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Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: G. Arcamone *et al* 2025 *J. Phys.: Conf. Ser.* **3140** 122004

Journal of Physics: Conference Series **3140** (2025) 122004 doi:10.1088/1742-6596/3140/12/122004

Monitoring infrastructure for occupant well-being and comfort in a Living-Lab: a focus on wearable devices

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Abstract. Today, building design focuses on optimizing indoor environmental quality (IEQ) and ensuring the comfort and well-being of occupants. In this context, a continuous monitoring infrastructure can provide the necessary data to ensure that the environment adapts proactively and in real-time to the occupants' needs. This approach, applied in a research context, requires the simultaneous monitoring of three levels of measurement: objective-environmental parameters, using lab-grade instruments in the environment and wearable devices; subjective-psychological parameters, obtained through questionnaires and cognitive tasks; and physiological parameters, gathered via wearable devices. This paper presents a 3-layer monitoring infrastructure and its first demonstration use case, conducted in Politecnico di Torino for two weeks in March 2025. The aim is to investigate whether wearable sensors can provide objective insights into a deeper understanding of the relationship between IEQ and occupants' comfort and well-being. Some preliminary findings are discussed, along with a review of the state of the art in wearable technologies across the four environmental domains, and the rationale behind the selection of specific devices.

1. Introduction

The growing interest in the concept of "healthy buildings", defined as built environments that support the physical, psychological, and well-being of occupants, has highlighted the need for a more holistic approach to analyzing the relationship between environmental conditions and human responses[1]. The approach needs to be multi-domain and, in the context of the indoor environmental quality (IEQ), it should consider simultaneously thermal, lighting, acoustic, and air quality domains [2]. Monitoring both environmental conditions and occupant responses can significantly enhance research and practical efforts aimed at improving overall building performance. Monitoring infrastructures may include static sensors for tracking environmental variables, questionnaires to assess subjective psychological responses, and wearable sensors worn by occupants.

Wearable sensors are devices capable of continuously and dynamically monitoring biometric parameters and proximal environmental variables while worn by the user performing his or her normal activities. Although the field of wearables has always been strictly related to the medical sphere, there is currently a growing interest in the field of engineering. These devices can support research on well-being and productivity in relation to environmental quality, contribute to the development of personalized comfort models, and inform user-centered strategies for energy-efficient building operation. The growing development of wearable devices makes them suitable for use in real contexts, such as long-term longitudinal studies through field tests, or in Living Labs (LLs) to assess user comfort. In this case, the user itself can be considered as a "sensor", as wearable technology allows for objective assessment of IEQ from the perspective of the user's perception, also allowing for the detection and measurement of environmental stressors [3].

Within the framework of the MIRABLE project, which aims to develop a Measurement Infrastructure for Research on Healthy and Zero-Energy Buildings within Novel Living Lab Ecosystems, a preliminary study was conducted to support the development and testing of a monitoring infrastructure that integrates wearable sensors, environmental sensors, and subjective surveys. The goal is to explore the potential and limitations of wearable technologies for a comprehensive assessment of IEQ and user comfort. Additionally, the state of the art in wearable devices across the four environmental domains is reviewed to clarify the logic behind the selection of specific sensors. This paper explores whether wearable technologies can provide objective insights to deepen the understanding of the relation between IEQ and occupants' comfort and well-being.

2. Wearable device: state of the art and sensors selection

Physiological parameters are considerably more complex to assess than traditional environmental ones, as they vary between individuals and change dynamically over time and space [4], [5]. Wearable sensors offer a promising solution by addressing the spatial and temporal limitations of conventional fixed monitoring systems [6].

In recent years, wearable technologies have gained growing importance in investigating the effects of the built environment on human health, comfort, and productivity. This is largely due to their ability to continuously and unobtrusively collect personalized data on both environmental and physiological parameters. For example, in the field of lighting, wearables are now essential tools for studying how personal light exposure affects occupant health and well-being [7]. Beyond vision, light influences the human circadian system through non-image-forming (NIF) effects, which depend not only on intensity and spectral composition but also on the timing, duration, and history of exposure [8]. Some wearable devices are well-suited for this purpose, as they can track both photopic (Eph) and melanopic illuminance (mel-EDI), as well as correlated color temperature (CCT) or spectral power distribution (SPD), without interfering with users' daily routines. Measurement accuracy, however, varies depending on sensor placement [6]. Wrist-worn devices are more convenient but can deviate up to 27% from eye-level reference values, while sensors positioned near the eyes show deviations of around 7% [9]. Devices are often placed at chest or clavicle level and typically use low-cost RGB sensors or mini-spectrometers. Among commercially available solutions, the NanoLambda Spectrometer and LYS button are frequently used: the former allows spectral analysis but is more expensive and bulky, while the latter, based on an RGB sensor, is lighter, cheaper, and more wearable, making it suitable for large-scale, long-term studies. Glasses-mounted devices, although more accurate in measuring light entering the eye, are less commonly adopted due to their intrusiveness. Wrist-worn devices such as Actiwatch and GENEActiv are widely used in field studies but suffer from limited accuracy due to sensitivity to orientation and occlusion from clothing, and they do not measure melanopic quantities.

Beyond lighting, indoor air quality (IAQ) is another key area, given that people spend approximately 90% of their time indoors, often exposed to pollutants linked to conditions such as Sick Building Syndrome. Wearable IAQ monitors, typically worn on the wrist, belt, or attached to personal items, can track pollutants including carbon dioxide (CO_2), volatile organic compounds (VOCs), particulate matter (PM), and nitrogen dioxide (NO_2). Although various devices exist (both commercial and custom-built), such as Flow 2 and Atmotube PRO, issues related to size, battery life, and user comfort often limit their suitability for long-term, real-world studies [10].

Wearables are also being adopted in the acoustics domain to assess the impact of noise on human health. Prolonged exposure to high noise levels is associated with chronic conditions, including cardiovascular diseases and anxiety. Some solutions rely on mobile apps that turn smartphones into noise monitors, often used alongside physiological wearables like the Empatica E4 to correlate noise levels with heart rate variability. However, these solutions require calibration against professional instruments. Only a few commercial wearables, such as NEATVIBEwear and QuestDLX-1, are specifically designed for personal noise monitoring, and the market still lacks solutions optimized for low-noise indoor settings like offices.

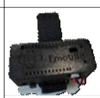
Wearable technology is also valuable for monitoring physiological responses related to thermal comfort. Relevant physiological signals include brain activity (EEG), electrodermal activity (EDA), skin temperature (Tsk), heart rate (HR), respiration rate, and physical activity. While EEG can provide insights into cognitive well-being, its intrusiveness limits its use outside the lab. In contrast, HR, EDA, and Tsk are effective indicators of thermal strain and are easier to measure [11]. Chest belts like those from Polar are accurate but uncomfortable; smartwatches such as Apple Watch or Fitbit offer greater wearability at the expense of accuracy. For Tsk, adhesive skin-contact loggers such as Pyrobutton and iButton are commonly used. EDA requires more sophisticated devices such as the Shimmer3 GSR or EdaMove4, which are suitable primarily for lab-based studies. The Empatica E4 stands out for its ability to measure multiple physiological signals, HR, EDA, Tsk, peripheral oxygen saturation (SpO_2), physical activity, and sleep, in a single, relatively non-intrusive device, making it suitable for both laboratory and field applications. More accessible alternatives like Fitbit and Samsung smartwatches are widely used in long-term studies for their ease of use and lower cost, although their Tsk reporting can be limited [4]. Newer multi-signal devices like EmotiBit offer promising capabilities, although their complexity and cost currently limit broader deployment.

Previous literature reviews [4], [7], [11], [12], [13] have addressed the use of wearable devices in environmental monitoring. This paper focuses on the added value that wearable technologies bring to human-centered monitoring, particularly in connecting objective environmental data with individual perception and physiological response.

From the reviewed options, three wearable devices were selected to be integrated into a monitoring infrastructure for field studies and living lab applications, with a focus on visual and thermal comfort in indoor environments. The selection was based on inclusion and exclusion criteria. First, devices needed to measure specific parameters: in the lighting domain, this included vertical-plane photopic illuminance (Ev), melanopic equivalent daylight illuminance (mel-EDI), CCT or spectral data, and sleep-related variables. In the thermal domain, Tsk, EDA, and HR were considered. Devices also had to be non-intrusive, easy to wear, and user-friendly, key aspects for use in living labs. Wireless data transmission (e.g., Bluetooth) and compatibility with APIs for automated data extraction were also prioritized. Finally, commercially available, ready-to-use devices were preferred.

Table 1 summarizes the characteristics of the selected wearables:
(1) LYS button, (2) EmotiBit, (3) Fitbit Inspire 3.

Table 1. Selected wearable sensors characteristics

Sensors	Dimensions (mm)	Parameters	Position	Data sampling	Storage	Communication	APP	Battery life	Price (Jan 2025)	PROs	CONs	Ref.
LYS button	 D 24 x 12	E, mel(EDI) CCT	chest	15 s	internal memory to Cloud	BLE	yes	7 days	299	Easy to wear, low cost, dedicated cloud	Requires a stable bluetooth connection to avoid data loss	Khanie et al., 2023 Karen van Creveld, 2020 Banasiak et al., 2023 Aries et al., 2022 van Lieshout-van Dal et al., 2021 Davidoff et al., 2022
Emotibit	 50 x 25 x 8	EDA Tsk HR	arm, ankle	editable	micro SD	-	no	24 hrs	475	Open source, multi parameter	Dimensions, low battery	Montgomery et al., 2023 Montgomery et al., 2024 Balta et al., 2024
Fitbit Inspire 3	 39 x 18 x 11	Sleep, HR activity SPO2	wrist	during the night	Cloud	BLE	yes	10 days	99	Easy to wear, good prediction of total sleep, price	Lower accuracy compared with polysomnography standards (PSG)	Hassinger et al., 2024 Kainec et al., 2024 Robbins et al. 2024

3. Case study
The selected wearable devices were used in a preliminary demonstration case study to assess their potential for IEQ research when integrated into a monitoring infrastructure that includes both objective and subjective measurements. The experiment was conducted at Politecnico di Torino over two working weeks in March 2025. The complete monitoring setup included environmental sensors for air temperature (Ta), relative humidity (RH), horizontal illuminance (Eh), sound pressure level (SPL), CO_2

concentration, and TVOC levels. In addition, a custom questionnaire was designed and administered four times per day (9 AM, 12 PM, 3 PM, and 5 PM) using Microsoft Forms and Power Automate. The questionnaire focused on four areas of the subjective domain: sleep quality, environmental perception across the four IEQ domains, well-being (defined as self-assessed mood and health), and productivity.

Before the monitoring period began, users were trained on how to wear, operate, and synchronize the wearable devices. Participants were instructed to wear the LYS and Fitbit devices throughout the day, while the EmotiBit was worn only during working hours.

3.1 Data analysis

Wearable sensor data may include abnormal values (e.g., unusually high or zero) due to device accuracy or improper use. Moreover, these sensors often sample at different rates compared to environmental sensors, requiring data aggregation and time alignment. The post-processing and analysis followed four steps: (1) outlier removal, (2) temporal averaging and alignment with environmental sensor timestamps, (3) computation of specific indicators, and (4) comparison of environmental, subjective, and physiological data.

(1) Outliers in Tsk, Ev, and mel-EDI were identified using the Median Absolute Deviation (MAD) method, with a threshold factor of 3. For each point, the median and MAD were calculated over a sliding window of 15 values (7 before and 7 after). Values exceeding $3 \times 1.4826 \times MAD$ were replaced with the local median. (2) Data were averaged and aligned with environmental sensor timestamps. (3) Metrics were then derived. For instance, illuminance data were processed to quantify light intensity, duration, and timing. For each monitoring day, light levels were calculated using the arithmetic mean and standard deviation of Ev and mel-EDI values, averaged over 1-minute intervals. To quantify exposure duration, the time above threshold of 250 melanopic lux (TAT(250)) and the time below threshold of 10 lx (TBT(10)) were used, representing the amount of time spent above 250 lx during 24h and the time spent below 10 lx 3 hours before sleep. These values were selected based on recommendations found in the literature [14]. Additionally, to quantify timing, the mean timing of light above the 250-lux threshold (MLiT(250)) and the first/last timing of light above the same threshold (FLiT(250), LLiT(250)) were used to identify both the time range and the midpoint of exposure to melanopic light levels above 250 lx. A similar elaboration approach will be used for thermal data. (4) Environmental, subjective, and physiological data were compared. Fig. 1 shows the daily values of Eh, Ev, and mel-EDI recorded during working hours (8:00–17:00) over the monitoring period. Notable differences can be observed between horizontal and vertical illuminance trends, highlighting the complementary role of measurements taken on both planes. Furthermore, vertical measurements at eye level follow the user's actual movements, as they change position or move through different environments.

4. Results and discussion

Data collected from a user on a typical clear-sky day were analyzed. Fig. 2 shows the trends of Eh, Ev, and mel-EDI, along with perceived visual comfort (rated from 1 "uncomfortable" to 4 "comfortable") at each questionnaire response. Ev values from wearable sensor, in particular, helps explain some user responses. For instance, during the last questionnaire, the environment was rated as "slightly uncomfortable" for “low lighting levels” despite Eh is around the 500 lx recommended on the horizontal plane. Ev, however, was below 50 lx. The key benefit of wearable sensing is the ability to capture light exposure even outside the office, which fixed sensors cannot track. On this day, the user left the building from 3:30 to 4 PM (gray rectangle), as he noted in the logbook section of the questionnaire. Personal light exposure was also compared with self-assessed work performance, rated 7/10 in the 5:00 PM questionnaire. Finally, a daily well-being score was calculated as the percentage of the total score from well-being-related items in the questionnaire (Likert scale 0–5) over the maximum possible. Fig. 3 presents, for each monitoring day (24 h), the melanopic illuminance values in relation to TAT(250), TBT(10), FiLT, LiLT, MLiT, mel-EDI mean value, standard deviation, and sleep scores. Fitbit sleep scores range from 0 to 100: 80–100 indicate excellent sleep, 70–79 good, 60–69 fair, and below 60 poor. The Groningen Sleep Quality Score (GSQS), based on 15 items, ranges from 0 to 15: scores from 0–6 indicate good sleep, while scores from 7–15 indicate poor sleep.

The graph shows that the highest sleep score (84) occurred after a day in which the user was exposed to mel-EDI levels above 250 lx for 451 minutes. A general trend suggests that shorter exposure durations tend to correspond with lower sleep scores. All the values of the calculated metrics are reported in Tab.2.

Fig. 4 shows Tsk and HR data in relation to air temperature (Ta) and subjective thermal comfort responses and thermal sensation vote. The comfort range from ISO 11300 (20–26 °C) and the neutral skin temperature threshold of 34 °C are also highlighted. At the time of each questionnaire, the thermal sensation appears to correspond with Tsk. For instance, when the user reports a "neutral" sensation (0), Tsk values are 34.04 °C and 34.24 °C. When the environment is perceived as "slightly cool" (-1), Tsk drops below 34 °C. In the last entry, Tsk reaches 36.51 °C, corresponding to a "slightly warm" sensation (+1). If only ambient temperature were considered, always within the comfort range, important insights into thermal perception would be missed. When the user leaves the building, Tsk decreases due to lower outdoor temperatures, while HR increases due to the shift from sedentary to moderate activity.

In conclusion, wearables could bridge the gap between objective and subjective data, offering a clearer understanding of subjective environmental perception. They can also help detect sources of local discomfort. For example, high Ev levels may indicate glare conditions that horizontal Eh alone cannot reveal. However, wearable sensors often require calibration and active user involvement, including proper use and occasional manual synchronization via dedicated apps. Data loss or outliers are common due to handling errors or device limitations, making data post-processing and interpretation a critical step.

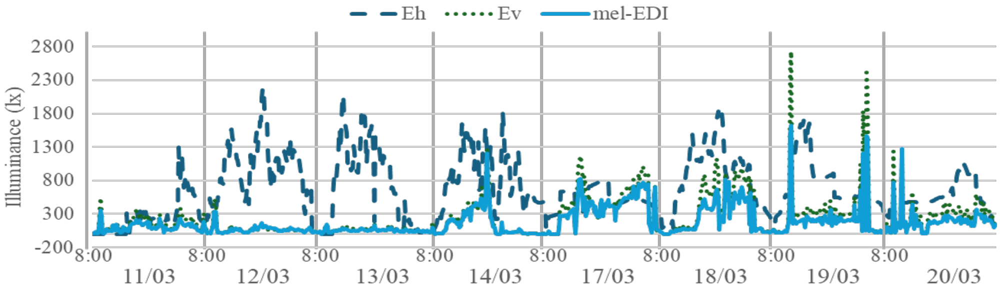


Figure. 1. General overview of environmental and proximal data for lighting domain

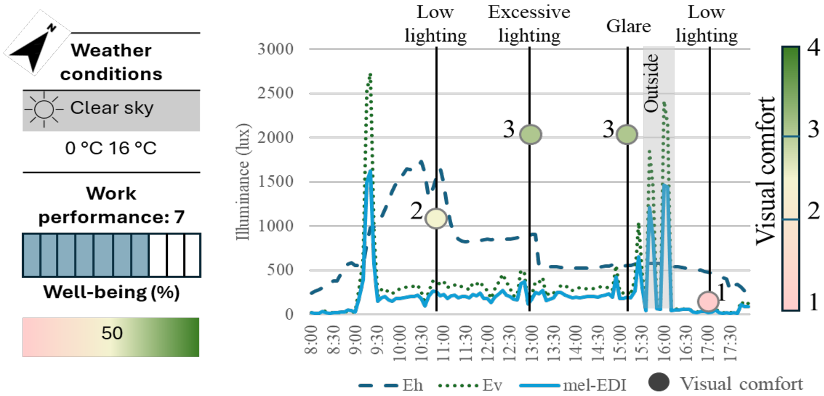


Figure. 2. Focus on lighting data (environmental, subjective and proximal) in one type-day

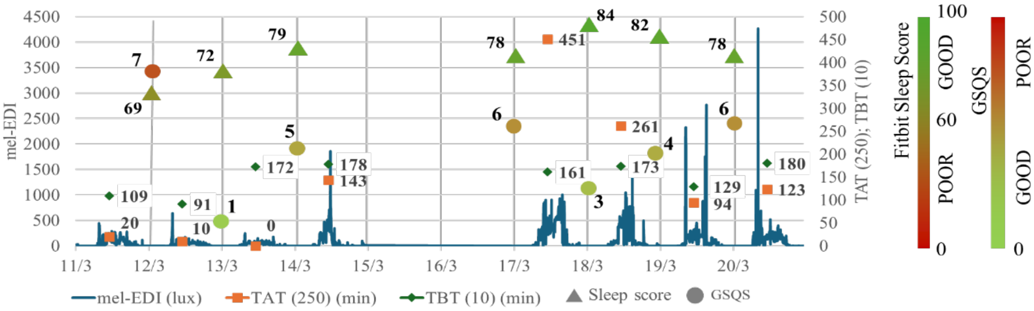


Figure. 3. Mel-EDI (melanopic equivalent daylight illuminance), TAT (250) (Time Above Threshold 250 lx), TBT (10) (Time Below Threshold 10 lx), sleep scores over 8 monitoring days

Table 2. Calculated metrics for each monitoring day: GSQS (Groningen Sleep Quality Score), FiLT (First Timing of light above threshold), LLiT (Last timing of light above the threshold), Mean value, SD (Standard Deviation), TAT (250) (Time Above Threshod 250 lx), TBT (10) (Time Below Threshold 10 lx)

	11/03	12/03	13/03	14/03	17/03	18/03	19/03	20/03
GSQS	1	7	1	5	6	3	4	6
Sleep score	/	69	72	79	78	84	82	78
FiLT(250)	8:38	8:38	/	9:17	9:00	11:05	9:09	8:19
LLiT(250)	17:47	08:47	/	13:58	18:14	19:33	16:07	16:27
MLiT(250)	13:12	8:42	/	11:37	13:37	15:19	12:38	12:04
Mean ± SD	48.4 ± 68.3	29.7 ± 46	24.1 ± 32	66.1 ± 153	170.7 ± 244	114 ± 205	102 ± 241	88.9 ± 187
TAT (250)	20	10	0	143	451	261	94	123
TAT (10)	109	91	172	178	161	173	129	180

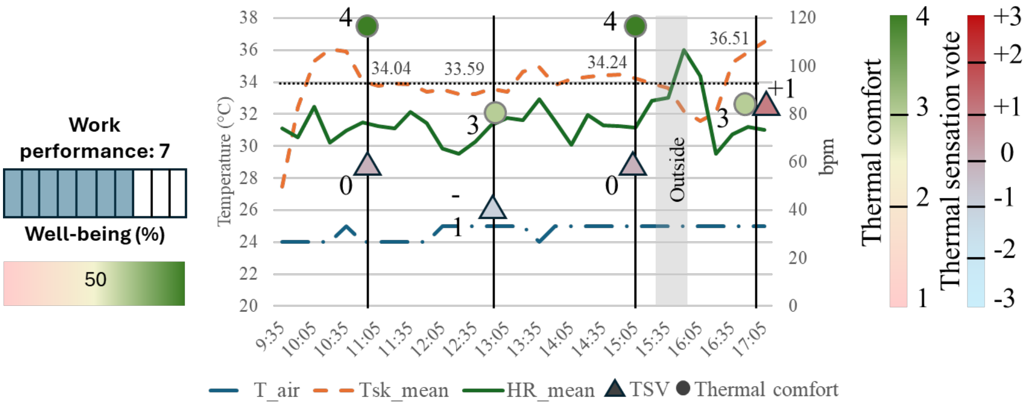


Figure. 4. Focus on thermal data (environmental, subjective, and physiological) in one type-day

5. Conclusions and future work

This paper presents the qualitative results of a pilot test of a three-layer monitoring infrastructure (environmental, subjective, and physiological) for studies on IEQ and environmental comfort, aiming to explore the added value, potential, and limitations of wearable technologies.

An overview of the state of the art supported the selection of three wearable sensors in the lighting and thermal domains, based on criteria like minimal intrusiveness, wearability, continuous data transmission, and commercial availability. The selected devices were: LYS button (Ev, mel-EDI, CCT), EmotiBit (EDA, Tsk, HR), and Fitbit Inspire 3 (sleep monitoring). These were tested for two weeks at Politecnico di Torino along with environmental sensors (Ta, RH, Eh, SPL, CO_2, TVOC) and four daily questionnaires. After post-processing and timestamp alignment, the data were analyzed and compared. Findings indicate that wearable technologies offer valuable insights into users' environmental perception that fixed sensors may miss. A key benefit is their ability to follow users in space and time, capturing data even outside the building and detecting potential local discomfort. However, their use requires user cooperation, guidance, possible calibration, and careful data cleaning and interpretation. Considering the observed limitations and opportunities, the longitudinal study will be repeated in different seasons.

Ethical Considerations

The study complies with the Declaration of Helsinki, and all adult participants provided written informed consent. Ethical approval is currently pending, as the Ethics Committee requested additional clarification regarding cross-border data transfer. The revised documentation has been submitted, and we are awaiting the Committee's final decision.

Acknowledgment
The authors would like to acknowledge the EU – NextGen for funding the project MIRABLE (2022ZNJHHY), within the call "PRIN 2022" (D.D of MUR n. 104, 2 Feb 2022), in the PNRR funding framework, Mission 4 Component 2 Investiment 1.1.

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