A Health-Enhancing Design Framework: Ecological-Enabling Product and Environmental Design Strategies for Sedentary Populations

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Abstract—**Background: As digitally enabled and "smart" workplace settings become increasingly common, prolonged sitting in offices has evolved into a worldwide public-health issue. Sustained sedentary exposure is associated with markedly higher probabilities of cardiovascular disease, metabolic syndrome, and increased all-cause mortality. Although many organizations have introduced countermeasures—such as wellness seminars, periodic health education, or the provision of single-purpose exercise devices—these efforts frequently show weak durability over time. A major limitation is that such interventions are often separated from everyday work practices and do not adequately account for the continuously shifting person–environment relationship that shapes behavior in real contexts. Accordingly, current research still lacks a systematic approach for coupling products with environmental features to establish an integrated, ecology-based health-support system.**

Methods: To respond to this research gap, the present study develops a Health-Enhancing Design Framework (HEDF) grounded in ecological psychology, with Affordance Theory as its primary conceptual foundation. Instead of relying on external pressure or explicit enforcement, the framework is designed to prompt and invite movement in a natural manner during routine office activities. This objective is achieved by defining and designing Ecological-Enabling Units (EEUs)—coordinated assemblages of product attributes and environmental signals that operate synergistically to encourage activity with minimal disruption to work.

Implementation: A mixed-methods strategy was adopted to validate both the framework and its practical application. First, contextual inquiry combined with direct observation was conducted to examine behavioral routines, constraints, and health-related needs among 30 sedentary office employees. Second, following HEDF guidance, an ecological-enabling product–environment system (HED-PES) was designed and prototyped, consisting of a smart sit–stand workstation, floor-level visual guidance elements, and a desktop micro-interaction object intended to trigger subtle, low-effort movement opportunities. Third, a four-week pragmatic, parallel-group randomized trial (N = 60) was implemented in an operational office environment. Because blinding is inherently difficult for interventions that modify both products and surroundings, masking was not implemented; therefore, the evaluation emphasized objective accelerometer-derived metrics, collected under standardized protocols during defined work-hour periods.

Results: The findings indicate that the intervention developed under HEDF principles produced robust and statistically significant benefits. Relative to baseline, the experimental group demonstrated a 75.3-minute decrease in average daily total sedentary duration ($p < 0.001$), a 48.5% increase in the frequency of sedentary interruptions ($p < 0.01$), and a 60.8-minute increase in light physical activity (LPA) time ($p < 0.001$). Qualitative feedback further suggested that, by embedding prompts and action opportunities directly into the workflow, the system reduced the cognitive effort required for behavior change while strengthening intrinsic motivation and perceived health self-efficacy.

Conclusion: The proposed Health-Enhancing Design Framework (HEDF) provides a structured and context-sensitive design paradigm for mitigating sedentary behavior in office environments. Rather than treating products or spatial modifications as isolated solutions, the framework emphasizes designing for an enabling feedback loop between individuals and their surroundings, thereby supporting sustained behavior change through everyday affordances. In doing so, HEDF offers designers, organizational leaders, and public-health decision-makers a theoretically grounded and practically actionable toolset for developing scalable, durable workplace health-promotion strategies.

Keywords—Health-Enhancing Design, Sedentary Behavior, Affordance Theory, Ecological Enablement, Product-Environment Systems, Design Strategy

I. INTRODUCTION

The global transition toward knowledge-intensive, digital-first economic models has profoundly altered how office work is organized and performed. Widespread computer use, routine remote collaboration, and the embedding of intelligent workplace systems have improved productivity, yet they have also intensified a serious public-health concern: sedentary behavior has become pervasive in modern offices [1]. In 2024, the World Health Organization (WHO) reported that close to one in three adults worldwide — about 1.8 billion people — do not achieve sufficient physical activity, placing them at heightened health risk [2]. A large body of clinical and epidemiological evidence links extended sitting with greater incidence of cardiovascular disease, type 2 diabetes, several cancers, and higher all-cause mortality [3, 4]. Moreover, a recent Journal of the American Medical Association (JAMA) report noted that workers in predominantly seated occupations face a 16% increase in all-cause mortality risk and a 34% increase in

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cardiovascular mortality risk [5]. These findings indicate that sedentary behavior is no longer merely an individual preference; it has become a structural issue shaped by social and environmental conditions, requiring systematic remedies.

Over the last decade, multiple strategies have been deployed to reduce workplace sitting, including corporate wellness talks, onsite exercise initiatives, and the adoption of single devices such as sit – stand desks or office exercise bikes. Although such measures can enhance awareness, their sustained impact is often limited. A central reason is that many interventions remain at the level of "delivering information" or "adding functional options," without directly addressing how behavior is produced through a shifting interaction between individuals and their surrounding context. In practice, healthy actions are frequently positioned as extra tasks that demand willpower, while the continuity and immersion of work processes make persistent adherence difficult. This mismatch — often described as an "intention – behavior gap" — reveals deficiencies in integration, contextual fit, and long-term viability within current approaches [6]. Accordingly, research needs to move beyond isolated, point-based solutions and toward the construction of an enabling ecosystem that makes healthier behavior more attainable by design.

From an environmental design standpoint, scholars have begun to explore approaches such as the "Active Design" movement, which promotes physical activity through architectural planning and spatial configuration [7]. Yet, as Koohsari et al. (2024) argued, much of the evidence still centers on the effects of individual design features (e.g., stair visibility) rather than explaining how workplace norms, organizational culture, and overall spatial layout jointly shape behavior [8]. In addition, a notable gap persists in connecting macro-level environmental strategies with micro-level, user-adjacent product design so that the two operate as a coherent "Product – Environment System" (PES). When broader spatial modifications are not aligned with daily workflow and proximate interactions, design intentions may fail to translate into natural, durable behavior change.

To address this disconnect, the present study adopts Affordance Theory from ecological psychology as a conceptual link between perception and environmental action possibilities [9]. In this view, environments present opportunities for action to an actor: a cup supports grasping, a chair supports sitting, and an open field supports running. Affordances are neither purely subjective impressions nor solely objective properties; rather, they are relational characteristics of an "actor – environment" system, contingent on both environmental structures (e.g., chair form) and the actor's capabilities and goals (i.e., "effectivities"). This perspective suggests a design shift: instead of instructing users to move, designers can shape product and environmental affordances that gently invite and guide movement as part of everyday activity.

Building on this foundation, the study proposes and validates a Health-Enhancing Design Framework (HEDF). Its central aim is to create an office ecosystem that repeatedly prompts light physical activity and interrupts prolonged sitting by systematically composing a series of interconnected, synergistic Ecological-Enabling Units — coordinated product and environmental cues that function together.

This interdisciplinary design research integrates public health, human – computer interaction, environmental psychology, and product design. Beyond introducing a framework, the work demonstrates feasibility and effectiveness through a full "design – develop – validate" pathway. Specifically, the study first identifies key needs and behavioral barriers among sedentary office users via empirical research, then develops an ecological-enabling product system guided by HEDF, and finally assesses outcomes through a quasi-experimental evaluation using objective measurement.

The remainder of the paper is organized as follows. Section 2 reviews prior work on sedentary-behavior interventions, affordance theory, and health-oriented environmental design to clarify the contribution of this study. Section 3 outlines the theoretical structure of HEDF and the methods used for user research, system development, and experimental procedures. Section 4 reports results, combining quantitative behavioral indicators with qualitative feedback. Section 5 discusses implications relative to existing literature, and Section 6 summarizes contributions, practical and theoretical significance, limitations, and future research directions.

II. Related Work

Positioned at the intersection of public health, design science, and environmental psychology, this research requires an integrated review of three streams. First, it examines dominant intervention approaches for sedentary behavior and their limitations. Second, it surveys environmental design efforts intended to increase physical activity, highlighting unresolved challenges. Third, it introduces affordance theory as the primary theoretical basis for an operational design framework, thereby articulating the study's distinctive positioning.

A. Evolution and Limitations of Sedentary Behavior Interventions

Workplace sedentary interventions can be roughly grouped into three stages.

Phase 1: Information-driven approaches. These efforts assume that increasing knowledge will lead to healthier actions, typically via lectures, posters, and email reminders about the harms of sitting and the benefits of movement [10]. While awareness may rise in the short term, extensive evidence shows that knowledge gains do not reliably translate into sustained behavior change [6]. The core weakness is an overly rational model of decision-making that downplays the constraints imposed by environments, habits, and workflow.

Phase 2: Device-centric approaches. This stage is exemplified by ergonomic products, especially sit – stand desks. Systematic reviews indicate that sit – stand desks can reduce total sitting time [11, 12]. However, maintaining usage over time is difficult; without ongoing prompts, standing frequency often declines [13]. Additionally, reductions in sitting do not consistently yield clear improvements in cardiovascular markers such as blood pressure [14]. These findings imply that a single device, when not supported by broader context and routines, produces effects that are isolated and prone to attenuation. Other devices (e.g., under-desk treadmills or cycles) face scalability challenges due to cost and disruption of work activities.

Phase 3: Digital intervention approaches. Here, wearables and apps support tracking and motivation, often using gamification and persuasive technology through goal-setting, feedback, and social comparison [15, 16]. Although personalization and continuous monitoring are strengths, limitations remain: repeated prompts can create notification fatigue; many systems emphasize abstract targets (steps, calories) rather than embedding change within concrete tasks and physical settings; and motivation may rely heavily on external rewards, with uncertain transfer from virtual achievements to natural physical activity.

Overall, many strategies reflect a persistent "subject–object" separation that treats health behaviors and work tasks as distinct—and sometimes competing—domains. This framing turns interventions into add-on activities that consume additional cognitive resources, making them hard to weave into everyday workflow and weakening long-term outcomes. Future work should therefore aim to dissolve this divide, allowing healthier behavior to become endogenous to work contexts.

B. The Role and Challenges of Environmental Design in Health Promotion

"Active Design"represents a major shift from individual-focused solutions toward environment-oriented interventions. It promotes daily activity through architectural and planning strategies such as attractive staircases, improved connectivity, and optimized walking routes [7, 17]. Within offices, studies have examined open layouts, shared-space placement, and the inclusion of natural elements as determinants of movement and interaction [18]. Collectively, these findings suggest that physical settings can function as a quiet regulator of behavior.

Nevertheless, Koohsari et al. (2024) identified several persistent gaps in active design research [8]. First, many studies use a linear "element–behavior" lens, linking a single feature (e.g., a window) to a discrete behavior (e.g., standing) while neglecting the systemic influence of overall layout. Connectivity, accessibility, and functional zoning create a space syntax that shapes movement patterns more fundamentally. Second, socio-cultural factors are often underexamined: meeting norms, overtime practices, and organizational culture can amplify or suppress environmental effects. The same open plan may encourage movement in a communication-oriented culture but generate resistance in settings prioritizing quiet focus. Third, measurement constraints limit insight. Questionnaires and simple observation may miss fine-grained indoor trajectories; GPS is unreliable indoors, hindering precise "space–time–behavior" modeling.

Thus, environmental design remains promising but demands a more integrated and higher-resolution analytical framework that: (1) shifts from single elements to system-level layout; (2) jointly considers physical and socio-cultural context; and (3) leverages advanced sensing to quantify behavior precisely. Crucially, a theory is needed to connect environmental properties, psychological perception, and observed behavior.

C. Affordance Theory as a Link Between Environment and Behavior

Affordance theory, introduced by ecological psychologist James J. Gibson, provides a strong conceptual foundation for these needs [9]. It argues that environments present actionable possibilities to organisms. Affordances are relational: they emerge from the pairing of environmental structures and an actor's capabilities and goals ("effectivities"), rather than residing solely in objects or solely in subjective interpretation.

The concept has been widely used in HCI and product design, and Donald Norman extended it through "perceived affordance," emphasizing how visible cues communicate possible actions (e.g., a door handle signaling push vs. pull) [19]. This notion aligns with the aim of shaping behavior through design—guiding action without relying on explicit instruction—thereby supporting an "invite, not coerce" approach to sedentary-behavior change.

Applied to office sedentariness, affordance theory reframes intervention from "adding features" to "building invitations." The goal is not simply to provide a sit–stand desk as an option, but to orchestrate a set of affordances that makes standing and micro-movement more likely. For instance, a smart sit–stand desk might detect sitting duration and prompt posture change via subtle rhythmic lighting; complementary floor cues could encourage small relocations while standing; and a distant view could invite gaze shifts and brief postural adjustments. In combination, these elements form an ecological-enabling system that establishes a contextual field in which movement becomes a fluid, environmentally elicited response rather than a separate willpower-dependent task.

D. Research Gap and Positioning

The review indicates three central gaps: (1) existing sedentary interventions often lack systemic integration and contextual alignment, undermining sustainability; (2) active design research, despite promise, insufficiently addresses whole-layout effects, socio-cultural moderators, and product–environment synergy; and (3) affordance theory is seldom translated into a structured, operational framework specifically for health promotion among sedentary office populations.

To address these gaps, this study develops and validates an affordance-based Health-Enhancing Design Framework (HEDF). The framework targets the creation of an ecological-enabling system that integrates with daily workflow and continuously guides transitions from sitting to light activity by designing synergistic affordances across products and environments. The study's contributions are summarized as follows:

Theoretical innovation: advancing affordance theory from an explanatory lens to a generative, implementable design framework (HEDF) for health-oriented intervention design.

System-level integration: introducing Ecological-Enabling Units and emphasizing coordinated product–

environment affordance design to build an integrated Product－Environment System.

Contextual intervention: prioritizing seamless embedding within real tasks and spaces to lower cognitive burden and improve long-term adoption.

Empirical validation: employing a mixed-methods “user research － prototype － quasi-experiment ” loop with objective measurement to test effectiveness.

Through this work, the study seeks to provide both a practical response to office sedentary behavior and a broadly applicable framework and methodology for health-oriented design.

III. Methodology

This study employed a mixed-methods design, systematically combining theoretical framework construction, qualitative inquiry, and quantitative experimentation to ensure both the depth and validity of the research. The entire process followed a structured, three-phase model: Phase 1 involved theoretical framework construction and user needs exploration; Phase 2 focused on the design and development of an ecological-enabling system based on the framework; and Phase 3 consisted of a quasi-experimental validation and effectiveness evaluation conducted in a real-world office environment. The overall technical roadmap of this study is illustrated in Figure 1.

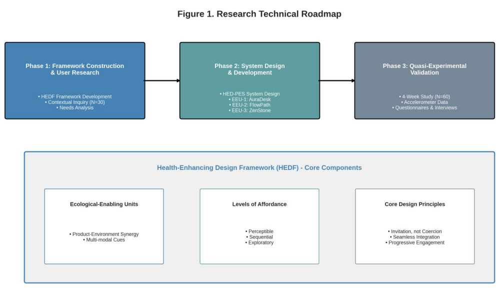

Fig. 1. Research Technical Roadmap

A. *Construction of the Health-Enhancing Design Framework (HEDF)*

The primary theoretical contribution of this study is the development of the Health-Enhancing Design Framework (HEDF). The framework is designed to equip designers with a systematic, implementable set of guidance for creating product － environment systems that support healthier behavior patterns. HEDF is rooted in ecological psychology—especially Gibson’s affordance perspective—and is further informed by established insights from behavioral science and human － computer interaction (HCI) design.

The framework is organized around three key elements:

1) Ecological-Enabling Unit (EEU)

EEU serves as the basic unit for both analysis and design within HEDF. In this study, an EEU is defined as “one or multiple coordinated product/environment cues that jointly generate a perceived affordance and thereby steer a specific health-related behavior.” For instance, combining “ambient-light prompts from a smart sit － stand desk” with “floor-projected dynamic light patterns” can together constitute an affordance that gently encourages standing and small-area movement. A central design task is to ensure that different EEUs are not isolated; instead, they should be connected to form an “ affordance network ” spanning the full office context.

2) Affordance Levels

To support a shift from passive compliance to active engagement, HEDF classifies the affordances involved in interventions into three tiers:

Perceptible affordance: Clear, immediately interpretable cues indicating that an action is possible (e.g., a lit control suggesting it can be pressed). This level functions as the entry point for behavioral guidance.

Sequential affordance: Cues that make the next action visible only after the user completes a preceding action. For example, floor guidance lighting appears after the user transitions to standing, enabling coherent behavioral sequences.

Exploratory affordance: Less explicit action possibilities that require users to discover them through interaction (e.g., staying in a certain area triggers an additional mode). This level is intended to maintain novelty and encourage sustained engagement over time.

3) Core Design Principles

HEDF further summarizes three principles to direct EEU design and deployment:

Invitation over coercion: Cues should remain suggestive, low-pressure, and minimally disruptive, preserving user autonomy. Mandatory alarms and hard interruptions are avoided in favor of gentle invitations via ambient light, sound, or atmosphere.

Seamless integration: Health-oriented prompts should be embedded within the primary workflow rather than treated as extra tasks. For example, reminders can be aligned with natural pauses (e.g., refilling water, printing documents).

Progressive engagement: The system should adapt intervention frequency and intensity in response to user behavior, enabling gradual progression from simpler actions (standing) toward more complex ones (stretching, brief walking), thereby reducing early-stage overload.

B. *User Research and Ecological-Enabling System Design*

Following the HEDF logic, we conducted user research to clarify requirements and translate them into a concrete product－environment solution.

1) Participants and Data Collection

Thirty sedentary office employees were recruited (18 men, 12 women; mean age 31.2 ± 5.6 years). All participants met the inclusion criterion of self-reported sitting time exceeding 6 hours per workday. Data were collected through contextual inquiry and an “ A Day in the Life ” mapping exercise. Participants were asked to reconstruct and describe their daily workflow, habitual behaviors, and interactions with the office setting while remaining in their actual work environment. Each session lasted about 90 minutes, with audio recordings and photographs taken for subsequent analysis.

2) Analysis and Extraction of Core Needs

Interview transcripts and visual mappings were analyzed using a grounded theory approach. Three primary barriers to interrupting sedentary patterns were identified:

- Time distortion caused by deep task immersion — participants often lost awareness of how long they had been seated.
- An initiation barrier—although many knew they shou ld move, transitioning from "sitting" to "standing/ walking" required considerable psychological activati on.
- Environmental negative affordances — conventional offices are saturated with cues that promote sitting (comfortable seating, highly reachable items) while offering few stimuli that invite movement.

Development of the Health-Enhancing Product – Environment System (HED-PES)

Based on these findings and the HEDF, we designed and implemented an ecological-enabling product – environment system termed HED-PES. It includes three core EEUs:

a) EEU-1: AuraDesk

AuraDesk is a smart sit – stand workstation equipped with micro-sensors and an ambient light strip. It monitors seated duration, and once sitting exceeds a predefined limit (e.g., 50 minutes), the desk-edge light begins a slow, "breathing-like" pulse in a warm, soft color (Invitation principle). This cue functions as a perceptible affordance, subtly prompting the user to consider standing. When the user chooses to stand (manual or voice control), the lighting changes to a steady gentle glow as positive reinforcement.

b) EEU-2: FlowPath

FlowPath is a micro-projection unit synchronized with AuraDesk. After a sit-to-stand transition, it projects slowly moving light textures onto the floor around the user's feet, thereby creating a sequential affordance. Rather than directing a fixed route, the projected pattern evolves within a limited zone, encouraging unconscious weight shifts or short steps that activate lower-limb muscles while remaining compatible with ongoing work (Seamless integration principle).

c) EEU-3: ZenStone

ZenStone is a pebble-like desktop object incorporating a gesture sensor and designed primarily around exploratory affordance. After extended work periods, if the system detects that the user has picked up and rotated the object, AuraDesk and FlowPath shift into a calmer "relaxation mode," accompanied by subtle natural soundscapes. This interaction is intended to invite a brief stretch or mindful pause. The design supports progressive engagement by introducing deeper interaction only after basic behaviors have been established.

These three EEUs are connected wirelessly through a central controller (Raspberry Pi – based), forming a coordinated, multi-modal affordance network spanning visual, auditory, and tactile channels.

C. Pragmatic Randomized Validation Study

To test real-world effectiveness, a four-week pragmatic, parallel-group randomized study was conducted in an operational office environment.

1) Recruitment and Random Allocation

Sixty employees meeting the same sedentary inclusion criteria were recruited; none had participated in the earlier phase. Informed consent was obtained from all participants. Individuals were randomly assigned to an experimental group (N = 30) or a control group (N = 30). The experimental group received workstations replaced with the HED-PES, while controls continued with standard desks. No statistically significant baseline differences were observed between groups in age, gender distribution, BMI, or physical activity level ($p > 0.05$).

2) Measurement Instruments

Both objective and subjective measures were employed:

Objective behavioral measurement: Participants wore a validated tri-axial accelerometer (ActiGraph wGT3X-BT) on the right thigh during weekday work hours. The device distinguishes sitting, standing, and walking, with sampling set at 30 Hz.

Subjective assessments: At baseline and at the end of week 4, participants completed questionnaires including:

- IPAQ-short for physical activity over the preceding 7 days;
- a Self-Efficacy for Health-Related Behaviors scale measuring confidence in healthy actions;
- the Intrinsic Motivation Inventory (IMI), administered only to the experimental group, assessing experience with HED-PES (interest/enjoyment, perceived competence, perceived choice).
- Semi-structured interviews: After the intervention, 15 experimental participants were interviewed to capture deeper insights on usability, acceptability, and perceived behavioral influence.

3) Procedure

The study followed a staged structure:

- Week 1 (baseline): Both groups used their original workstations while wearing accelerometers to establish naturalistic baseline behavior.
- Weeks 2 – 4 (intervention): The experimental group's workstations were replaced with HED-PES. Researchers provided a brief 10-minute orientation covering basic functions but did not prescribe usage patterns (Invitation principle). The control condition remained unchanged. Accelerometer wear continued for both groups.

4) Data Analysis

Accelerometer data processing: Raw signals were processed using ActiLife software. A validated algorithm (inclinometer function plus intensity thresholds) was used to derive core outcomes: mean daily total sedentary time (min), sedentary bouts per day, sedentary breaks per day, mean sedentary bout length (min), mean daily light physical activity (LPA) time (min), and mean daily moderate-to-vigorous physical activity (MVPA) time (min).

Statistical analysis: Quantitative analyses were performed in SPSS 26.0. Independent-samples t-tests compared baseline group differences. Intervention effects were examined via a 2 (group: experimental vs. control) × 2 (time: baseline vs. post-intervention) repeated-measures ANOVA, emphasizing the group × time interaction. Statistical significance was set at $\alpha = 0.05$.

Qualitative analysis: Interview audio was transcribed verbatim, and thematic analysis was used to code content and extract recurring themes capturing user experience and perceived mechanisms of change.

IV. Results

This section presents the data collected and analyzed from the quasi-experiment, aimed at evaluating the effectiveness of the Health-Enhancing Design Framework (HEDF) and the ecological-enabling product-environment system (HED-PES). The findings are organized to first report on participant characteristics and data integrity, followed by a detailed statistical analysis of the objective behavioral data, and finally, an integration of the subjective questionnaire and qualitative interview findings.

A. Participant Characteristics and Data Integrity

A total of 60 participants were recruited and randomly assigned to the experimental group (n=30) and the control group (n=30). All participants completed the four-week study with no dropouts. The accelerometer data demonstrated a high compliance rate, with 98.2% valid wear time, ensuring the integrity and reliability of the data. Baseline comparisons showed no statistically significant differences between groups in age, gender distribution, BMI, or baseline behavioral metrics (all $p > 0.05$), suggesting that the two groups were comparable prior to the intervention. Detailed baseline demographic and behavioral characteristics are presented in Table I.

TABLE I. Baseline Demographic and Behavioral Characteristics of Participants (Mean ± SD)

Characteristic	Experimental Group (n=30)	Control Group (n=30)	p-value
Age (years)	31.5 ± 5.8	30.9 ± 5.5	0.68
Gender (Male/Female)	17 / 13	11/19	0.59
BMI (kg/m²)	23.8 ± 2.5	24.1 ± 2.8	0.64
Daily Sedentary Time (min)	485.2 ± 55.1	490.5 ± 58.3	0.71
Daily Sedentary Breaks (n)	25.4 ± 8.2	24.9 ± 7.9	0.79
Daily LPA Duration (min)	85.7 ± 20.1	83.9 ± 19.5	0.72
Daily MVPA Duration (min)	28.1 ± 10.5	29.5 ± 11.2	0.61

B. Impact of HED-PES on Objective Behavioral Outcomes

To assess the intervention effects of the HED-PES, a 2 (group) × 2 (time) repeated measures ANOVA was conducted on the objective behavioral data from the baseline week (Week 1) and the intervention period (average of Weeks 2-4). The core results are summarized in Table II, with key trends illustrated in Figures 2 through 5.

TABLE II. Repeated Measures ANOVA Results for the Impact of the Intervention on Primary Behavioral Outcomes

Behavioral Outcome	Group	Baseline (Mean ± SD)	Post-Intervention (Mean ± SD)	Interaction Effect F(1, 58)	p-value
Total Sedentary Time (min/day)	Experimental	485.2 ± 55.1	409.9 ± 60.3	35.81	< 0.001
	Control	490.5 ± 58.3	488.1 ± 59.8		
Sedentary Breaks (n/day)	Experimental	25.4 ± 8.2	37.7 ± 10.5	21.45	< 0.001
	Control	24.9 ± 7.9	25.8 ± 8.3		
Mean Sedentary Bout Duration (min)	Experimental	19.1 ± 4.3	10.9 ± 3.1	30.17	< 0.001
	Control	19.7 ± 4.5	19.0 ± 4.6		
Light Physical Activity (LPA) Duration (min/day)	Experimental	85.7 ± 20.1	146.5 ± 28.4	45.23	< 0.001
	Control	83.9 ± 19.5	86.2 ± 21.0		
Moderate-to-Vigorous Physical Activity (MVPA) Duration (min/day)	Experimental	28.1 ± 10.5	30.5 ± 11.1	1.89	0.175
	Control	29.5 ± 11.2	29.8 ± 11.5		

Note: p-values reflect the group-by-time interaction effect. Significant results ($p < 0.05$) are highlighted in bold.

The analysis revealed a significant group-by-time interaction effect for all core sedentary-related metrics and for light physical activity (LPA), indicating that the HED-PES had a significant positive impact.

1) Significant Improvements in Sedentary Behavior

Post-intervention, the experimental group's mean daily total sedentary time significantly decreased from a baseline of 485.2 minutes to 409.9 minutes, an average reduction of 75.3 minutes ($p < 0.001$). In contrast, the control group's sedentary time showed no significant change (Figure 2). This result demonstrates that the HED-PES effectively reduces overall sitting time during the workday.

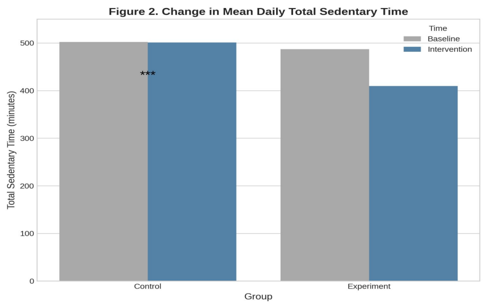

Fig. 2. Change in Mean Daily Total Sedentary Time

More importantly, the intervention significantly altered the pattern of sedentary behavior. The experimental group's mean daily number of sedentary breaks increased substantially from 25.4 to 37.7, a 48.5% increase ($p < 0.001$) (Figure 3). Correspondingly, their mean sedentary bout duration was sharply reduced from 19.1 minutes to 10.9 minutes ($p < 0.001$). This indicates that the HED-PES not only reduced the total volume of sitting but also effectively broke up prolonged, uninterrupted periods of sitting—a key risk factor—promoting a healthier pattern of more frequent postural changes.

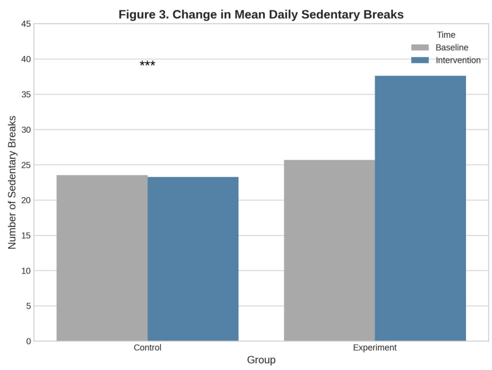

Fig. 3. Change in Mean Daily Sedentary Breaks

2) Significant Increase in Light Physical Activity (LPA)

Corresponding to the reduction in sedentary behavior, the experimental group's mean daily light physical activity (LPA) duration showed a remarkable increase, rising from a baseline of 85.7 minutes to 146.5 minutes, a net gain of 60.8 minutes ($p < 0.001$) (Figure 4). This increase was primarily composed of standing and small-scale movements around the workstation, which aligns perfectly with the design goals of the HED-PES (i.e., guiding standing and micro-movements via AuraDesk and FlowPath). Notably, there was no significant change in moderate-to-vigorous physical activity (MVPA) duration for either group ($p = 0.175$). This suggests that the impact of the HED-PES is mainly concentrated on converting sedentary time into low-intensity physical activity, rather than high-intensity exercise, which is more realistic and sustainable for health promotion in an office environment(Figure 5).

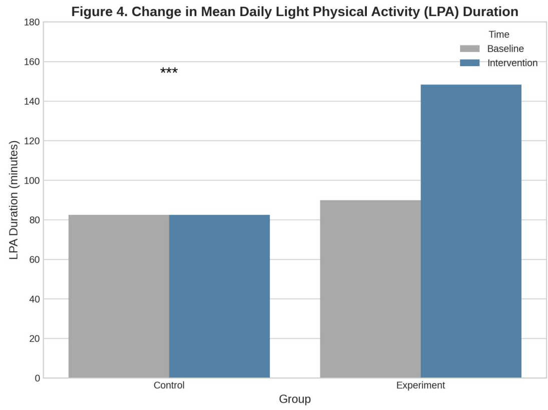

Fig. 4. Change in Mean Daily Light Physical Activity (LPA) Duration

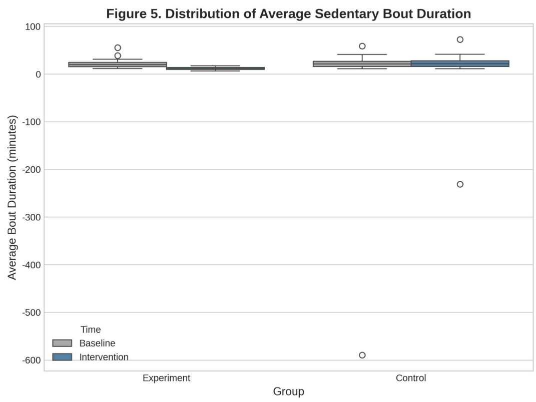

Fig. 5. Distribution of Average Sedentary Bout Duration

C. Qualitative Findings on Subjective Perceptions and Experience

The questionnaire and interview data provide rich qualitative evidence that helps to understand why the HED-PES was effective.

1) Enhancement of Self-Efficacy and Intrinsic Motivation

Questionnaire results showed that after the intervention, the experimental group's health self-efficacy scores were significantly higher than those of the control group ($p < 0.01$), indicating greater confidence in their ability to actively manage their own health behaviors. The Intrinsic Motivation Inventory (IMI) results further revealed that the experimental group users showed high levels of interest/enjoyment (5.8/7.0) and perceived competence (6.1/7.0) with the HED-PES, while also feeling that the system provided them with ample autonomy and choice (6.3/7.0)(Table III).

TABLE III. INTRINSIC MOTIVATION INVENTORY (IMI) SUBSCALE SCORES FOR THE EXPERIMENTAL GROUP (MEAN ± SD)

IMI Subscale	Score (out of 7.0)
Interest/Enjoyment	5.8 ± 0.9
Perceived Competence	6.1 ± 0.8
Perceived Choice	6.3 ± 0.7
Pressure/Tension	1.5 ± 0.6

2) User Experience of the "Invitation-Based" Intervention

Thematic analysis of the interviews with the experimental group distilled three core themes that strongly resonate with the design principles of the HEDF:

- 11"A Silent Reminder, A Gentle Invitation": Many participants emphasized that the "breathing light" reminder from the AuraDesk was very "friendly" and "non-intrusive." One participant described it as: "It doesn't interrupt me like a phone alarm. It's more like a friend gently tapping my shoulder, saying, 'Hey, maybe it's time to stand for a bit.'" This validates the success of the "Invitation, not Coercion" principle. Users perceived a choice rather than a command, which greatly reduced psychological resistance.

- 12"Moving Without Conscious Awareness": Regarding the FlowPath's floor light patterns, many participants said they did not consciously "follow" them, but while standing and working, they would "unconsciously" shift their weight or move around within the area of the light patterns. A designer mentioned: "I didn't even notice I was moving until I realized my ankles and knees weren't as stiff as before." This perfectly illustrates the essence of the "Seamless Integration" principle — internalizing the guidance for micro-movements into a near-subconscious background behavior that does not consume cognitive resources.

- "An Engaging Exploratory Process": The micro-interaction design of the ZenStone was universally praised, seen as a "small surprise" and a "switch for mindfulness." Participants felt that the simple act of flipping the stone provided a ritualistic way to briefly disengage from intense work. A project manager said: "When I feel stressed or stuck, I flip the stone. It's like a pause button that gives me permission to take a few seconds off, to rest and look out the window." This reflects the value of "Progressive Engagement" and exploratory affordances, where a low-barrier, engaging interaction guides users to initiate a higher-level health behavior (micro-breaks and relaxation)(Figure 6).

Fig. 6. Core Themes from Qualitative Interviews

In summary, the quantitative and qualitative results form a strong chain of evidence, collectively demonstrating that the HED-PES, designed based on the HEDF, achieved significant and meaningful success in reducing sedentary behavior and increasing light physical activity. The key to its success lies not only in the behavioral outcomes but also in its ability to effectively enhance users' intrinsic motivation and self-efficacy through an "invitation-based," seamlessly integrated, and progressively engaging design, laying a solid psychological foundation for sustainable health behavior change.

V. DISCUSSION

This study sought to develop and empirically examine a Health-Enhancing Design Framework (HEDF) grounded in affordance theory as a response to the escalating challenge of sedentary work in office settings. The results indicate that the ecological-enabling product – environment system (HED-PES), designed under HEDF guidance, produced a statistically and practically meaningful decrease in sedentary time and a concomitant rise in light physical activity. The following discussion interprets the core outcomes, situates them within prior scholarship, and summarizes theoretical value, applied significance, and study limitations.

A. Interpretation of Core Findings: From "Providing Functions"to "Ecological Invitation"

A key observation is that HED-PES improved outcomes not only in magnitude — reducing sedentary time by 75.3 minutes and increasing LPA by 60.8 minutes — but also in behavioral structure, evidenced by a 48.5% rise in sedentary breaks. These shifts suggest that the intervention did more than simply replace sitting with standing; it reshaped how sitting was distributed across the workday. The most plausible explanation is the paradigm shift embedded in HEDF: moving away from conventional information-based and device-focused approaches and toward an "ecological invitation" logic.

Many established strategies, including educational sessions and the installation of a single sit – stand workstation, often position activity as an additional requirement outside the work stream. In contrast, HEDF aims to remove the sense of "extra task" by embedding action cues within the lived work context so that healthier behavior emerges as part of routine interaction with the environment. Interview expressions such as " a gentle invitation" and "I moved without noticing" provide qualitative support for this mechanism.

At the workstation level, AuraDesk's "breathing" light operates as an atmospheric signal rather than a directive, leaving the decision to act with the user and preserving perceived autonomy. This aligns with self-determination theory, which identifies autonomy as a critical driver of sustained engagement and behavior change [20]. FlowPath's dynamic floor patterns further shift movement guidance from a deliberate, effortful decision to a low-threshold response to subtle visual dynamics, thereby reducing cognitive demands. Such a mechanism plausibly accounts for the substantial increase in LPA, because movement is no longer framed as a separate goal but becomes an almost automatic bodily adjustment.

ZenStone illustrates the potential of exploratory affordances. By coupling a simple tactile interaction with a transition into a calming multimodal mode, the object helps legitimize "micro-breaks" as acceptable and even desirable within work time. Importantly, it links health-supportive behavior with positive affect (relaxation, enjoyment), reinforcing continued use through a favorable experiential loop. This resonates with behavioral economics concepts such as priming and nudging, where minor contextual changes systematically shift choices without heavy-handed enforcement [21].

Taken together, the effectiveness of HED-PES should not be interpreted as the sum of three independent devices. Rather, the three Ecological-Enabling Units operate as an integrated, multi-modal and multi-level affordance network that repeatedly and respectfully prompts movement. In this designed contextual field, behavior change is elicited by the environment through invitation, rather than implemented through compliance.

B. Dialogue with Existing Research: Points of Integration and Advancement

Positioning these results alongside prior work helps clarify what HEDF adds.

First, relative to studies focused solely on sit–stand desks, the current outcomes appear stronger and more comprehensive. Whereas many sit–stand interventions report reductions in sedentary time on the order of 30–60 minutes [11, 12], this study observed a 75.3-minute reduction. More importantly, the intervention increased fragmentation of sedentary time via more frequent breaks. This distinction is consistent with the claim that "having a standing function available" is not sufficient; what matters is designing triggers that reliably activate standing and providing subsequent guidance once the user is upright. The findings therefore support the broader hypothesis that an ecosystem capable of repeatedly activating affordances can outperform isolated feature provision.

Second, compared with digital-only interventions, HEDF highlights the value of physicalized, ambient interaction. Many app- or wearable-based approaches rely on notifications, vibrations, or screen prompts, which can generate disengagement and notification fatigue over time [15]. By contrast, HED-PES uses ambient media—light and projection—as a quieter communication channel that is less intrusive and less likely to be dismissed, consistent with user comments regarding "silent reminders." In addition, digital systems frequently anchor motivation to abstract targets (steps, calories), while HED-PES couples prompts to the user's immediate bodily state and spatial context, potentially strengthening relevance and immediacy.

Third, the study extends the active design agenda by linking macro-environmental potential to micro-level activation. Traditional active design research emphasizes architectural and spatial configuration at a building scale [7, 8]. HEDF, in contrast, explicates a chain from macro environment to micro product to individual behavior, demonstrating how interactive products can dynamically "turn on" action possibilities already latent in space. For example, an open-plan area may afford walking, but HED-PES can time the activation of that possibility—such as immediately after prolonged sitting—through FlowPath's projected cues. In this sense, the approach can be understood as "products enabling environments," offering a more responsive and personalized operational route for active design practice.

Finally, the study advances the role of affordance theory in health-oriented design. Much prior work employs affordance as an interpretive lens [9, 19]; here it is translated into a generative framework with operational constructs (Ecological-Enabling Units and affordance levels) that specify how to design, sequence, and sustain affordances across an intervention. This helps shift affordance theory from primarily explanatory use toward actionable design methodology.

C. Theoretical and Practical Implications

The findings yield implications at both conceptual and applied levels.

Theoretical implications. HEDF offers a health behavior-change paradigm that is ecosystem-centric rather than individual-centric. It treats the individual, interactive products, physical space, and socio-cultural context as an interdependent system in which behavior emerges. Because the logic centers on contextualized invitations rather than domain-specific content, the framework may generalize beyond sedentary behavior to other health domains, including dietary routines, sleep practices, and mental well-being support, where sustained change similarly depends on everyday context.

Practical implications. Several stakeholder groups can draw actionable lessons:

Designers and engineers: HEDF and the HED-PES prototype demonstrate how ambient computing and multi-modal interaction can shape behavior in a low-friction, autonomy-respecting manner, offering a reference model for future smart workplace products and services.

Corporate managers and HR professionals: The results suggest that investing in "health-enabling" environments can deliver value beyond health outcomes, potentially reducing productivity loss associated with inactivity while also improving work experience, autonomy, and organizational attachment.

Public health policymakers: The study implies that policy levers should extend past health education alone and toward supporting environmental transformation in workplaces. For example, incentives, procurement guidance, or design standards could encourage organizations to adopt ecological-enabling systems and scale health behavior support at a population level.

D. Limitations and Future Research Directions

Several constraints should be acknowledged, alongside opportunities they open for future inquiry.

First, the sample was modest (N = 60) and drawn from a single technology company, limiting generalizability across industries, job types, and cultural contexts. Subsequent studies should validate HEDF across larger and more diverse cohorts to test robustness.

Second, the intervention exposure was relatively short (three intervention weeks). While meaningful changes were observed, longer follow-up is needed to determine durability, including whether effects diminish as novelty fades. Longitudinal evaluations over six months to one year would be particularly informative.

Third, although participants were randomly assigned, the pragmatic field setting constrained internal controls: blinding was impractical, and cross-participant contamination could not be fully ruled out. Future research could strengthen causal inference through multi-site trials, cluster randomization, pre-registered protocols, and improved contamination-control strategies.

Fourth, HED-PES primarily targets the micro-context around individual workstations. Extending HEDF to cover broader office areas — meeting rooms, corridors, informal collaboration zones — could enable a building-wide affordance network that supports both movement and social interaction. For example, adaptive corridor lighting could encourage alternative routes to shared spaces at strategic times.

Finally, individual differences were not examined as moderators. Responses to the system may vary by personality, job demands, health beliefs, and work rhythms. Future work could integrate psychometric profiles, task logs, and adaptive algorithms to provide more personalized affordance configurations and guidance strategies.

VI. Conclusion

In view of the increasingly widespread problem of sedentary office work, this study proposes and systematically verifies an innovative Health-Enhancing Design Framework (HEDF). By synthesizing ecological psychology — particularly affordance theory — with insights from behavioral science, the research completes a full pathway of design, development, and evaluation for an ecological-enabling product - environment system (HED-PES). In doing so, it offers a paradigm that is both theoretically grounded and practically deployable for confronting the complex health risks associated with prolonged sitting at work.

The central conclusion is that an affordance-based design approach—prioritizing "ecological invitation" rather than "function-driven coercion"—can support sedentary office workers in reducing sitting time and increasing light physical activity in a natural and potentially sustainable manner within real workplace conditions. Evidence from the four-week quasi-experimental evaluation indicates that HED-PES not only lowered mean daily sedentary time by 75.3 minutes, but also altered the temporal structure of sitting by disrupting long uninterrupted bouts; notably, average sedentary bout duration decreased from 19.1 minutes to 10.9 minutes. This qualitative restructuring of behavior is attributable to an "affordance network" created through the coordinated operation of smart products and environmental cues. Because the system was embedded into everyday workflow without interfering with core job tasks, it also appeared to support stronger intrinsic motivation and improved health-related self-efficacy.

This work yields layered implications. On the theoretical side, HEDF advances affordance theory from a primarily interpretive lens into a generative and operational design methodology, encouraging a shift in health-intervention thinking from an individual-centered model toward an ecosystem-oriented perspective. On the applied side, the findings deliver a clear message for designers, corporate decision-makers, and public health authorities: effective future strategies should not rely solely on isolated devices or didactic education, but should prioritize investment in intelligent, human-centered "healthy environments" that cultivate a virtuous interaction loop between individuals and their surroundings. As a functioning prototype, HED-PES demonstrates both the feasibility and the larger potential of this direction.

Several limitations should be acknowledged, including the relatively homogeneous participant pool, the short intervention duration, and the constraints inherent to a quasi-experimental field study. At the same time, these boundaries define productive paths for subsequent research. Future work should test and refine HEDF across longer time horizons and in more diverse organizational cultures and industries. It will also be valuable to scale the framework beyond the individual workstation toward office-wide affordance networks spanning meeting rooms, corridors, and shared spaces, and to incorporate artificial intelligence to enable deeper personalization of invitations and engagement trajectories. Ultimately, this study points toward a future of work in which well-being is not an added task, but a quality embedded within routine activity—supported by numerous ecological-enabling units that quietly and continuously make healthier behavior easier to realize.

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Qianyun Bi: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Visualization; Writing – original draft; Project administration; Supervision; Corresponding author responsibilities.Huan Yu: Methodology; Software; Investigation; Validation; Resources; Writing – review & editing.

COMPETING INTERESTS

The authors declare no competing interests.