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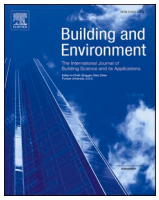

Occupant-centered indoor environmental quality management: Physiological response measuring methods

Minjin Kong, Jongbaek An, Dahyun Jung, Taehoon Hong *

Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea

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ABSTRACT

Recent studies have reported that occupants' physiological responses can be indicators of indoor environmental quality (IEQ). As a result, there is an emerging demand for devices to measure physiological responses, especially in wearable form. Previous reviews suggested and analyzed physiological responses that are affected by IEQ and corresponding measuring devices, but a full-scale review on the proper measuring method to give directions for future research and development is still necessary. In this regard, this study reviewed physiological response measuring methods to give directions to the improvement of existing wearable devices and the development of future wearable devices. Physiological responses related to IEQ were identified from review papers published over the last 10 years, and their measuring methods were classified based on locations of measurement, availability of wearables and existence of reference. Then each classification was analyzed and evaluated by four kinds of requirements for wearables in order to propose directions and guidelines for developing future wearable devices. This review is expected to be the guidelines to measure physiological responses for the future IEQ research and contribute to the development of the wearable devices that can be applied to monitoring or controlling IEQ in the future.

1. Introduction

As interest in occupants' health and satisfaction intensifies along with the energy crisis, it is reported that the global smart building market is expected to reach USD 127.69 billion by 2030 at a compound annual growth rate of 22.65% [1]. Smart building technologies strive to improve occupants' quality of life and sustainability, and one way to achieve these goals is to improve indoor environmental quality (IEQ). IEQ generally consists of thermal comfort (TC), indoor air quality (IAQ), acoustic comfort (AC) and visual comfort (VC) [2–5]. The number of related studies has soared since 2010s owing to the confirmation of the high correlation between IEQ and occupants' productivity and health [6]. Various research has been conducted on examining the relationship between each factor of IEQ and occupants' physiological response [7–9], and determined that perceived IEQ prediction is possible by physiological response measurement as their correlations are relatively high [10,11]. For example, Nkurikiyeyezu et al. [12] investigated the possibility of heart rate variability as a predictive biomarker of thermal comfort. Also, Choi and Zhu [13] indicated that pupil sizes can be used to estimate visual sensations in various lighting environments. Furthermore, models that predict or evaluate IEQ by setting the physiological responses with high correlation in the extensive body of research as predictive indicators have been developed [14–17]. In addition, while various controllers proposed for the efficient IEQ control are being developed, the effect of the occupant-centered controller has been confirmed by various studies, leading to further active research on related subjects [18–20]. Accordingly, research related to physiological response and IEQ has surpassed the conceptual stage and has reached the practical stage where the outcomes could be applied to smart buildings in the near future. However, a great number of research share a major barrier in the current status: measurement of physiological response.

The most important element in examining the correlations between IEQ and physiological response or developing predictive models is the measurement of physiological response. The review of previous studies has shown the following limitations of measuring physiological response. First, for machine learning-based IEQ predictive model or data-driven model, they had high dependency on continuous data measurement, but they were limited in data acquisition due to discrete data measurement [2,21–24]. Consequently, the need for devices allowing for continuous data measurement has been identified, and

* Corresponding author. Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, 03722, Republic of Korea.
E-mail addresses: min920606@yonsei.ac.kr (M. Kong), ajb2577@yonsei.ac.kr (J. An), danna23@yonsei.ac.kr (D. Jung), hong7@yonsei.ac.kr (T. Hong).

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Nomenclature list

AC	Acoustic comfort
CBT	Core body temperature
DEO	Degree of eye opening
EBR	Eye blinking rate
ECG	Electrocardiogram
EDA	Electrodermal activity
EEG	Electroencephalogram
EMG	Electromyogram
$ETCO_2$	End-tidal carbon dioxide
LDF	Laser doppler flowmetry
FEV	Forced expiratory volume
FVC	Forced vital capacity
HRs	Heart rate/Heart rate variability
IAQ	Indoor air quality
IEQ	Indoor environmental quality
PaO_2	Partial pressure of oxygen
pCO_2	Partial pressure of carbon dioxide
PEF	Peak expiratory flow
PPG	Photoplethysmogram
PRs	Pulse rate/Pulse rate variability
$PtcO_2$	Partial pressure of transcutaneous oxygen
SaO_2	Arterial oxygen saturation
SBF	Skin blood flow
SpO_2	Peripheral oxygen saturation
TC	Thermal comfort
$TcCO_2$	Transcutaneous carbon dioxide
VC	Visual comfort

recently developed devices often focus on such aspects [14,25]. Also, to apply related technologies to actual smart buildings, monitoring technologies is essential, but the measurement of physiological response often uses devices that are difficult or impossible to use in daily life in terms of usability or data accessibility [21,26–28]. For example, even if it is known that electroencephalogram (EEG) is affected by visual environment, it is very hard to expect occupants to wear the EEG cap everyday. As such, existing devices sometimes degrade the applicability of technology, leading to the need for highly applicable devices. Towards this end, recent studies have started to measure physiological responses related to IEQ factors and level of comfort (e.g., thermal or visual comfort) by using wearable devices [10,15,29–32]. Omidvar and Kim [33] developed theoretical thermal comfort predictive model which use wearable devices to collect predictors such as skin temperatures and heart rates. Feng et al. [34] proposed alert-based wearable sensing system in the form of wristband that measures heart rate, skin conductance, skin temperature, and motion based activity. Choi et al. [35] measured physiological response using wearable devices to examin indirect effects of IEQ on task performance. Still, not all physiological responses have been covered, so existing wearable devices have various limitations as mentioned above. For example, some research proposed that data reliability should be improved [36,37]. While the development of various sensors has allowed for multiple device options in measuring a type of physiological response, references on which method would be most accurate in measuring said data are still lacking [14,38]. For example, Bradley et al. [39] reviewed wearable devices that the reliability in a walking situations has been verified in some ways. However, it was found out that most cases did not provide clear standards for walking situations and reliability. As such, the development of various wearables has allowed for multiple options in measuring physiological responses, but also led to the unclear standards and criteria for verification of accuracy. Therefore, it is necessary to establish generalized standards such as references on the most accurate method to measure specific data [14,40]. Thus, it is necessary to conduct a full-scale review on the existing measuring method for physiological responses in order to propose the direction toward the development of wearable devices.

As the number of studies on physiological response and IEQ increases, reviews on these studies have also been actively performed. Most reviews examined the physiological responses that could be the indicator of IEQ up to the present point in time targeting the research of physiological response related to IEQ [11,41–43]. Lowther et al. [42] reviewed physiological responses such as respiratory systems and neurological symptoms that have been associated with carbon dioxide level. Hamedani et al. [43] reviewed research papers that investigated physiological responses associated with visual comfort and presented research methods and main findings of previous studies. However, most of them focused on the main findings as they were performed to present the psychological responses that could be IEQ indicators, and as such, they merely mentioned but failed to review related devices. Also, as with the recent rise in the use of wearable devices, the following articles have reviewed wearable devices for measuring physiological responses. Abboushi et al. [24] reviewed which health performance indicators should be measured by wearable devices and also assessed data accessibility. Mansi et al. [10] reviewed wearable devices that measured physiological responses for thermal comfort, specifically EEG, electrocardiogram (ECG) and skin parameters. As such, studies that reviewed IEQ-related wearable devices have focused on which physiological responses are measured by the wearable device and the types and limitations of such wearable device. However, previous studies did not propose directions on which physiological responses should be measured by wearable devices or what kinds of consideration are needed to develop or improve wearable devices for measurement of physiological responses.

Therefore, this study aims to review the existing physiological responses' measuring devices including wearables, and analyze them to give directions for developing future wearable devices. First, 324 review papers about IEQ and physiological responses were searched. And after filtering, 59 review papers were reviewed to identify the physiological responses that are found to be indicators of IEQ (refer to Fig. 1). Then, physiological responses' measuring methods were classified based on their location of measurement, availability of wearables and existence of reference. Each classification was analyzed and evaluated by four kinds of requirements for wearables which will be explained in section 2.3. To this end, directions for developing future wearable device to measure physiological responses are proposed.

2. Review methodology

This research was conducted in three stages to review the current development status of wearable devices for measurement of physiological responses: (i) Stage 1: Identifying physiological responses related to IEQ; (ii) Stage 2: Investigation and classification of the physiological responses' measuring methods; and (iii) Stage 3: Analysis and evaluation of the measuring methods according to each classification.

2.1. Stage 1: Identification of physiological responses related to IEQ

The present study aimed to examine the occupants' physiological responses required for the monitoring of IEQ and related measuring methods. Thus, in Stage 1, it had to perform the identification of the types of occupants' physiological response affected by each IEQ factor. Toward this end, the study was conducted with the following steps (refer to Fig. 1).

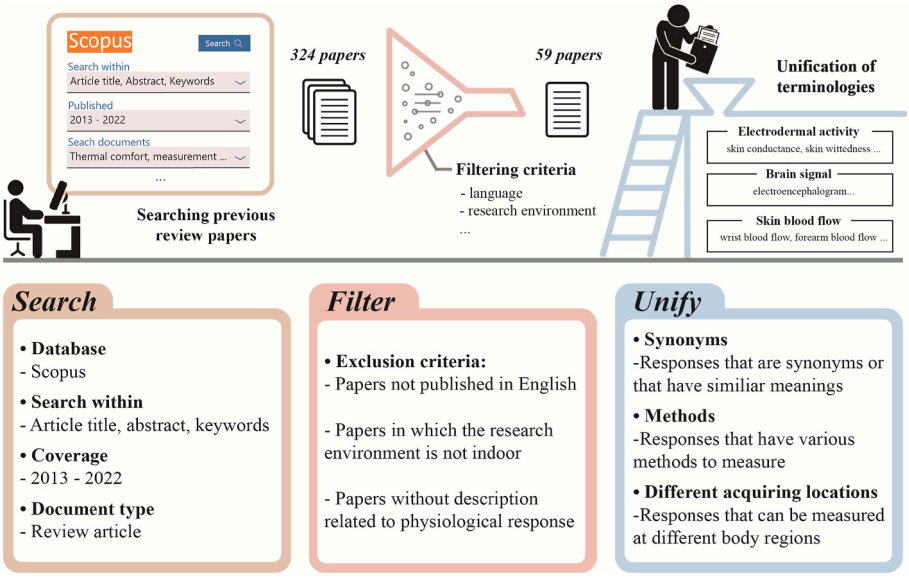


Fig. 1. Description of steps to identify physiological responses related to IEQ.

- *Search for previous review papers:* To identify the occupants' physiological response affected by each IEQ factor, search options and scope of previous studies were determined (refer to Table 1). Stage 1, aiming to identify the IEQ-related physiological responses investigated by research up to now, set review papers as its target. In this stage, review papers were reviewed to explore the types of physiological responses that were found to be significantly correlated to IEQ factors. These review papers analyzed research papers that investigated IEQ factors and affected physiological responses. According to previous studies, there is no significant difference in the search results of SCOPUS and Web of Science [44], but in some studies, it was mentioned that SCOPUS covers a wider range of journals, so the SCOPUS database was used [45]. Also, to determine the search coverage, it examined the trend of the previous studies on IEQ factor and physiological responses between 1992 and 2022. Results showed that the number of these studies from 1992 and to 2022 has consistently increased. To reflect recent studies, the search coverage was set to review papers published within the last ten years between 2013 and 2022 (refer to Fig. 2). The search for the identification of physiological responses was performed by combining search keywords based on IEQ factor and those based on physiological responses (refer to Table 2). For example, the search keywords for TC were "thermal environment" and "thermal sensations" among others that had a similar meaning to and could be substituted for TC. The search keywords for physiological response were set to "measurement", "variable", "parameter", "index", "response", and "factor", the terms that were similar to physiological responses in meaning and often used in the previous studies [9,46–50]. Using these search options yielded a total of 324 review papers.

- *Filtering by exclusion criteria:* Among 324 review papers searched, article title, abstract, and keywords were reviewed to exclude papers with low correlation to the present study. For this filtering process, the following criteria were used: (i) papers not published in English; (ii) papers whose research environment is not indoor; and (iii) papers without descriptions related to physiological response. In addition, those papers that could not be easily filtered based on the above criteria were reviewed for their whole content. Filtering process yielded 33 out of 94 papers on TC, 17 out of 185 papers on IAQ, 4 out of 16 papers on AC, and 5 out of 29 papers on VC.

- *Unifying terminologies:* Since terminologies of the searched physiological responses may differ per paper, the unification was performed in the following three cases (refer to SM Table S1). First, different terminologies may be used even with the identical physiological response. For example, it was confirmed that electrodermal activity (EDA) used a total of five terminologies: skin conductance, skin wettedness, skin resistance level, skin potential level, and skin conductivity. In this case, these were unified to the most representative terminology [51]. Second, the method for monitoring specific physiological response was substituted for the physiological response that it ultimately targeted for measurement. For example, since electroencephalogram is one of the methods used to monitor brain activity, it was substituted for brain activity [52]. Third, there are cases where different terminologies for the identical physiological responses are used, depending on the measured location. For example, wrist blood flow and forearm blood flow both indicate skin blood flow of different locations. In this case, they were unified to skin blood flow without separating them by the monitoring location. Finally, some physiological responses also have alternative physiological responses. For example, arterial oxygen saturation (SaO_2) stated as standard of oxygen saturation may be replaced by peripheral oxygen saturation (SpO_2). In this case, it was unified into a physiological response that is known as the specified standard (refer to SM Tables S2 and S3).

Table 1
Search options for deriving physiological response.

Search options	Contents
Database source	SCOPUS
Search algorithm	SCOPUS advanced search engine
Search within	Article title, Abstract, Keywords
Search coverage	2013–2022
Document type	Review papers

2.2. Stage 2: Investigation and classification of the physiological responses

At Stage 2, research papers and review papers were reviewed to investigate measuring methods of physiological responses that were found in Stage 1. Unlike in Stage 1, various online databases such as Google Scholar, Web of Science and Scopus were used. Particularly in this stage, the investigation was performed in terms of the location of measurement and measuring device. Specifically, location of measurement refers to the body region for measuring the physiological response [53], while measuring device refers to the device, sensor, or technique

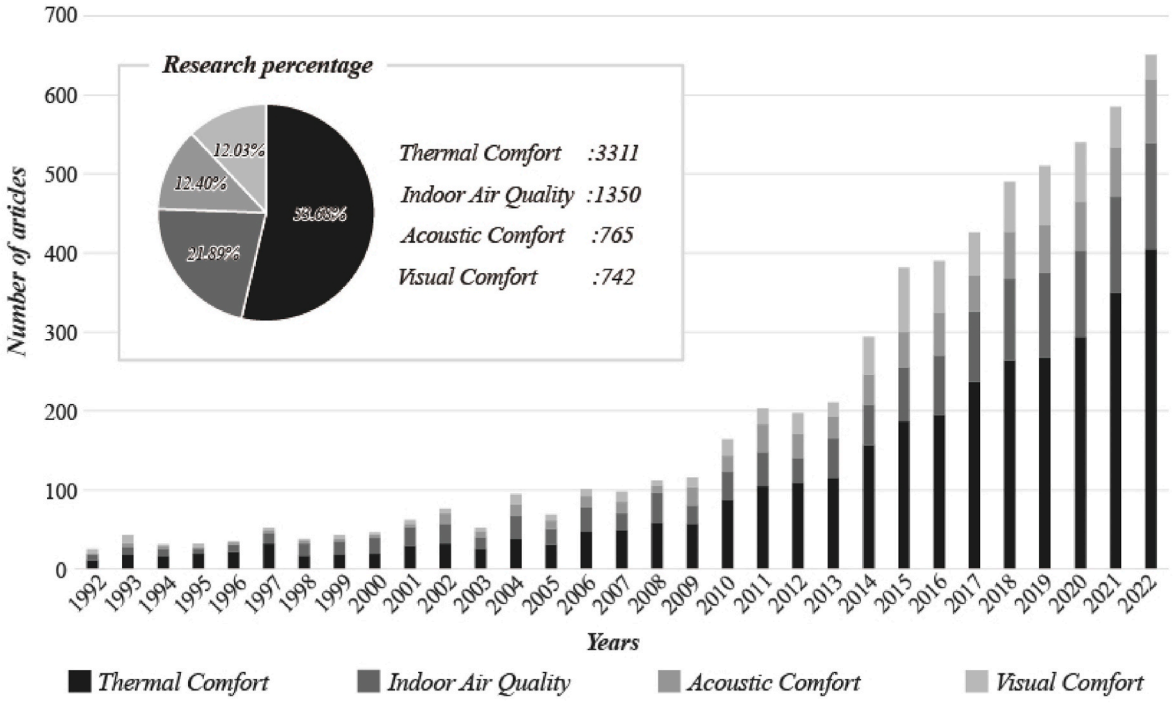


Fig. 2. Number of research that investigated physiological response as indicators of IEQ factor.

Table 2
Search keywords for TC, IAQ, AC and VC.

IEQ factor	Search keywords
TC	"Thermal Comfort"; "Thermal Environment"; "Indoor Thermal Comfort"; "Thermal Sensations"; "Thermal Sensation"; "Indoor Thermal Environments"; "Thermal Condition"
IAQ	"Indoor Air Pollution"; "Air Quality"; "Indoor Air Quality"; "Indoor Air"; "Air Pollution, Indoor"; "Air Pollution"; "Air Pollutant"; "Air Pollutants"; "IAQ"
AC	"Acoustic Comfort"; "Acoustic Noise"; "Acoustic Environment"; "Acoustic Conditions"; "Sound Quality"; "Sound Environment"; "Acoustic Quality"; "Acoustic Perception"; "Acoustical Comfort"
VC	"Visual Comfort"; "Visual Discomfort"; "Visual Perception"; "Lighting Conditions"; "Visual Environments"; "Lighting Quality"

for measuring the physiological response [54–56].

Next, for the analysis of the investigated measuring methods, classification was performed based on three criteria: (i) Criterion 1: location of measurement; (ii) Criterion 2: availability of wearables; and (iii) Criterion 3: existence of reference (refer to Fig. 3).

First, Criterion 1 was used to classify physiological responses into two types: (i) fixed location of measurement; and (ii) non-fixed location of measurement. In other words, they were classified to see that they can only be measured within the specific body region or measured in multiple body regions. Second, Criterion 2 was used to classify them into two types: (i) wearables available; and (ii) wearables unavailable. This classification determined whether a wearable device that can measure said physiological response at this point in time has been developed or not. The wearables available classification includes the device that has been identified as wearable in previous studies, the device just before the commercialization stage, or the non-invasive sensors that are wearable. Finally, Criterion 3 classified physiological responses into three types: (i) Class I – physiological response with specified reference; (ii) Class II – physiological response with specified reference and alternatives; and (iii) Class III – physiological response without any specified reference. Specified reference refers to the measuring methods that have been medically specified as reference or standard (refer to SM Table S2).

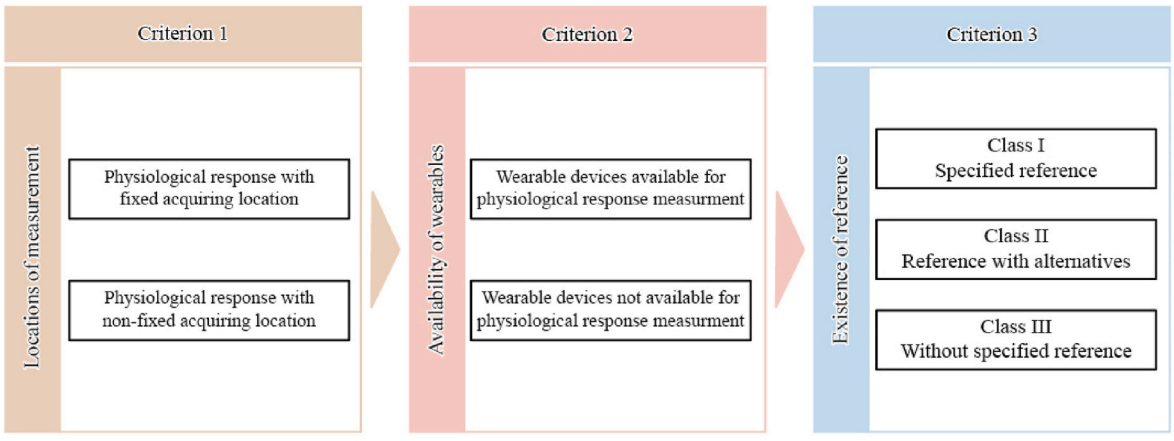


Fig. 3. Criteria for classifying physiological response.

Alternatives refer to the measuring methods in addition to the specified methods (refer to SM Table S3). Lastly, physiological responses that do not have any specified reference among the measuring methods refer to Class III.

2.3. Stage 3: Analysis and evaluation of the measuring methods according to each classification

This study aimed to review the current development status of wearable devices for measuring physiological responses, through which to present directions towards future development of wearable devices. Toward this end, Stage 3 analyzed and evaluated each measuring method of the physiological responses classified in Stage 2 in terms of the six wearable device categories and the four requirements for wearables. For the wearables available classification (i.e., Criterion 2), the categories of the corresponding wearable devices were investigated (refer to Table 3) and they were evaluated based on the four requirements for wearables. For the wearables unavailable classification (i.e., Criterion 2), existing devices were analyzed and evaluated in terms of the four requirements for wearables.

Wearable devices were classified into six categories based on the existing studies that surveyed and classified wearable devices by examining the features and specifications of diverse wearable devices (refer to Table 3) [57,58]. Non-invasive sensors were classified into the category similar to the method that used said sensor in the previous studies that were reviewed above. For example, if a temperature sensor was attached onto the skin with tape, it was classified as E-Patches.

The wearable devices used in occupant behavior and healthcare can generally be evaluated based on the following four requirements for wearables [59,60]. Thus, the following criteria were used for the evaluation in this study.

- *Continuous measurement*: continuous measurement at a specific cycle for a specific period of time without issues.
- *Unobtrusive design*: good and frequent wearability and no resistance to body structure, body temperature and skin when worn, and no obstruction in the user's daily movements and activities.
- *Easy data accessibility and interaction*: quick and easy access to data and interactivity.
- *Reliability*: permissible level of accuracy at measurement, which is maintained during operation.

To assess the fulfillment of requirements of wearables, there are four criteria: (i) fulfilled, (ii) conditional, (iii) unfulfilled and (iv) information unavailable. If the device meets the requirements for wearables, it belongs to 'fulfilled' while it it is not, it is marked as 'unfulfilled'. When the device meets the requirements only under certain conditions, it is marked as 'conditional'. Finally, if there is no information about the corresponding requirement for wearable to assess, it is marked as 'information unavailable'. Noticeable reports that describe reasons for not fulfilling the requirements for wearables are stated in SM Tables S17, S18, S19, and S20.

Table 3
Six wearable device categories.

Category	Examples
Wrist-Worn	smartwatches, wristbands
Head Mounted	smart eyewear, headsets
Ornament	smart jewelley, rings and chains
E-Textiles	smart garments, smart T-shirts and wears
E-Patches	sensor patches and E-tattoos
Others	straps, belts, bands

3. Physiological responses as indicators of IEQ factor

3.1. Thermal comfort

A total of 94 review papers were searched using thermal comfort and physiological response-related keywords (refer to Tables 1 and 2). Through filtering, 33 of them were selected [11,41,61–91]. Out of the selected review papers, 14 physiological responses were used to predict occupants' thermal comfort (refer to Table 4). Core body temperature (CBT), rectal temperature, oral temperature and skin temperature indicate thermoregulation of the occupants. Thermoregulation consists of three main components: thermogenesis, sweating and vasomotion [92]. Muscle activity and respiration rate are related to thermogenesis while electrodermal activity (EDA) and sweat rate are related to sweating. Blood pressure, skin blood flow (SBF), heart rate (HRs), and pulse rate (PRs) are part of vasoconstriction and vasodilatation. Brain activity can reflect occupant's physiological and psychological responses to the thermal environment [8,93]. Salivary α-amylase is a physiological measurement related to various stresses in the occupant, and is used to measure stress for thermal comfort [94].

3.2. Indoor air quality

A total of 185 review papers were searched with IAQ and physiological response-related keywords (refer to Tables 1 and 2). Through filtering, 17 of them were selected [41,42,95–109]. From them, 16 physiological responses were used to predict IAQ (refer to Table 5). Respiration rate, forced expiratory volume (FEV), forced vital capacity (FVC), pCO_2, PaO_2, $ETCO_2$, and peak expiratory flow (PEF) are used to measure lung function [110]. Brain activity and salivary α-amylase are used to investigate psychological response such as stress to IAQ and thermal comfort, and physiological response. In addition, SBF, EDA, skin

Table 4
Physiological measurements for thermal comfort.

Physiological response	Terms used in reference	Reference
Core body temperature	core body temperature	[11,70,72,73,85,89,91]
	body temperature	[62,63,65,67,68,74,75,82,91]
Rectal temperature	rectal temperature	[41]
Oral temperature	sublingual temperature	[41]
Brain activity	electroencephalogram	[11,62,91]
Skin blood flow	skin blood flow	[91]
	forearm blood flow	[41]
Blood pressure	blood pressure	[41,62,65–69,76,82]
Heart rate/Heart rate variability	heart rate	[11,41,61–69,71,82,86–91]
	heart rate variability	[41,62,91]
	electrocardiogram	[62,91]
Pulse rate/Pulse rate variability	pulse rate	[62,90]
	pulse rate variability	[91]
	PPG	[91]
Muscle activity	electromyogram	[91]
Respiration rate	breathing rate	[71,85]
Electrodermal activity	skin conductance	[11]
	skin wettedness	[63,87]
	skin resistance level	[91]
	skin potential level	[91]
	skin conductivity	[62]
Skin temperature	skin temperature	[11,41,61–65,67,68,70,71,73–75,77–83,85–91]
	posterior upper arm skin temperature	[64]
	back skin temperature	[64]
	mean skin temperature	[72]
	local skin temperature	[72]
Sweat rate	sweat rate	[71,84,85,89]
	sweating rate	[63,65,68]
	perspiration rate	[64]
Salivary α-amylase	salivary α-amylase	[41]

Table 5
Physiological measurements for indoor air quality.

Physiological response	Terms used in reference	Reference
Brain activity	electroencephalogram	[42,105,106]
Skin blood flow	peripheral blood flow	[42]
Blood pressure	diastolic blood pressure	[42,106]
	blood pressure	[42,102–104]
	systolic blood pressure	[107]
Heart rate/Heart rate variability	heart rate	[104,108]
	heart rate variability	[42,102,106,109]
Salivary α-amylase	salivary α-amylase	[42,106]
Eye blinking rate	eye blinking rate	[105]
	eye blink frequency	[95]
Eye dryness	eye dryness	[42,95,96,108]
Forced expiratory volume	forced expiratory volume	[42,97,98]
Forced vital capacity	forced vital capacity	[42,97,98]
pCO_2	pCO_2	[42]
PaO_2	PaO_2	[42,106]
$ETCO_2$	$ETCO_2$	[42,106]
Peak expiratory flow	peak expiratory flow	[97,98]
Respiration rate	respiratory rate	[42,95,99,106]
	breathing rate	[105]
	breathing frequency	[100,101]
	respiration rate	[41]
Eletrodermal activity	skin dryness	[42,97]
	facial skin dryness	[41]
Skin temperature	facial skin temperature	[41]

temperature, eye blinking rate (EBR), and eye dryness are physiological responses related to skin and eyes in contact with indoor air.

3.3. Acoustic comfort

A total of 16 review papers were searched with acoustic comfort and physiological response-related keywords (refer to Tables 1 and 2). Through filtering, 4 of them were selected [41,62,69,111]. From them, six physiological responses were used to predict occupants' acoustic comfort (refer to Table 6). In addition to CBT, vital signs such as respiration rate, blood pressure, and HRs, arterial oxygen saturation (SaO_2) [112] and EDA [94] that are derived to be related to acoustic stress.

3.4. Visual comfort

A total of 29 review papers were searched with visual comfort and physiological response keywords (refer to Tables 1 and 2). Through filtering, 5 of them were selected [41,64,68,113,114]. Out of these review papers, 10 physiological responses were used to predict occupants' visual comfort (refer to Table 7). Degree of eye opening (DEO), EBR, eye movement, gaze direction, and pupil size are related to eye activity. In addition, melatonin levels is affected by daylight exposure [115,116]. CBT, SBF, blood pressure and HRs were also derived to be related to visual comfort.

3.5. Available IEQ factors by physiological response

The physiological responses summarized by IEQ factor in Section 3.1–3.4 can be classified into two categories: (i) physiological responses affected by multiple IEQ factors; and (ii) physiological responses affected by single IEQ factors. That is, caution is required in selecting occupants' physiological responses to be measured based on the IEQ factor to be evaluated. To offer such information, the study summarized the effect of each of the 28 physiological responses on IEQ factors (refer to Table 8). As shown, certain physiological responses that are commonly known as vital signs, such as blood pressure, HRs, respiration rate, and body temperature were related to multiple IEQ factors. On the other hand, physiological responses (e.g., FVC and DEO) that are confined to a specific body region, such as lung or eye, were mostly related to single IEQ factor.

Table 6
Physiological measurements for acoustic comfort.

Physiological response	Terms used in reference	Reference
Core body temperature	body temperature	[41]
Blood pressure	blood pressure	[41,62,69,111]
Heart rate/Heart rate variability	electrocardiogram	[111]
	heart rate	[41,69]
	heart rate variability	[41]
SaO_2	SaO_2	[69]
Respiration rate	respiratory rate	[69]
Eletrodermal activity	skin humidity	[41]

Table 7
Physiological measurements for visual comfort.

Physiological response	Terms used in reference	Reference
Core body temperature	body temperature	[41]
	core body temperature	[68]
Skin blood flow	forearm blood flow	[41]
Blood pressure	blood pressure	[41]
Heart rate/Heart rate variability	heart rate	[41]
	heart rate variability	[41]
Degree of eye opening	degree of eye opening	[113]
Eye blinking rate	blink rate	[113]
Eye movement	eye movement	[113]
Gaze direction	gaze direction	[113]
Pupil size	pupil size	[64,113,114]
Melatonin level	melatonin level	[41]

4. Classification of physiological responses

In this section, the measuring methods for the physiological responses derived from Section 3 were categorized and examined into three criteria; (i) Criterion 1: location of measurement; (ii) Cirterion 2: availability of wearables; (iii) Criterion 3: existence of reference (refer to SM Tables S2, S3, and S4). First, Section 4.1 and 4.2 were divided by Criterion 1 (i.e., location of measurement). Next, Sections 4.1 and 4.2

Table 8
IEQ factors affecting physiological response.

Physiological response	Unit	IEQ factor			
		TC	IAQ	AC	VC
Blood pressure	mmHg	✓	✓	✓	✓
Heart rate/Heart rate variability	ms	✓	✓	✓	✓
Respiration rate	bpm	✓	✓	✓	
Electrodermal activity	μS	✓	✓	✓	
Skin blood flow	$W/m^2 \bullet HZ$	✓	✓		✓
Core body temperature	°C	✓		✓	✓
Brain activity	mV	✓	✓		
Skin temperature	°C	✓	✓		
Salivary α-amylase	U/ml	✓	✓		
Eye blinking rate	bmp		✓		✓
Rectal temperature	°C	✓			
Oral temperature	°C	✓			
Pulse rate/Pulse rate variability	ms	✓			
Muscle activity	mV	✓			
Sweat rate	$\mu L/cm^2 \bullet min$	✓			
Eye dryness	mm		✓		
Forced expiratory volume	L		✓		
Forced vital capacity	L		✓		
pCO_2	mmHg		✓		
PaO_2	mmHg		✓		
$ETCO_2$	mmHg		✓		
Peak expiratory flow	L/min		✓		
SaO_2	%			✓	
Degree of eye opening	L/L_{max}				✓
Eye movement	deg				✓
Gaze direction	deg				✓
Pupil size	mm				✓
Melatonin level	pg/mL				✓

were divided into subsections by Criterion 2 (i.e., availability of wearables). Finally, class of each physiological response that is defined by Criterion 3 (i.e., Existence of reference) was stated under corresponding classification (refer to Fig. 4).

4.1. Physiological response measured at fixed location

Table 9 shows the physiological responses with a fixed location of measurement. Among them, a total of 16 physiological responses, seven wearables available and nine wearables unavailable physiological responses, had a fixed location of measurement. Physiological responses in Class I (refer to SM Table S4) all had a fixed location of measurement with wearables unavailable. In the case of Section 4.1, corresponding physiological responses were stated according to specific body region (i.e., fixed location of measurment).

4.1.1. Physiological response – wearables available

A total of seven physiological responses had a fixed location of measurement and were classified as wearables available. Four body regions, head – crown, head – eye, thorax, and hand – finger, were the locations of measurement (refer to Fig. 5 and SM Table S5).

4.1.1.1. Head – crown.

- Class II: The physiological response that corresponds to Class II, which can only be measured on the head – crown, is brain activity (refer to SM Table S5) [117–121]. The specified reference among the brain activity measuring methods is to wear EEG device on the head – crown and can be measured using a head-mounted wearable device. In terms of unobtrusive design, which is one of the requirements for wearables, there are issues in pressure generated by tight chin strap. In terms of reliability, caution is required in case of being disconnected by slight movements. Alternatives among the measuring methods had no fixed location of measurement and all could substitute references (refer to SM Tables S6 and S7) [120–124].
- Class III: The physiological response corresponding to Class III, which can only be measured on the head – crown, is the degree of eye opening (DEO) (refer to SM Table S5) [125]. DEO can be measured by the head mounted camera on the head – crown. It has no issue, except that there is no information about unobtrusive design among the requirements for wearables.

4.1.1.2. Head – eye.

- Class III: The physiological responses corresponding to Class III, which can only be measured on the head – eye, are eye movement, gaze direction, and pupil size (refer to SM Table S5) [126–132]. All can be measured using a camera-based eye tracker on the head – eye, and the pupil size can also be measured with a mobile pupilometer. In terms of reliability among the requirements for wearables, the performance drop in the measurement of gaze direction may occur due to user activities, so sufficient review in this area is required.

4.1.1.3. Thorax.

- Class II: The physiological responses corresponding to Class II, which can only be measured in the thorax, are heart rate/heart rate variability (HRs) (refer to SM Table S5) [133–138]. The specified reference among the HRs' measuring methods is to use a 12-channel ECG device on the thorax and can be measured by wearing only the vest with dry electrodes. Analyzing reliability among the requirements for wearables showed that noise interference worsens when dry electrode is used. This is because, compared to wet electrodes that are attached to the skin, dry electrodes are not attached so displacement change exists between the electrode and skin. In case of alternative measuring methods for HRs, they have several locations of measurement, but some of them are less acceptable to substitute for the specified references (refer to SM Table S6) [134–137,139].

4.1.1.4. Hand – finger.

- Class II: The physiological response corresponding to Class II, which can only be measured on the hand – finger, is EDA (refer to SM

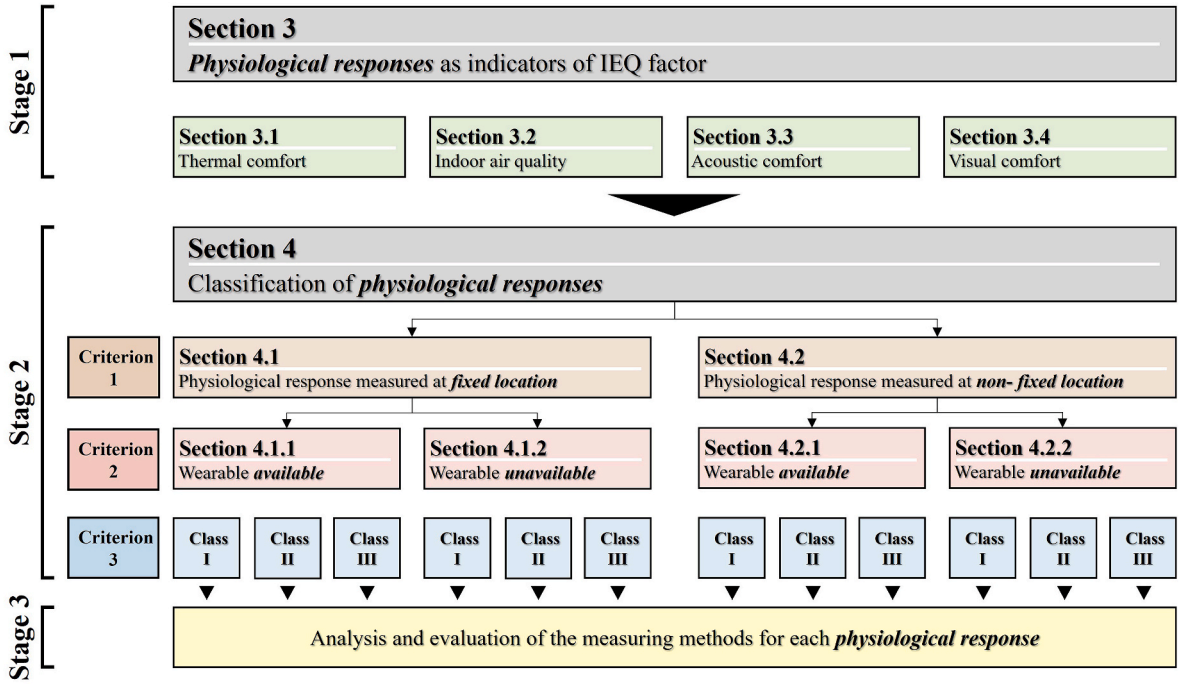


Fig. 4. The composition of Section 4.

Table 9
Physiological response with fixed location of measurement.

Availability of wearables	Location of measurement	Class	Physiological response	IEQ factor			
				TC	IAQ	AC	VC
WA[a]	Head - crown	II	brain activity	✓	✓		
		III	degree of eye opening				✓
	Head - eye	III	eye movement				✓
		III	gaze direction				✓
		III	pupil size				✓
	Thorax	II	heart rate/heart rate variability	✓	✓	✓	✓
	Hand - finger	II	electrodermal activity	✓	✓	✓	
WU[b]	Head - eye	I	eye dryness		✓		
	Head - mouth	I	oral temperature	✓			
		I	salivary α-amylase	✓	✓		
		I	peak expiratory flow		✓		
		II	forced expiratory volume		✓		
		II	forced vital capacity		✓		
		II	respiration rate	✓	✓	✓	
		II	$ETCO_2$		✓		
	Others - rectum	I	rectal temperature	✓			

Note: WA[a] stands for wearables available; WU[b] stands for wearables unavailable.

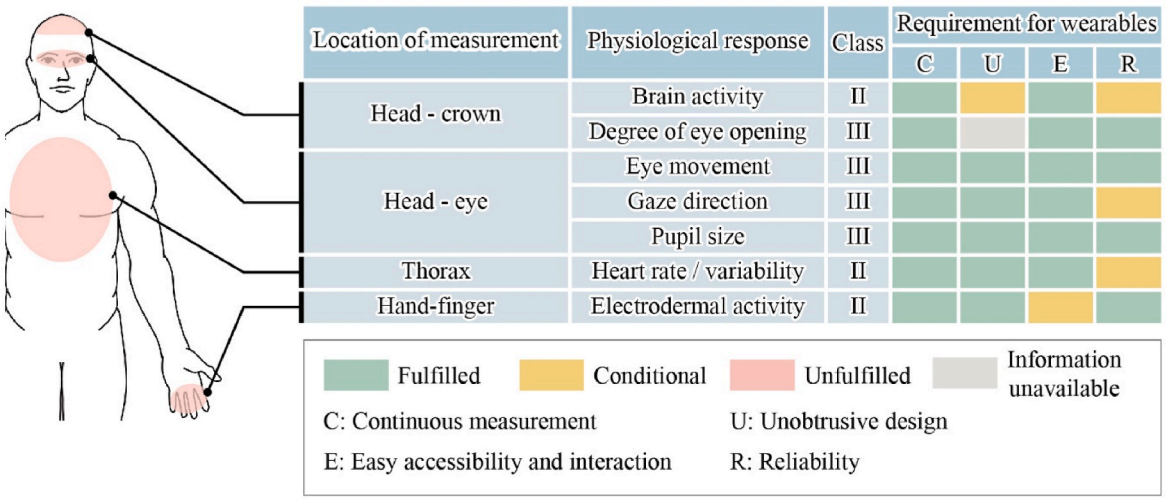


Fig. 5. Physiological response with fixed location of measurement – wearables available.

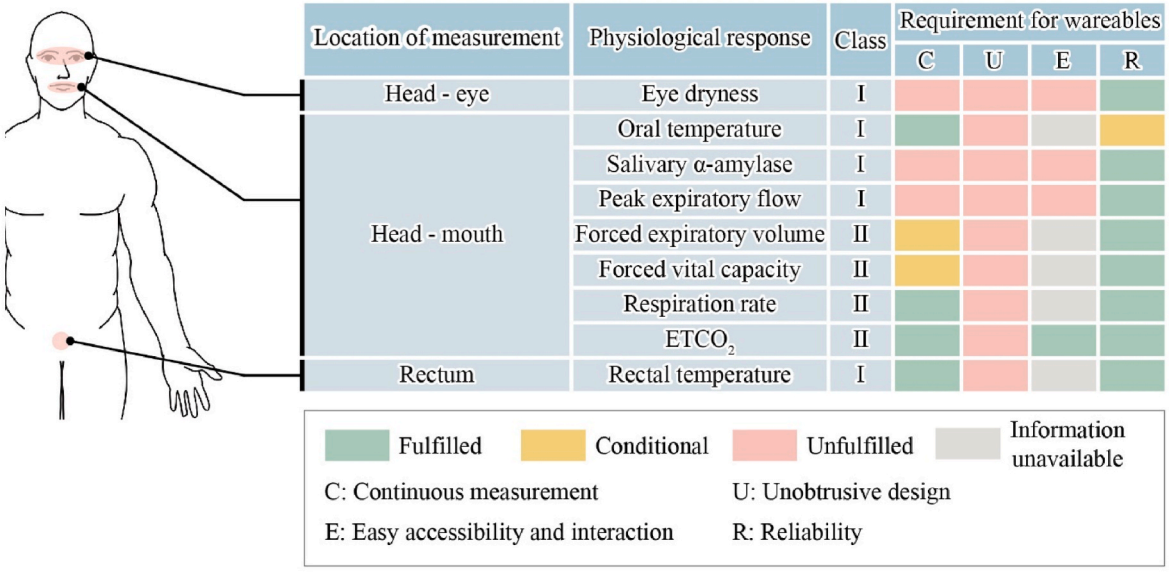


Fig. 6. Physiological response with fixed location of measurement – wearables unavailable.

Table S5) [140–145]. The specified reference among the EDA measuring methods is to wear the EDA device on the hand – finger. E-Patches or E-Textiles type EDA device can be used. There is an issue with easy data accessibility and interaction among the requirements for wearables. Since the size of the measuring device should be small enough for measurement on the hand – finger, it is difficult to install a data transmission device. Alternative measuring methods of EDA have several locations of measurement, but some of them are less acceptable in substituting reference (refer to SM Table S6) [143–145].

4.1.2. Physiological response – wearables unavailable

There are a total of six physiological responses with wearables unavailable among those that need fixed location of measurement. The three body regions, head – eye, head – mouth, and others – rectum, were shown to be the fixed location of measurement. In case of the physiological responses with wearables unavailable, they were analyzed in terms of the requirements for wearables (refer to Fig. 6 and SM Table S8).

4.1.2.1. Head – eye.

- Class I: The physiological response corresponding to Class I, which can only be measured on the head – eye, is eye dryness (refer to SM Table S8) [146]. Eye dryness can be measured by inserting a Schirmer test strip under the low eyelid. But this method is problematic in all areas, except reliability, among the requirements for wearables. It is unfulfilled in continuous measurement, and the test strip makes contact with the eyelid, so it cannot satisfy unobtrusive design. Furthermore, there is a time lag until the test result is acquired in terms of easy data accessibility and interaction.

4.1.2.2. Head – mouth.

- Class I: The physiological responses corresponding to Class I, which can only be measured on the Head – mouth, are oral temperature, salivary α-amylase, and peak expiratory flow (PEF) (refer to SM Table S8) [147–150]. First, oral temperature can be measured by placing a thermometer under the tongue. This was shown to have issues in unobtrusive design and reliability. In terms of unobtrusive design, the measuring method for oral temperature is shown to be inappropriate since it is an invasive method where the device makes contact with the mucous membrane under the tongue. In terms of reliability, probe placement and environmental factors may affect the measurement and should be reviewed as well. In case of salivary α-amylase, it can collect and analyze saliva by inserting it into an amylase assay kit, and PEF can be measured by placing a peak flow meter in the mouth. These two physiological responses also have critical issues in all areas, except reliability, among the requirements for wearables. Salivary α-amylase is unfulfilled in continuous measurement since it has to perform amylase assay and is an invasive method in terms of unobtrusive design since it needs to collect blood. Furthermore, in terms of easy data accessibility and interaction, occupants cannot easily access information via applications. PEF is unfulfilled in continuous measurement, since it can only be measured under special circumstances. Since occupants have to breathe forcefully, it is also unfulfilled in terms of unobtrusive design. Finally, similar to salivary α-amylase, occupants cannot easily access information via applications in terms of easy data accessibility and interaction.

- Class II: The physiological responses corresponding to Class II, which can only be measured on the head – mouth, are forced expiratory volume (FEV), forced vital capacity (FVC), respiration rate, and $ETCO_2$ (refer to SM Table S8) [55,151–159]. First, FEV and FVC can be measured by placing a spirometer in the mouth and can be problematic in terms of continuous measurement and unobtrusive design. The spirometer is limited in terms of continuous measurement due to cost and size. It also cannot offer ambulatory measuring. Second, the respiration rate can be measured by placing a spirometer or capnometer in the mouth, but as with FEV and FVC, it has issues in unobtrusive design. Third, $ETCO_2$ can be measured by placing a breath-based CO_2 monitor in the mouth. Among the requirements for wearables, it shows issues in unobtrusive design as the subject needs to keep holding the CO_2 monitor in the mouth. Alternative measuring methods of FEV, FVC, and $ETCO_2$ have fixed location of measurement and are acceptable in substituting specified reference (refer to SM Table S9) [153,154]. Alternative measuring methods of respiration rate have several locations of measurement and are acceptable for substituting reference (refer to SM Tables S10 and S11) [155–159].

4.1.2.3. Others – rectum.

- Class I: The physiological response corresponding to Class I, which can only be measured on others – rectum, is rectal temperature (refer to SM Table S8) [160,161]. Rectal temperature can be measured by placing a rectal thermometer in the rectum. While it does not have issues in continuous measurement, it has issues in terms of unobtrusive design. The measuring method of rectal temperature is a very invasive method where the device has to make complete contact with the rectum, and the development of future wearable device is believed to be difficult.

4.2. Physiological response measured at non-fixed location

Table 10 shows several locations of measurement in case of the non-fixed location of measurement of the physiological response, corresponding to a total of 12 physiological responses, including five physiological responses corresponding to wearables available, six to wearables unavailable, and one to both (i.e., skin blood flow).

4.2.1. Physiological response – wearables available

There are a total of six physiological responses with non-fixed acquiring location and wearables available, all of which are in Class III. Among them, five physiological responses are all wearables available in the measuring methods, and one physiological response (i.e., skin blood flow) is in the wearables available only in several measuring methods. This section analyzed the wearables available among the methods of measuring skin blood flow (refer to Fig. 7 and SM Table S12).

4.2.1.1. Class III.

- Eye blinking rate (EBR) can be measured by wearing either a camera integrated hat on head – crown or sensor integrated glasses or camera based eye tracker on the head – eye (refer to SM Table S12) [162–166]. First, wearing a camera integrated hat shows no issue in the requirements for wearables. Second, wearing sensor-integrated glasses is problematic in terms of unobtrusive design and reliability. Specifically, ultrasonic transducers integrated glasses block sight as the sensor is relatively large and heavy, while capacitive sensor integrated glasses offer poor performance if the glasses do not fit with the user's head form. Third, wearing camera-based eye tracker was shown to offer poor performance in reliability among the requirements for wearables depending on user activity.

- Skin blood flow (SBF) can be measured by attaching to the forearm E-Patches type doppler ultrasound device or wearing lase doppler flowmetry (LDF) device onto the forearm, forearm – wrist, hand – finger, or leg – calf (refer to SM Table S12) [167–171]. While there is

Table 10
Physiological responses with non-fixed location of measurment.

Availability of wearables	Class	Physiological response	Location of measurment	IEQ factor			
				TC	IAQ	AC	VC
WA[a]	III	eye blinking rate	head - crown head - eye		✓		✓
	III	skin blood flow	forearm forearm - wrist hand - finger leg - calf	✓	✓		✓
	III	pulse rate/pulse rate variability	head - temple head - ear arm forearm forearm - wrist forearm - wrist and hand - finger hand - finger	✓			
	III	muscle activity	forearm thigh	✓			
	III	skin temperature	head - forehead thorax - upper thorax abdomen thorax - upper back shoulder girdle - scapula axilla arm forearm forearm - wrist hand thigh leg - calf	✓	✓		
	III	sweat rate	arm forearm forearm - wrist	✓			
WU[b]	II	core body temperature	head - mouth others - rectum others - internal organs neck/thorax - collarbone/thigh	✓		✓	✓
	II	pCO_2	arm/forearm - wrist/thigh - groin		✓		
	II	SaO_2	arm/forearm - wrist/thigh - groin		✓		
	II	PaO_2	arm/forearm - wrist/thigh - groin		✓		
	II	blood pressure	arm/forearm/thigh	✓	✓	✓	✓
	III	skin blood flow	arm and forearm - wrist forearm thigh and leg - calf leg - calf	✓	✓		✓
	III	melatonin level	head - mouth others - artery others - urethra				✓

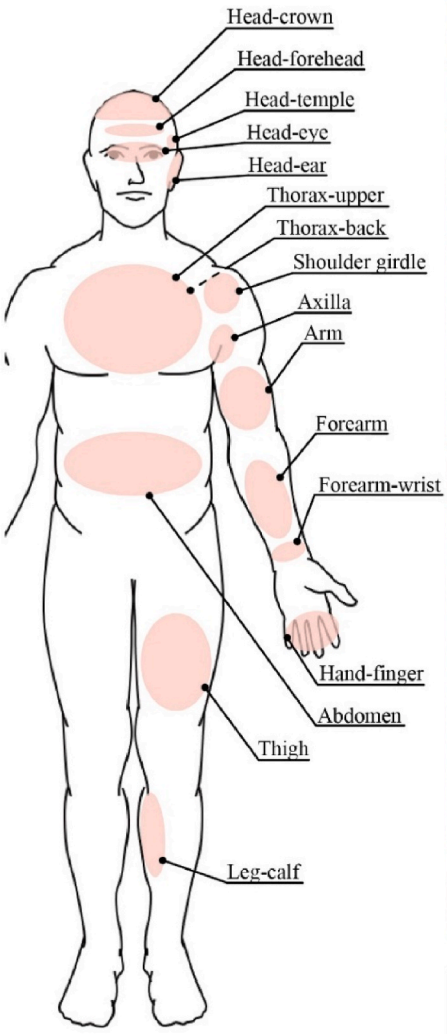
Note: WA[a] stands for wearables available; WU[b] stands for wearables unavailable.

no issue, except in terms of unobtrusive design among the requirements for wearables where some LDF device information is unavailable, the measuring method of wearing LDF device on the forearm may cause the body motion artifacts to impact upon measurement of physiological response, and as such, reliability needs to be reviewed.

- Pulse rate/pulse rate variability (PRs) is generally derived by analyzing the photoplethysmogram (PPG) signal. PPG signal can be measured by placing a pulse oximetry device to various body regions from the head – temple to hand – finger (refer to SM Table S12) [172–181]. In terms of unobtrusive design among the requirements for wearables, this method can be uncomfortable for occupants if the pulse oximetry device is placed on the ear for a long time. Also, pulse oximeter integrated wristbands or smartwatches may offer poor performance depending on the body motion artifacts and user activities. Wearing them would affect the measurement, posing questions in terms of reliability. Wearing wristband and placing pulse oximetry probe on the finger hinders the finger activities and movements in terms of unobtrusive design. Similarly, placing the pulse oximetry device on the ear is also shown to cause issues in reliability because it causes poor performance based on user activities. The other measuring methods, except the ones mentioned above, do not show any particular issues in terms of the requirements for wearables. However, there have been reports of degraded performance due to user activities or body motion artifacts, and as such, overall review of reliability is required.

- Muscle activity can be measured by placing E-Textiles, E-Patches or armband type electromyogram (EMG) sensor onto the forearm or thigh (refer to SM Table S12) [182–185]. In terms of unobtrusive design among the requirements for wearables, there is no issue, except that no information on E-Textiles or E-Patches type EMG sensors is available. Both E-Textiles and E-Patches are attached on the skin, so additional review is required on whether long-term attachment of sensors on the skin would cause discomfort or irritation.

- Skin temperature can be measured in many different body regions from the head – forehead to leg – calf, and the measuring device is also varied in wrist-worn, E-Textiles, or E-Patches type temperature sensors (refer to SM Table S12) [48,49,186–196]. The most



Physiological response	Class	Location of measurement	Requirement for wearables			
			C	U	E	R
Eye blinking rate	III	Head - crown				
		Head - eye				
Skin blood flow	III	Forearm				
		Forearm - wrist				
		Hand - finger				
		Leg - calf				
Pulse rate / variability	III	Head - temple				
		Head - ear				
		Arm				
		Forearm				
		Forearm - wrist				
		Wrist and finger				
		Hand - finger				
Muscle activity	III	Forearm				
		Thigh				
Skin temperature	III	Head - forehead				
		Thorax - upper				
		Abdomen				
		Thorax - back				
		Shoulder girdle				
		Axilla				
		Arm				
		Forearm				
		Forearm - wrist				
		Hand				
		Thigh				
		Leg - calf				
Sweat rate	III	Arm				
		Forearm				
		Forearm - wrist				

Fulfilled Conditional Unfulfilled Information unavailable

C: Continuous measurement U: Unobtrusive design

E: Easy accessibility and interaction R: Reliability

Fig. 7. Physiological response with non-fixed location of measurement – wearables available.

frequently used temperature sensor types are thermocouples using Seebeck effect and thermistors that use resistance changes due to temperature change [197–199]. The investigated measuring methods are mainly thermocouples, thermistors, or similar temperature sensor, but skin-like wearable optical sensors attached onto the forehead measure the wavelength-dependent change in the light that passed through the sensor to sense the temperature change. Since said optical sensor is highly sensitive to skin deformation, it is attached onto the forehead where there is little skin deformation due to body motion. With the light source and light detector, device for supplying power to the sensor itself or data transmission is unnecessary so that it can offer advantages in terms of the sensor size and weight. However, it is limited because the sensor only operates in the location where a light source and a light detector exist. It was shown that generic E-Patches type temperature sensors except optical sensors could be attached to many different body regions, and most measuring methods showed problems in unobtrusive design. Tape is required to fix the sensor onto the skin, or it limits daily activities and causes irritation or sweaty conditions on the skin. Consequently, the measuring methods that use E-Patches type temperature sensors require caution against discomfort and irritation. Research has shown that attaching patches on the thorax – upper thorax among various body regions would be less uncomfortable on sweaty skin compared to the axilla, thigh or back [190]. As opposed to E-Patches type temperature sensors which are attached to the skin directly, E-Textiles type temperature sensors make contact with the skin as the sensor attached to the textile touches the skin. They do not cause issues in terms of unobtrusive design, but no information is available on whether such sensor integrated T-shirts would be sufficiently comfortable for occupants. Wrist-worn type temperature sensors have problems in terms of reliability among the requirements for wearables due to the sampling rate change over time issue in some wristbands.

- Sweat rate can be measured by attaching to the arm an E-Patches type dermal patch or wearing a capacitive sensor onto the forearm or forearm – wrist (refer to SM Table S12) [22,200–202]. Sweat rate measuring methods pose problems in easy data accessibility and interaction. All methods, except the one where a capacitive sensor-based strap is worn on the forearm, cannot transmit data. In addition, if exposed to wind with air velocity exceeding 1.5 m/s, sweat is evaporated and data reliability can drop, making it essential to restrict environmental effects.

4.2.2. *Physiological response – wearables unavailable*

There are a total of seven physiological responses with wearables

unavailable that have non-fixed location of measurement, and two of which correspond to Class II and five to Class III. This section included wearables not available among the skin blood flow measuring methods (refer to Fig. 8 and SM Table S13).

4.2.2.1. Class II.

- There are four reference physiological responses to core body temperature (CBT): esophageal temperature measured on the head - mouth; rectal temperature measured on others – rectum; gastrointestinal temperature measured on others – internal organs; and pulmonary artery temperature measured on the arm, neck, thorax – collarbone, and thigh – groin (refer to SM Table S13) [147,203,204]. First, esophageal temperature can be measured by placing the esophageal temperature probe to the esophagus, which shows serious issues in terms of unobtrusive design. As an invasive method making contact with the esophagus and also as an invasive method that prevents the occupants from closing their mouth during the measurement process, the current methods cannot be easily developed into a wearable device. As has been discussed in Section 4.1.2.3. Others – rectum, the existing measuring method for rectal temperature is very invasive, so it is difficult to develop it into a wearable device. Gastrointestinal temperature can be measured by having the occupants swallow an ingestible telemetric temperature pill, but this poses problems in continuous measurement. The ingestible telemetric temperature pill needs to be swallowed at least 6 h before the measurement of the gastrointestinal temperature. The measurement can also be delayed because it is impossible to predict the duration in which the ingestible telemetric temperature pill is extracted from the body. In addition, while it has no issue in terms of easy data accessibility and interaction, data access can only be possible at least after 6 h. Pulmonary artery temperature can be measured by inserting an arterial catheter into the artery located in the arm, neck, thorax – collarbone or thigh – groin and connecting it to the thermometer. This method is very invasive since the arterial catheter needs to be inserted into the artery and it cannot be developed into a wearable device. Alternative physiological response of CBT has non-fixed location of measurement, and whether it can substitute the reference physiological response is described in SM Tables S15 and S16 [47,48,161,193,205–210].

- The specified reference of pCO_2, SaO_2, and PaO_2 is to insert an arterial catheter or syringe to the artery located in the arm, forearm – wrist or thigh – groin to collect an arterial blood sample, and measure them by performing the arterial blood gas test (refer to SM Table S13) [211–213]. It has issues in all areas of the requirements for wearables, except reliability. This has to do with the limitations of the arterial blood gas test. It takes 10–15 min to analyze an arterial blood sample and obtain the result [214]. Consequently, it has problems in terms of continuous measurement and easy data accessibility and interaction. As an invasive method, it is problematic in terms of unobtrusive design. Alternative physiological responses to pCO_2 and PaO_2 are $TcCO_2$ and $PtcO_2$, respectively, and have several locations of measurement (refer to SM Table S15) [215,216]. Alternative physiological response to SaO_2 is SpO_2 and has a fixed location of measurement (refer to SM Table S14) [217–219].

- The reference measuring method for blood pressure is to insert an arterial catheter into the arm, forearm or thigh and connect it to the blood pressure monitor (refer to SM Table S13) [220]. This is very similar to the pulmonary artery temperature measuring method, the reference physiological response of CBT. As a very invasive method, it has problems in terms of unobtrusive design. The location of measurement for the alternatives to blood pressure is non-fixed (refer to SM Table S15) [221–227].

4.2.2.2. Class III.

- Measuring methods of SBF corresponding to wearables unavailable are to wear venous occlusion plethysmography equipment and laser doppler imaging device (refer to SM Table S13) [168]. Venous occlusion plethysmography equipment can be worn on the upper limb

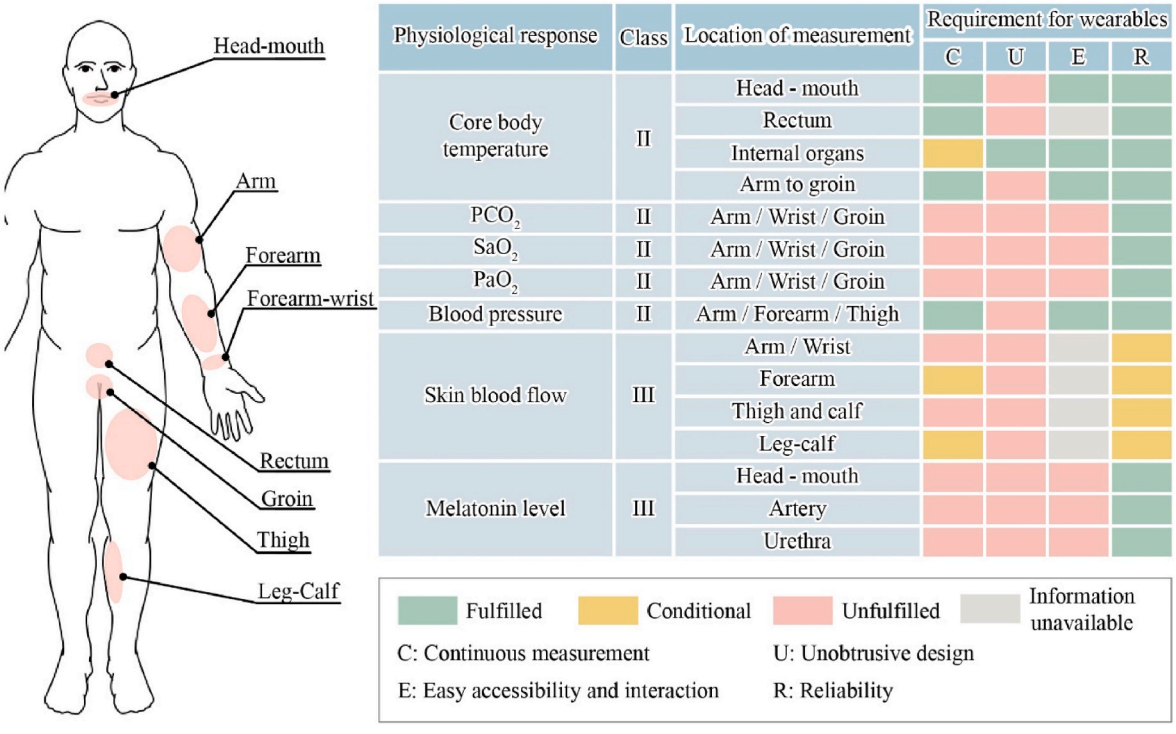


Fig. 8. Physiological response with non-fixed location of measurement – wearables unavailable.

or lower limb, and the detailed method of wearing is to wear the cuff on the arm or thigh, and place venous occlusion plethysmography equipment on the forearm – wrist or leg – calf. The venous occlusion plethysmography equipment is very large in size and is heavy so ambulatory measurement is impossible. Also, the cycle length of about 15 s makes continuous measurement impossible. Particularly, it has been mentioned that high variability is possible compared to other methods. In other words, the measuring methods based on this equipment has problems in all areas of the requirements for wearables, except easy data accessibility and interaction. A laser doppler imaging device can be worn on the forearm or leg – calf, but due to the size and weight of the device, ambulatory measurement is impossible. Also, due to the characteristics of the measuring device, it provides poor temporal resolution and is heavily affected by body motion artifacts.

- There are several measuring methods for the melatonin level, but they are all wearables unavailable (refer to SM Table S13) [50,228]. The melatonin level can be measured by inserting a sample to the melatonin assay kit, and saliva collected from the head – mouth, blood from others – artery, and urine from others – urethra could be used as a sample. None of the measuring methods can offer continuous measurement, and sampling is complicated or invasive. Also, since the data can be verified after analyzing the result with the assay kit, they have problems in terms of unobtrusive design and easy data accessibility and interaction.

5. Discussion and research roadmap for the future wearable device

5.1. Directions for wearables through analysis of existing measuring methods

This study proposed research directions for wearable device development based on the following two perspectives: (i) physiological response - wearables available; and (ii) physiological response - wearables unavailable. The primary objective is to improve the performance of wearable devices with the physiological responses that are wearables available among those categorized in Section 4 and to develop wearables for the physiological responses that are wearables unavailable.

5.1.1. Physiological response - wearables available

There are a total of 28 physiological responses of the occupants affected by IEQ (Class I: 5 EA, Class II: 12 EA, and Class III: 11 EA), among which 13 responses are wearables available (Class II: 3 EA, and Class III: 10 EA). Some of those physiological responses for which a wearable device has been developed have problems in terms of the requirements for wearables. To improve these issues, the present study proposed the following solution.

- Class II: Only three physiological responses (i.e., brain activity, HRs, and EDA) among the 12 Class II physiological responses where specified reference and alternatives coexist among the measuring methods were wearables available. **Brain activity** can be measured by placing an EEG device on the head-crown. But, in terms of unobtrusive design, pressure is generated due to the tight chin strap, and in terms of reliability, occupants' slight movements would lead to the disconnection of the device. As solutions to improve the unobtrusive design issues, various methods that are close to improvisations have been proposed, including the limiting of usage duration, relieving of the pressure by inserting a sterile gauze between the chin and the strap, or less tightening of the chin strap. However, these are closer to after-measures instead of actual solutions to the problems [118,229]. That is, to solve the fundamental issues of the EEG device in terms of unobtrusive design, fundamental solutions are proposed, such as the redesign of the strap or the development of device substituting for the strap [230]. To improve reliability, the introduction of an algorithm to eradicate EEG motion artifacts and other various studies to develop more effective and accurate algorithms are recommended [231–233]. **HRs** can be measured by placing a 12-channel ECG device to the thorax. But there is a reliability issue since noise interference worsens if dry electrode leads are used. To improve this, effective signal conditioning technologies to remove noise were introduced, and accordingly various studies have been conducted [234–237]. While **EDA** can be measured by placing an EDA device on the hand-finger, it causes issues in easy data accessibility and interaction. To improve this issue, all functions could be miniaturized in order to allow ring-sized data to transmit wireless data, or integration of EDA devices attached to the finger into the glove in order to add the function of wireless data to the glove [46,238].
- Class III: Nine out of 10 Class III physiological responses that have no specified reference excluding the melatonin level (i.e., DEO, eye movement, gaze direction, pupil size, EBR, SBF, PRs, muscle activity, skin temperature, and sweat rate) were wearables available. **DEO** can be measured by wearing the head-mounted camera on the head-crown, there was no information about unobtrusive design. Related to this issue, there have been reports that when other head-mounted device was actually used, it was heavier and more uncomfortable than expected [239–241]. Consequently, it should be verified whether there is any issue in unobtrusive design. Eye movement, pupil size, and gaze direction, which are measured similarly to DEO, have been measured using a head-mounted camera, but recently, miniaturized glasses-type device is used for the measurement [242–244]. Accordingly, while DEO has yet to be measured with a head-eye worn glasses-type device, such measurement is expected to be possible if a high-resolution and miniaturized camera can be used to acquire images required for the calculation of DEO. **Eye movement** and **pupil size** can be measured by wearing a glasses-type eye tracker on the head – eye, and there were no issues in the requirements for wearables. However, it is possible that the verification of reliability in terms of various user activities may have been omitted. **Gaze direction** can be measured with a method similar to that for the eye movement and pupil size, but performance degradation was identified in terms of reliability based on user activities. To improve this issue, the introduction of head straps to prevent device slippage or enhancement of the device's recording frequency have been proposed [129], which are deemed to be equally implemented for improved reliability of eye movement and pupil size. Among **EBR** measuring methods, wearing sensor-integrated glasses causes an unobtrusive design issue as the sensor is relatively large and heavy. It also blocks the sight and leads to performance degradation in terms of reliability if the glasses do not fit to the user's head form. To improve these issues, recent research has proposed fit assessment with which to reduce the sensor size and weight and design glasses that fit various types of head form [245]. Similar to gaze direction, the measuring method that uses the wearing of glasses-type eye tracker causes performance degradation by user activities, and thus, the same solution cannot be applied. Among **SBF** measuring methods, using LDF devices partly omitted information in terms of unobtrusive design, so further review is required. In terms of unobtrusive design, the long-time measurement of **PRs** makes users uncomfortable, and in terms of reliability, performance degradation may occur due to body motion artifacts and user activities, or even the actual wearing of the device may affect the measurement. As a solution to improve design, wearability considerations have been proposed. To improve reliability, recent research has proposed the mitigation of motion artifacts via sensor redundancy [246]. No information on **muscle activity** is available in terms of unobtrusive design, so further review is required. In the case of the skin-like wearable optical sensor attached to the forehead among the skin

temperature measuring methods, the sensor only operates when a light source and a light detector exist, so it is necessary to develop a wearable device that integrates light source and light detector into one. Also, several **skin temperature** sensors require tape to fix the sensors onto the skin, so in terms of unobtrusive design, it restricts daily activities and causes skin irritation and discomfort under sweaty conditions. This is because the direct attachment of flexible substrates to the skin requires tape or patch for the long-term and stable contact with the human body [192]. To solve the issues, recent research has proposed biostickers that can cope with the dynamic form of the skin due to user activities [247]. **Sweat rate** measuring methods cannot transmit data in terms of easy data accessibility and interaction and they are sensitive to external environments in terms of reliability. In terms of easy data accessibility and interaction, there was no issue mentioned with the addition of wireless data transmission function, so it is proposed that said function be added. In terms of reliability, the places in which sensing of the external environment need to be blocked must be considered in the design of wearable devices [248].

5.1.2. Physiological response - wearables unavailable

There are a total of 28 physiological responses of the occupants affected by IEQ (Class I: 5 EA, Class II: 12 EA, and Class III: 11 EA), with 15 wearables unavailable physiological responses (Class I: 5 EA, Class II: 9 EA, and Class III: 1 EA). Even for the physiological responses for which a wearable device has not been developed until now, a wearable device can be developed through research and development. To develop future wearable devices, the present study has proposed the following research roadmap.

- Class I: Class I physiological responses have no wearable device at the moment that satisfies specified references due to the specialized test for measurement (i.e., eye dryness, salivary α-amylase, and PEF) or the highly invasive measuring methods (i.e., oral temperature, and rectal temperature). But **eye dryness** and **salivary α-amylase** are related to biofluids like tear and saliva, and studies have been conducted for non-invasive sampling [249–251]. While no solution has been reviewed on implementing the test for the measurement of said physiological response to wearable device, a device for the sampling of tear has been developed. Therefore, it is possible that a wearable device for eye dryness may be developed in the near future. Since there has been no other research on the development of wearable device for the other Class I physiological responses, it can be considered that alternatives similar to Class II physiological responses may be developed.
- Class II: Those with the highest potential in the development of wearable devices among the Class II physiological responses are FEV, FVC, respiration rate, and $ETCO_2$. For **FEV**, **FVC**, and **respiration rate**, ambulatory measurement should be made possible by miniaturizing and making lighter spirometer. While there is no wearable device yet, mobile spirometers that occupants can operate directly have been developed [252,253]. **$ETCO_2$** can also be measured using a wearable device if small breath-based CO_2 monitor that can be installed inside the head-mouth could be developed. As this physiological response is all measured in the head – mouth, it may be developed into a mask-type wearable device. For example, a research proposed a mask-type respiratory monitoring device integrated with a temperature sensor, and if realized with future research and development, it could make a significant contribution to the monitoring of physiological responses [254]. Furthermore, it is acceptable to use alternative measuring methods for FEV, FVC, respiration rate, and $ETCO_2$, and advancing such alternatives, instead of developing wearable devices, could be considered. **pCO_2**, **SaO_2**, and **PaO_2** can be measured by blood sampling, and as opposed to tear or saliva, blood is biofluid obtained by needles or syringes, which makes it difficult to develop a wearable device due to its non-invasive sampling [255]. But, minimally invasive blood sampling has already been studied [256,257] so additional research on the continuous gas monitoring of blood sample is required. In addition, since it is acceptable to use alternative physiological responses to pCO_2, SaO_2, and PaO_2, the advancement of such alternatives, instead of the development of wearable device, could be considered. **Blood pressure** can be measured by inserting an arterial catheter and connecting it to the pressure monitor. This is a very invasive method, and it is reasonable to develop alternatives instead of the reference. The use of a cuffless blood pressure device among the alternative measuring methods for blood pressure should not be discouraged, and the advancement and verification process of this technology is required. Among **CBT**, esophageal temperature, rectal temperature, gastrointestinal temperature, and pulmonary artery temperature, nown as the reference physiological responses of CBT, cannot be measured with the development of wearable devices. Thus, studies have focused on combining various locations of measurement and alternative physiological responses to find the closest estimated value to the reference physiological responses or alternative physiological responses to CBT [193,258]. Since the locations and physiological responses proposed by each study somewhat vary by study, the estimated values closer to the reference physiological responses could be derived by newly combining locations and physiological responses that have not been considered in the previous studies.
- Class III: The wearables unavailable physiological response among the Class III physiological responses is the melatonin level. The biofluids to measure the **melatonin level** are saliva, blood, and urine [228,249]. Previously, in the research roadmap for eye dryness and salivary α-amylase, non-invasive sampling of biofluids has been discussed. As has been mentioned, the minimally invasive sampling of blood has also by conducted, and as a result, there has been some progress up to the biofluids sampling to measure the melatonin level using a wearable device. In the end, the development of wearable devices needs plans to substitute the melatonin assay kit, but there has been no report on the technology that would allow for continuous measurement of the melatonin level.

5.2. Research roadmap and guideline for future wearable device development

To realize the occupant-centered IEQ control, it is essential to develop wearable device with which to accurately measure the occupants' physiological responses. Therefore, the present study proposed a guideline and research roadmap for the development of future wearable devices.

First, for the development of future wearable devices, the target IEQ factor and related physiological response should be defined. As has been analyzed in Section 3, there are different IEQ factors affected by each physiological response. The physiological responses can be categorized into two types: (i) physiological response affected by multiple IEQ factors; and (ii) physiological response affected by a single IEQ factor. To monitor specific IEQ factors according to the objectives of future wearable devices, the physiological responses affected by a single IEQ factor are selected, and to monitor the overall IEQ, the physiological responses affected by multiple IEQ factors are selected. However, the physiological responses affected by multiple IEQ factors cannot allow us to discern clearly which IEQ factors affected which physiological responses of the occupants, so a technology that can allow for such an analysis should be developed. It is expected that future wearable devices will be able to evaluate multiple IEQ factors by measuring minimum physiological responses.

Second, the location of measurement of the physiological responses should be considered. As opposed to the environmental factors (e.g., indoor temperature, indoor CO_2 concentration, and etc. …), physiological responses are collected from the occupant's body, and thus, acquiring the location is limited. In other words, a wearable device is

attached to a specific body region (i.e., head - crown, thorax, hand – finger, etc.), and one wearable device cannot measure another physiological response with a different location of measurement. In addition, even with the same location of measurement, two different physiological responses cannot be measured if there is any interference between the sensors [259–264]. To overcome such limitations, various alternatives to the measurement of physiological responses need to be developed.

Third, wearable devices should meet requirements for wearables in addition to the location of measurement mentioned above. To ensure the capability of wearable devices as predictor of a certain IEQ, generalized and quanitified standards to assess and evaluate these requirements are needed. To establish these standards, future research should consider the following directions.

- Continuous measurement: A number of studies which stated that continuous measurement was conducted did not mention the accurate specifications of device (i.e., available time duration of wearables). Most of the cases where the specifications were stated used devices with batteries as primary power source. Specifically, the battery lasted for minimum of 2 h to maximum of ten years. In this regard, it has been reported that a rechargeable battery power supply of wearables should guarantee normal use of at least 8 h or more without recharging [265]. Measuring devices that do not meet such requirement should be improved to enable continuous measurement. Devices and sensors that are attached to the skin using adhesive materials such as E-Patches need a different approach. For example, for EEG or ECG devices that use wet electrodes, the time for the electrolytic gel to dry up can be considered as the actual continuous measurement time [138,230]. Also, usability and safety should be considered to decide the continuous measurment time. When the device is used for a certain period of time, it may cause side effects such as irritation, but studies rarely describe safety-related information of continuous measurement devices [265,266]. Along with the battery capacity, available time duration of continuous measurement should consider different approaches for each type of wearables, usability and safety, and provide generalized standards.
- Unobtrusive design: A number of studies using measuring devices have been insufficient to investigate whether they satisfy unobtrusive design. Most studies did not systematically graded or analyzed how much comfort or discomfort was caused for users that wore the measuring devices [163,190]. To review and analyze unobtrusive design systematically in future studies, consensus among experts and researchers on genralized guidelines and standards for unobtrusive design are needed.
- Easy data accessibility and interaction: For easy data accessibility and interaction, the device itself should be able to provide information to the user or through other devices basically. Most measuring devices transmit data wirelessly through Bluethooth or Wi-Fi, analyze the received data with applications, and finally provide the analyzed data to the users. Since Bluetooth or Wi-Fi device increase the size and weight of the measuring device, wires were used to transmit data periodically making the device far from easy data accessibility and interaction. Thus, an extensive body of research has recently emphasized wireless wearables for improved data accessibility, interaction and usability [267–269]. Furthermore, the power consumed by data transmission also must be taken into account, and various studies have introduced methods that can transmit data with low power, such as Bluetooth low energy devices, for wearable devices [270,271]. In the case of Bluetooth low energy, sufficient review is needed since the sampling rate is lower than that of normal Bluetooth [272,273].
- Reliability: Few studies evaluated the accuracy and feasibility of the measuring devices in practical aspects [190]. Even the research that mentioned accuracy or validation of the measuring device did not present criteria of accuracy or precision while it is necessary to verify the reliability by comparing to the reference measuring methods. Lack of specific standard of required accuracy to verify reliability, especially for physiological responses that belong to Class III, is a critical issue. Also, in general, the reliability of the measuring devices was confirmed in the laboratory with the user seating steadily. The most frequently mentioned problem related to reliability is the performance degrade due to users' movements or activities. The interpretation of data can be adversely affected not only by changes in measurement position or measurement failure caused by movements or activities, but also by noise such as body motion artifacts resulting from those movements or activities. In order to develop practical wearable devices, it is essential to assess the reliability of devices under conditions that involve users' movements and activites. Studies that suggest generalized standards for intensity of users' movements and activities are insufficient. Therefore, future research should investigate the specific standards of acceptable accuracy and intensity of user's activity to improve reliability of practical wearable devices.

From the review of previous studies, this study has identified the following limitations according to the wearable device categories, which should be resolved when developing future wearable devices.

- Since head-mounted type wearable devices are worn relatively far away from the center of the body, they are susceptible to shaking due to the occupant's movements or activities. To prevent this, some implement a tight chin strap, which can cause the occupant's some discomfort in terms of unobtrusive design when worn for a long time.
- If sufficiently attached to the wrist, wrist-worn type wearable devices may not offer reliable measurement. Relatively far away from the center of the body, it tends to be heavily affected by the occupant's movements or activities, leading to poor reliability.
- With regard to ornament type wearable devices, the ring type pulse oximetry device worn on the finger was the only available device. Since it is worn on the finger, it should be small, and such size causes issues in data storage and transmission, requiring a plan for easy data accessibility and interaction.
- Due to the sticky tape or patch, E-Patches type wearable devices manifest issues in unobtrusive design. Occupants may experience discomfort as the device is frequently reattached due to the weak attachability or the lifespan or battery capacity of the device.
- E-Textiles type wearable devices have been used to overcome or compensate some of the limitations of E-Patches type wearable devices. While E-Textiles have improved the limitations of E-Patches in terms of unobtrusive design, their sensor is not firmly fixed, leading to poor reliability.
- Other types of wearable devices vary, including chest straps, arm bands, and finger probes. As such, there is lack of information on the requirements for wearable devices, but it is possible that these devices may become key wearable device types in future research.

In addition, future wearable devices will inevitably face challenges regarding invasion of privacy. Future wearable devices have to overcome these challenges in prior to applications in actual sites [272,274,275]. Blockchains and data encryptions can help to reduce these challenges [276–278].

6. Conclusion

It has been investigated that the occupants' physiological response can be indicators of IEQ, devices that measure physiological responses have become increasingly important in monitoring IEQ. Accordingly, demand for wearable devices that have high usability and capacity to collect continuous data has increased. Therefore, this study reviewed devices for measuring physiological responses to propose directions for the development of future wearable devices.

The present study reviewed 59 out of 324 review papers on the IEQ and physiological responses published in the last ten years and identified physiological responses related to each IEQ factor. It investigated the measuring methods used for each physiological response and examined them by (i) location of measurement; (ii) availability of wearables; and (iii) existence of reference. To this end, the study presented the points to be improved and the potential for development of wearable devices based on the results of analysis of wearables available and unavailable physiological responses in line with the four requirements for wearables. A guideline that included considerations for the development of future wearable device to measure physiological responses to IEQ was also presented.

This review can contribute to future research on IEQ and physiological responses and to the development of future wearable devices. First, the present study can serve as a guideline on the suitable location for measuring physiological responses in future study where monitoring physiological responses to control or predict IEQ factors is needed. Also, this study can contribute to maximize the applications of wearable devices to develop personal or occupant-centered IEQ control or to suggest IEQ predictive models. Based on the reviews that this study presented, researcher can measure physiological responses more accurately and efficiently with wearable devices which have high usability compared to stationary devices or sensors. The findings of this study can also contribute to the improvement of existing wearable devices and the development of future wearable devices by considering the measuring methods for various physiological responses. However, the present study also has the following limitations. The physiological responses targeted in this review were selected through review papers over the past 10 years, so some of the physiological responses that have been investigated as possible indicators of IEQ through recent research were not included. For example, recent findings on new potential physiological responses such as blood glucose, hormones and circadian rhythm were not included in this review [14,31]. In addition, this review could have offered a more comprehensive analysis if a quantitative approach such as statistical or numerical inferences was used. In the future study, it is necessary to include quantitative methodologies to derive objective analyses and minimize subjective biases in reviews. Also, while the study analyzed the potential of wearable device development, it did not consider the cost aspects particularly in terms of development and commercialization.

CRediT authorship contribution statement

Minjin Kong: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Jongbaek An:** Visualization, Resources, Methodology, Investigation, Formal analysis. **Dahyun Jung:** Visualization, Resources, Methodology, Formal analysis. **Taehoon Hong:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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