly calculate D Prime, which reflects the ratio of hits to "false alarms".



The d' (D Prime) score is a response discriminability score reflecting the ratio of hits to "false alarms". The measure is derived from Signal Detection Theory and has been shown to help distinguish non-impaired individuals from those diagnosed with attention disorders (Mussgay & Hertwig (1990). The score reflects the accuracy of target (signal) and nontarget (noise) discrimination and can be interpreted as a measure of "perceptual sensitivity." The calculation of D Prime is complex, and is detailed below.

Calculating D Prime (d')

1. Obtain the Omission and Commission percentage from the quarter, half, or total for which you wish to calculate D Prime (these can be found in the Results Table).

2. Calculate the Hit Rate and the False Alarm Rate:

$$\text{Hit Rate} = 1 - \frac{\text{Omission Percentage}}{100} \tag{5}$$

$$\text{False Alarm Rate} = \frac{\text{Commission Percentage}}{100} \tag{6}$$

- If the Hit Rate is exactly 0, then set the Hit Rate equal to 0.00001
- If the Hit Rate is exactly 1, then set the Hit Rate equal to 0.99999
- If the False Alarm Rate is exactly 0, then set the False Alarm Rate equal to 0.00001
- If the False Alarm Rate is exactly 1, then set the False Alarm Rate equal to 0.99999

3. Calculate the probabilities (called pHit Rate and pFalse Alarm Rate):

$$\text{pHit Rate} = 1 - \ (\text{Hit Rate}) \tag{7}$$

$$\text{pFalse Alarm Rate} = 1 - \ (\text{False Alarm Rate}) \tag{8}$$

- If the pHit Rate > 0.5, then subtract the pHit Rate from 1 - i.e., the new pHit Rate = 1 - (old pHit Rate)
- If the pFalse Alarm Rate > 0.5, then subtract the pFalse Alarm Rate from 1 - i.e., the new pFalse Alarm Rate = 1 - (old pFalse Alarm Rate)

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T.O.V.A. 7.3 Professional Manual 1 INTRODUCTION TO THE T.O.V.A.

4. Calculate the Z scores (called zHit Rate and zFalse Alarm Rate):

If you have access to a spread sheet or statistical program:

- zHit Rate = InverseDistributionFunction(pHit Rate)
- zFalse Alarm Rate = InverseDistributionFunction(pFalse Alarm Rate)
- Skip directly to Part 5

Otherwise (Ref 1),

$$\text{Let T} = \sqrt{\ln \frac{1}{\text{pHit Rate}^2}} \tag{9}$$

$$\text{zHit Rate} = T - \frac{2.515517 + 0.802853 \times T + 0.010328 \times T^2}{1 + 1.432788 \times T + 0.189269 \times T^2 + 0.001308 \times T^3} \tag{10}$$

$$\text{Let T} = \sqrt{\ln \frac{1}{\text{pFalse Alarm Rate}^2}} \tag{11}$$

$$\text{zFalse Alarm Rate} = T - \frac{2.515517 + 0.802853 \times T + 0.010328 \times T^2}{1 + 1.432788 \times T + 0.189269 \times T^2 + 0.001308 \times T^3} \tag{12}$$

- If the pHit Rate was ≤ 0.5 , multiply the zHit Rate by -1
- If the pFalse Alarm Rate was ≤ 0.5, multiply the zFalse Alarm Rate by -1

5. Calculate D Prime:

D Prime = zFalse Alarm Rate - zHit Rate

(Ref 1: Approximation to the Inverse Normal Distribution Function. The Handbook of Mathematical Functions, Abramowitz and Stegun, Section 26.2.23)

The ADHD score is a comparison between the subject's T.O.V.A. performance to an identified ADHD sample's performance. The score tells how similar the performance is to the ADHD profile.

The formula used to derive the ADHD score is as follows:

ADHD Score = Response Time Z score (Half 1) + D' Z score (Half 2) + Variability Z score (Total)

Post-Commission Response Time is the measure of time (in milliseconds) that the subject took to respond to a target immediately after a commission had been recorded.

The formula used to derive the Post-Commission Response Time is as follows:

$$\text{Post Commission Response Time} = \frac{\Sigma \text{ Post Commission Response Times}}{\#\text{ Post Commission Responses}} \tag{13}$$

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G. TOVA Result with "ADHD Relief Music"

The motivation for this project was partly inspired by anecdotal reports and personal observations of "ADHD Relief Music," which is widely circulated online as enhancing focus (see https://www.youtube.com/watch?v=RG2IK8oRZNA). To preliminarily explore this phenomenon, a supplementary test was conducted following the same within-subject design as the main study. Participants were divided into a standard-order group (Group 1, n = 9) and a counterbalanced-order group (Group 2, n = 8).

For Group 1, paired-sample t-tests revealed a significant improvement in attentional performance across sessions (p = .013). Normality assumptions were met (Shapiro–Wilk

W(9) = .86, p = .092). In contrast, Group 2 did not show significant improvement (p = .498), with data again satisfying normality (Shapiro–Wilk W(8) = .87, p = .180). These findings suggest that the observed benefits of ADHD Relief Music were primarily evident in the standard-order condition and may have been obscured by order effects in the counterbalanced group.

ADHD Relief Music By GREENRED Productions

The ADHD Relief Music condition was associated with reliable performance gains when presented after a baseline session (standard order), but not when presented first. The significant between-group ANOVA on improvement indicates a pronounced sequence (order) effect, suggesting interaction between the intervention and session order (e.g., novelty/contrast or carryover interacting with test–retest characteristics). These exploratory findings support continued development and testing of music patterns while highlighting the need for order-robust designs (e.g., between-subjects comparisons, longer washout, or three-session AB/BA with a follow-up baseline) to isolate intervention effects from sequence influences.