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On the understanding of the mean radiant temperature within both the indoor and outdoor environment, a critical review

Hongshan Guo[a,b], Dorit Aviv[a], Mauricio Loyola[a], Eric Teitelbaum[a], Nicholas Houchois[b], Forrest Meggers[a,b,*]

[a] School of Architecture, Princeton University, USA
[b] Andlinger Center for Energy and the Environment, Princeton University, USA

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ABSTRACT

Mean radiant temperature is central to our understanding of the radiant heat exchange between the human body and surrounding environment. This paper will present a review of the concept's evolution including its qualitative definition, methods of quantitative evaluation and corresponding challenges. In the process, this review suggests that more effort needs to be invested in addressing the geometric complexities of radiant heat transfer in research into MRT; the ASHRAE definition is broad and is liable to simplification, and research which uses the definition relies on a variety of simplifications, often without acknowledging the degree of geometric complexity which exists in reality. Existing means of obtaining an estimate of mean radiant temperature range from direct measurements using globe thermometers or net radiometers, to computational simulations, and are widely used for studies within indoor and outdoor environments. Previous literature studying the correlation between air temperature and MRT has found equivalence ratios, the relative importance of convection to radiation, ranging from 0.71 to 1.4, however, it is often assumed to be 1.0 in current research practices. We also identified a rapid increase in the usage of MRT in biometeorological studies during the last ten years on top of the increased usage in indoor environment sensing and modeling in light of recent developments in heating and cooling systems. Recent efforts to include the short-wave component in indoor MRT characterization have shown an increase in cooling capacity of radiant floors from 32 to 110 W/m^2; significantly decreasing peak energy demand.

1. Introduction

According to U.S. Energy Information Agency (EIA), about 39% of the total energy used in the United States went to buildings in 2018 [1]. Roughly half of this energy was used to heat and cool the buildings. Decreasing the energy necessary to ensure occupant comfort could therefore result in significant energy savings. Existing studies [2] have demonstrated that half of thermal comfort is driven by radiant heat exchange between the occupant and environment. The mean radiant temperature (MRT) is critical in understanding this relationship. Its importance has increased during the last twenty years, as radiant systems have become more common while interest in the impact of outdoor solar irradiance also increased. The complexity of MRT's definition and measurement methodologies have created obstacles to comprehending, modeling, and evaluating mean radiant temperature in both indoor and outdoor environments.

Originally, MRT was used to characterize the radiant heat exchange between occupants and environments where the majority of the sources of heat were radiant: the hearth, radiant floors as well as boilers and industrial machinery. Much of the pioneering research on thermal comfort originated from concerns regarding industrial hygiene and productivity [3,4] in addition to those on heating and cooling buildings [5,6]. This changed after the introduction of central air-conditioning, and the dominant means of controlling heat transfer between the human body and the environment became convection instead of radiation. Despite contributing to overall heat transfer, the MRT of a room has over time become a homogeneous environmental parameter within indoor environments [7]. However, as many studies have pointed out, the MRT does vary within the indoor environment [8], particularly when there are radiant systems present [9]. Improved understanding of MRT is thus more crucial when understanding the radiant component of human thermal comfort. A clear definition of MRT is necessary to design better systems for comfort delivery.

In the 1930s, thermal comfort studies focused on ensuring the productivity of occupants in factories and incorporated both radiant and convective heat transfer [4,10]. As more systems became air-based,

* Corresponding author. School of Architecture, Princeton University, USA.
E-mail addresses: hongshan@princeton.edu (H. Guo), fmeggers@princeton.edu (F. Meggers).

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the focus of thermal comfort studies gradually shifted to convective systems [8,11]. MRTs began to be treated as the equivalent of the temperature measured by globe thermometers [12]. However, recent findings on the energy benefits [13] of radiant systems [14]have increased interest in this significant component of thermal comfort. As reviews on radiant heating and cooling systems have indicated, it is of critical importance to review MRT; its definition, and its methods of evaluation [15]. This will provide insights for future radiant system design and further energy savings. Additionally, it will address the challenges of evaluating thermal comfort and energy consumption when using heterogeneous radiant surfaces to deliver personalized comfort [16].

Aside from the energy implications of using MRTs within the indoor environments, we have found the quantity and accuracy of outdoor MRT research has increased rapidly despite its relatively short 20 year history. This has led to better awareness of the spatial variation of MRTs. We finish by emphasizing the importance of using MRT as a performance indicator of radiant systems against more conventional parameters such as operative temperature, where the operative temperature is a quantity that further simplifies MRT by averaging convective and radiant components of indoor environment heat transfer, and it is often calculated by simply averaging air temperature and MRT [21].

Existing reviews which interrogate the definition of MRT come from areas including human-biometeorology [17], numerical simulation [18], and a more extensive range of thermal comfort reviews that generally limit their evaluations of MRT to the same limited sample of studies [15,19]. We aim to present a comprehensive review of MRT that characterizes and critiques the discrepancies in its definition, evaluation, and utilization to understand performance in the built environment.

The paper is structured with the following sections:

- **Defining MRT** as a means of simplifying radiant heat transfer due to the complexity of radiant heat transfer, and acknowledging that a broad range of disparate assumptions occur in practice.
  - The qualitative and quantitative definitions of MRT through time
  - Geometric complexities from view factors - Air temperature and MRT relationship; radiation vs convection
  - Analytical expressions of MRT from empirical measurements
- **Evaluating MRT** by measuring(with sensors) and by modeling (with simulations) indoor and outdoor environments
  - Measuring MRT with globe thermometers,net radiometers, infrared thermography and other indoor instruments
  - Modeling MRT; indoors and outdoors
  - Challenges in measuring and modelling MRT; spatial distributions of MRTs, complexity caused by human body geometry
- **Utilizing MRT** to realize energy savings with radiant heating and cooling systems and a review of its use in research
  - Opportunities in using MRT to control the built environment for operational efficiency
  - Past and present MRT-related research; thermal Comfort and MRT publication analysis, growth of MRT in characterizing the urban environment

2. Defining MRT - variations, abstractions and simplifications

Mean radiant temperature (MRT) is a physical construct developed to facilitate radiant heat transfer calculations. Currently it can include both short wave (visible and solar) and long wave (infrared and terrestrial) radiant heat exchange between a human body and a given environment, hence its importance in evaluating human energy balance and thermal comfort models both indoors and outdoors [20]. It is defined as the ‘uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure’ [21]. The concept of mean radiant temperature was first termed by Barker in 1931 to be used to account for the radiant heat exchange between a theoretical black body's heat exchange and its surrounding surfaces at different temperatures (T_i) using different view factors (F_{p-i}) [5,6], allowing researchers to abstract radiant heat exchange about the human body to a single temperature.

Radiant heat transfer between two surfaces (both assumed to be perfect blackbody emitters) follows Equation (1) with units W/m^2, and is a result of the Stefan Boltzmann constant, σ, the surface temperatures, T_1, T_2, and the view factor between the surfaces, $F_{1\to 2}$. $F_{1\to 2}$, or view factor is the proportion of radiation leaving surface 1 that strikes surface 2.

$$Q_r = \sigma * F_{1\to 2} * (T_1^4 - T_2^4) \tag{1}$$

Unlike the view factors between two surfaces, the view factor between the human body and all the surfaces of the surroundings is complex, and MRT offers a method of abstracting that part of the problem so it can be simplified. Determining MRT enables the direct calculation of radiant heat transfer to the human body because the MRT already accounts for the view factors by using them to weight all the surrounding temperatures. As shown in Equation (2), obtaining the mean radiant temperature T_r is essentially weighing the surface temperatures, T_i, using view factors (sometimes also expressed as angle factors [22]) between the person and all the surroundings, $F_{p\to i}$.

$$T_r^4 = \sum_{i=1}^{N} T_i^4 F_{p\to i} \tag{2}$$

As the MRT accounts for the view factors, Equation (3) can be simplified to calculate radiant heat transfer directly.

$$Q_r = \sigma * (T_p^4 - T_r^4) \tag{3}$$

Equation (2) explains how MRT can be approximated from the surface temperatures and view factors and was quickly introduced to engineers through publications and textbooks [23]. It simplifies radiant heat transfer in Equation (3), but then MRT is left with the inherent complexities of variations of view factor between the human body geometry and the surrounding surfaces, which remains a significant challenge to researchers [24–26]. If the human body is abstracted to a solid sphere, it is easier to consider a point (i.e. an infinitely small sphere) at the very center of this sphere to calculate the view factors from all surrounding surfaces to the ’point’ rather than an actual human body. This is by far the most ubiquitous simplification of MRT calculation commonly used in textbooks [27–29]. As the ’Father of Radiant Heating’ [30,31], Barker's expertise and understanding of the difference in surface temperatures could potentially have led to his choice of words, which eluded the complexities of the human body geometry by using both ’solid body’ and ’occupant’ in his proposed definition for MRT. To better illustrate what an MRT of a human body could be, we have created an illustration, as shown in Fig. 1. From the definition of MRT, for a person surrounded by different surfaces at different surface temperatures, their combined equivalent is a sphere in which the uniform temperature is the resulting MRT for that location.

For an actual human body, characterizing the actual relationship between the human body and surrounding individual planes with different orientations and surface temperatures is challenging. As was shown in Fig. 1, both the temperatures and the orientations as well as the different parts of the body need to be considered for an equivalent value of MRT. Several researchers have approached this question by using different human-shaped models to account for the body [25] instead of treating it as a point such as shown in Fig. 2, but researchers have yet to arrive at an efficient and easy-to-use way of accounting for an entire human body in evaluating the radiant heat exchange.

The definition of MRT has also changed significantly over the years in existing standards. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) provided a first standard definition of mean radiant temperature in 1966 as ‘the temperature of a

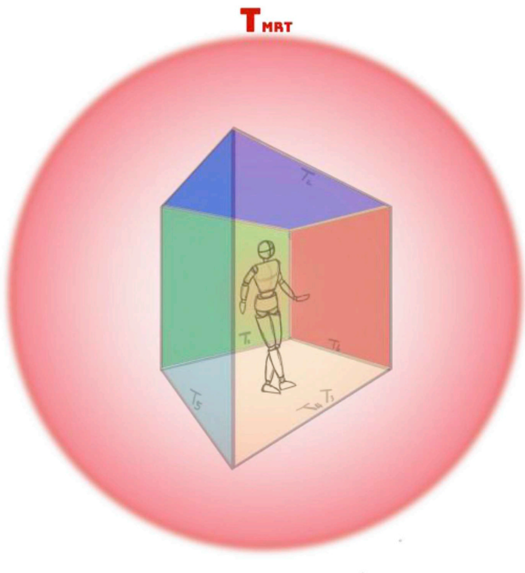

Fig. 1. Diagram of the verbal MRT definition of a person inside a room with six different surfaces at different temperatures facing the body.

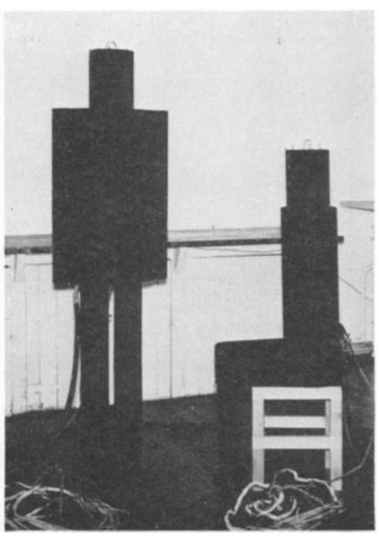

Fig. 2. Metal human models used to investigate angle factor's influence on mean radiant temperature [25].

uniform black enclosure in which a solid body or occupant would exchange the same amount of radiant heat as in the existing non-uniform environment' [32]. This definition has evolved to the 2017 version : 'the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings' [21]. The 1985 changes included a wording change from "environment" to "enclosure" [33], and in 2003 "solid body or occupant" was changed to "a person" as well as the addition of "actual surroundings" [34]. As the standards continue to acknowledge the inherent complexity of characterizing MRTs, these continuous semantic changes appear to be rooted in the difficulty of accounting for all surfaces with varying temperatures and view factors between a complex occupant and room surfaces.

This is also the core challenge in determining MRT through measurement and simulation. Most recently in 2017, ASHRAE added more complexity by expanding their definition for MRT to include both the short-wave and long-wave components: t_{rsw} or short-wave mean radiant temperature that accounts for direct and diffuse solar radiation, and t_{rlw} or long-wave mean radiant temperature that characterizes the radiation from interior surfaces weighted by their view factors [21]. The standard acknowledges that t_{rsw} serves as an adjustment to t_{rlw} when calculating mean radiant temperature, while the latter remains to be defined by Equation (2). These standards evolved in the course of research in the indoor environment. Despite the potential for MRT to simplify understanding of radiant heat transfer for thermal comfort in the built environment, research reviewing biometeorological aspects of human thermal comfort has shown that MRT remains highly complex and variable [17].

2.1. Geometric complexities from view factors

The concept of MRT enabled the use of a single term to represent different surface temperatures and their weighted view factors for radiant heat transfer. While being a means to simplify the calculation in Equation (3), the temperature and geometric complexities remain within MRT. Therefore, MRT requires considerable computational resources or geometric simplifications to be calculated. It could be argued that a true calculation meeting the definition of exchange between a human and the surroundings would require an infinitely resolved geometric model of both the body surfaces and the surrounding surfaces with their varying temperatures.

An ideal mathematical model for view factor would determine the precise, solid angle fraction between every surface on the human with every surrounding surface the body surface faces.This is computationally intensive, and thus the view factor calculations are scaled down to reasonable sets of surface exchange, or defined for typical orthogonal building geometries. A further common simplification is the calculation of the view factor to the surrounding surfaces as their solid angle from a single point, not a human. The solid angle still requires the calculation of the fraction of a spherical solid angle around the specific position. A gross approximation is using simplified view factors that are taken as the angle to a surrounding surface in a 2D plane to represent a fraction of the total field-of-view. Another gross approximation is the simple weighting of surrounding surfaces by their area against the entire area of surrounding surfaces, which further reduces accuracy since the non-uniform distance from any point cannot be considered.

There are two conventional methods for more precisely approximating view factors for MRTs, namely the Fanger-Rizzo method[35] and the Nusselt Analog method. Fanger proposed a slightly simplified method and verified with experimental results in the 1970s to account for surfaces' view factors, while the Nusselt Analog was used from the 1928 research where the geometrical relationship between an infinitesimal surface and a random surface in space is defined[37].

The Fanger method categorizes surfaces into either vertical or horizontal. An indoor space is abstracted into a parallel ellipsoid enclosure. It can be divided into six different geometrical situations as indicated in Fig. 3. For every single vertical/horizontal surface, it is then divided into four different surfaces to be analyzed using the geometric relationship between a person and a surface in a Cartesian coordinate system as illustrated in Fig. 3. Here, a is the dimension in the x-direction, b is the dimension in the y-direction, and c is the distance from the location of the person to the surface of interest. Fanger solved this equation by providing graphs for both the seated and standing persons where the view factor weightings can be expressed as a function of the dimensionless parameters a/c and b/c. This method was further developed by Rizzo et al. [35] and became a prevailing method of determining view factors for indoor environment with orthogonal geometries [7,36].

An alternative method of calculating the view factor utilizes the Nusselt Analog. An arbitrary surface can be projected onto a unit-radius hemisphere, and then projected onto a unit circle at the bottom of the hemisphere - the area of the projection is equal to that of the view factor from the center of the hemisphere (as shown in Fig. 4). Nusselt first developed this geometric analog for the form-factor integral in 1928 and was widely applied to photography and planimetry, and became

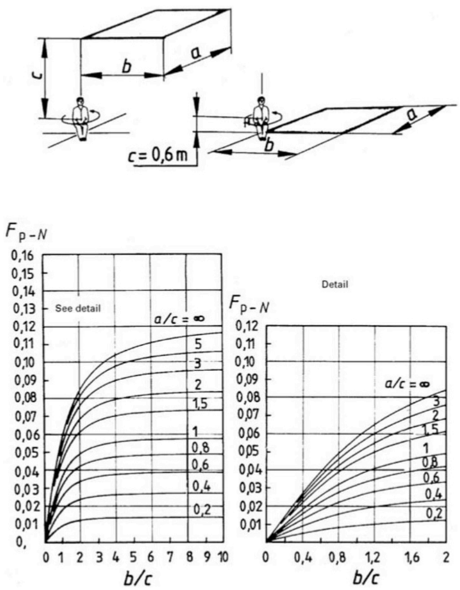

Fig. 3. Fanger's method of accounting for the relationship between the human body and the surrounding surfaces [24].

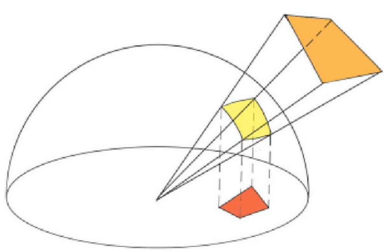

Fig. 4. Graphical representation reproduced from the definition of Nusselt Analog.

widely adopted in computer graphics in the 1980s [37]. Visualizing the 3D space has led to an increased interest among researchers to represent the real 3D environment with simulation, and has resulted in several computer-assisted MRT evaluation methods [38,39].

The Nusselt analog commonly used in computer graphics allows for vectoric representations of view factors by using a finite number of vectors spherically arrayed emanating from that point. The MRT at the central point can be calculated through the temperature value obtained at the intersection of the vectors with each surrounding surface [40]. Furthermore, this vectoric representation allows for accurate ray-tracing of the radiation flux as it is reflected between surfaces, as each individual vector from a point can be traced along multiple surface-bounces. Additionally, it is possible to mathematically weight the vectors according to the Lambertian distribution from a surface, to account for different emissivity values of each surface encountered in the multiple bounces. Thus, if enough vectors are traced for a good representation of the space, the obtained MRT can statistically represent the material and geometric properties of the surrounding surfaces as well as their view factors and temperature values.

2.2. *Air temperature and MRT relationship - radiation vs convection*

MRT abstracts the radiant heat transfer calculation to a single temperature variable analogous to the commonly measured and referenced air temperature. One objective of its creation was to allow radiant heat transfer to be easily compared and considered relative to the effect of convective heat transfer from air temperature. As radiation and convection are known to make up the vast majority of heat transfer between a person and the environment, investigations using MRT often output a ratio of convective to radiant heat transfer, which has produced a series of explorations characterizing this ratio.

Linearizing the fourth power radiant heat transfer from Equation (1) is a common simplification where a radiant heat transfer coefficient h_r (analogous to the convective heat transfer coefficient, h_c) is assumed. This results in the two heat transfer equations for radiation, Q_r, and convection, Q_c, taking the same form as shown in Equations (4) and (5).

$$Qr = h_r * (T_p - T_r) \tag{4}$$

$$Q_c = h_c * (T_p - T_a) \tag{5}$$

A desire to understand the role of both radiation and convection drove researchers to conduct a series of experiments to identify this relationship which we summarized in Table 1. Many of these experiments tried to produce an Equivalence Ratio that represented the ratio of change in air temperature T_a that can be compensated by change in MRT, T_r (or the same perception to subjects during real-time tests).

The Equivalence Ratio was not pursued much further after proposition of PMV/PPD in 1970s. [24] Within the modern pedagogy, some Equivalent Ratios from Table 1, in particular the results from Yaglou [42] and guidelines from ASHRAE [32] are still introduced and taught with different levels of detail. Olgyay referred to the Yaglou study and suggested that the air temperature change can be compensated for with a 0.8° Fahrenheit change of mean radiant temperature in *Design with Climate*[49]. Szokolay referred to this ratio as having the value ranging from 1.25 to 2 without providing a clear definition of mean radiant temperature but rather as a place holder for thermal comfort [50], while Cowan and Smith alluded to a specific ratio and provided an even vaguer definition of mean radiant temperature [51]. Similarly [52], Givoni suggested that mean radiant temperature was the emissivity-weighted average temperature of the surfaces surrounding the space [53] and suggested that MRTs can be used to evaluate a radiant cooling system in a subsequent publication [54]. The European passive solar handbook published in 1992 introduced the mean radiant temperature was simply put in as "the average temperature of the surrounding surfaces" [55]. On the engineering side, Dagostino appeared to have been inspired by the ASHRAE Standard 55–1966 data and wrote the Equivalent Ratio as 1.4° of air temperature change to be compensated

Table 1
MRT vs dry bulb temperature relationship investigated for neutral thermal sensations from previous investigators.

Researcher	Year	Equivalent Ratio (T_a/T_r)	T_a Range (F)	MRT Range (F)	T_a Range (C)	MRT Range (C)
Mackey et al. [41]	1943	0.841	[70,90]	[72,88]	[21.11,32.22]	[22.22,31.11]
Yaglou [42]	1947	1.250	[75,89]	[65,74]	[23.89,31.67]	[18.33,23.33]
Nielsen et al. [43]	1953	0.688	[73,86]	[71,90]	[22.78,30.00]	[21.67,32.22]
Koch [44]	1962	0.699	[72.97,85.83]	[70.27,80.50]	[22.76,29.90]	[21.26,26.94]
ASHRAE [32]	1966	1.400	[71,93]	[70,80]	[21.67,33.89]	[21.11,26.67]
Fanger et al. [45]	1967	0.813	[73,87]	[72,88]	[22.78,30.56]	[22.22,31.11]
McNall et al. [46]	1968	0.714	[74,85]	[71,90]	[23.33,29.44]	[21.67,32.22]
McIntyre et al. [47]	1972	0.791	[69.44,74.84]	[75.20,83.30]	[20.80,23.80]	[24.00,28.50]
Fanger et al. [48]	1980	0.885	[66.2,74.84]	[76.10,83.30]	[19.00, 23.80]	[24.50,28.50]

by 1° of change in MRT [56] and was carried on towards its 5th edition published in 2010 [57].

Both popular literature for architectural education, the Olgyay and Dagostino's publications could be extremely problematic for designers and engineers to correctly understand the concept of mean radiant temperature. Similar concerns were echoed in a more recent publication, stressing that separating the air temperature from the mean radiant temperature would be useful for designers, contractors and building operators [58].

The last of such experiments exploring Equivalence Ratio that this study has been able to identify took place in 1980 from Fanger whose team proposed one of the most widely-used thermal comfort concepts, predicted mean vote (PMV). Mean radiant temperature had, therefore, become instead of the output of building systems, the input to a mathematical model to produce a synthetic 'vote' as output - which could partially explain the lack of more recent research interest to understand and quantify the correlation of mean radiant temperature and air temperature in thermal neutrality.

2.3. Analytical expressions of MRT from empirical measurements

The mathematical definition of MRT in Equation (2) is most commonly simplified to describe the heat exchange between the environment and a single point in space instead of the full geometry of a human. This has in turn led to the development of a variety of methods to evaluate MRTs, which despite their inherent strengths and weaknesses, have became well-accepted over the last several decades. We have summarized the most popular expressions for quantifying MRT inTable 2.

As can be seen in Table 2, we can roughly categorize the means of evaluation by either the need of view factors, or whether there is a convective correction term.

View factors from the human body to the surrounding environment can be challenging to quantify, particularly with an ever-changing relationship between the occupants posture and the surrounding surfaces orientations as the occupants move through space. Out of the three methods that include the view factor calculation in Table 2, only one contained the actual view factors of various surfaces, while the rest merely relied on simplified readings from different directions assuming known view factors.

The convective correction terms were either the result of empirical, experimental studies [59], exposing two sensors to a comparable amount of convective heat loss, or keeping the sensors at the same temperature of the air so that the need to account for convective heat transfer is neutralized.

3. Evaluating MRT - measurement and simulation

Due to the literal definition of MRT, it is inherently impossible to measure or simulate it accurately: not only is the geometric relationship between the human body and the surrounding environment computationally expensive to characterize, the calculation can be more complicated when considering the different segments of the human body and the corresponding skin emissivities and the skin temperatures are dynamic, changing with vasoconstriction and dilation, sweat, and clothing coverage, etc. Therefore, for both the measurement techniques using sensors and the modeling methods for simulation, the concept of MRT must be simplified in order to be determined. As we have summarized in Table 2, some of the most common simplifications, like the black globe thermometer measurement and the point-wise view factor calculation, can lead to misconceptions about its definition being for a point in space, not for a human. In his seminal work in 1970, Fanger wrote, "The mean radiant temperature refers to the shape of the human body and for this reason alone, is a factor which is difficult to measure" [24]. We present some of the common methods for measurement and simulation and then discuss some of the inherent spatial and geometric challenges.

3.1. Measurement of MRT

3.1.1. Globe thermometers

First developed by Aitken, the globe thermometer was initially considered to be an effective piece of equipment as radiation thermometer [60]. The globe thermometer was first introduced to measure human comfort by Vernon as a device that can measure the radiation from the surrounding environment to a human body[3]. A conventional globe thermometer consists of a thermometer with its thermally sensitive element located at the center of a blacked hollow sphere [61]. Assuming the globe thermometer is in equilibrium, its reading from the internal thermometer will reflect the convective and radiative heat exchange around the globe thermometer. Bedford and Warner [4] first attempted to quantify this relationship between convective and radiative heat transfer at the globe thermometer. Their work was further improved by a variety of researchers [62,63] and improved further by Kuehn et al., in 1970 [64] before being introduced into the ASHRAE Standards [34]. In comparison to the then-existing attempts such as the kata-thermometer [65] and the Eupatheoscope [10], the globe thermometer quickly gained attention due to its simplicity [66,67]. First globe thermometers were generally constructed from ball valves with a 6-inch hollow copper sphere and a variety of thermometers [61], which had been used since their initial development in the 1930's [4]. The use of globe thermometers were further refined by investigating a wide range of globe thermometers with different diameters h_{cg} which was adequately to be approximated to $1.1 \times 10^8 V_a{}^{0.6}$ where V_a a is the air velocity.

$$=\left[\left(\left(T_g + 273.15\right) + 273.15\right)^4 + \frac{1.1\ \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a)\right]^{0.25} - 273.15 \quad (6)$$

Table 2
Expressions for different methods evaluating MRTs (Nomenclature to be clarified within the corresponding text.).

Method of evaluation	Governing equation	View Factor	Results influenced by Convection
1. Globe thermometer	$T_r = \left[(T_g + 273.15)^4 + \frac{1.1\times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a)\right]^{0.25} - 273.15$	No	Yes
2. Two sphere radiometer	$T_r = T_s^4 \frac{P_p - P_b}{\sigma(\varepsilon_b - \varepsilon_p)}$	No	Yes (Compensated)
3. Constant-air-temperature sensor	$T_r^4 = \frac{T_S - P_S}{\sigma - \varepsilon_S}$	No	Yes (Compensated)
4. Thermal comfort meter	$T_r = 2T_{op} - T_a$	No	Yes
5. Net Radiometer	$T_r = \sqrt[4]{S_{str}/(\varepsilon_p^{\sigma})}$	Yes	No
6. Plane radiant temperature	$(0.18(T_{up} + T_{down}) + 0.22(T_{right} + T_{left}) + 0.30(T_{front} + T_{back}))/1.4$	Yes (Approximated)	No
7. Non-contact sensing/thermography	$T_r = \sum_{j=1}^{N} T_i F_{ij}$	Yes	No

The settling time is the time a globe thermometer needs to reach equilibrium [68]. For globe thermometers of various diameters there is a tradeoff between error and settling time: for a smaller diameter the globe material mass and air mass reach thermal equilibrium quicker at the cost of a higher sensitivity to the movement of the surrounding air [12]. Quantifying this relationship was therefore crucial; a larger (6-inch) [4,61] and smaller (38 mm) globes [59,62,69] were tested by a number of researchers. The 6-inch globe thermometers were found to have a settling time of up to 20 min before the globe reaches equilibrium [68], while the 38 mm ones could reach equilibrium within 5 min. The settling time could go down to 4 min if a non-metallic acrylic Ping-Pong ball is used, according to Nikolopoulou et al. [69]. It became agreed among researchers that the larger globe thermometer, the longer the settling time, while the smaller globe thermometer, the less accurate it becomes since they're more prone to be affected by air temperature and air velocities: globe thermometers should, therefore, always be selected accordingly with the required settling time in different applications [70].

The only reliable method of calibrating both the radiation and convection experienced by a globe appears to be with a kata thermometer [4,65,71]. Side by side comparisons where sensing elements have the same geometry, air speed, and therefore identical convective losses over the silvered and black globes are important. Maintaining a constant temperature assures that the driving forces for heat transfer are equal, the only inequality is the environment's driving force for radiant heat transfer. This allows for an analog measurement of convective losses, an analog integration of the nonlinearity of convection for varying wind speeds and free convection losses. Corrections proposed by de Dear and others correct for a singular air speed [59,62,69], which does not account for eddies, vortices, and other convective anomalies.

The materials of the globe are also of critical importance because the mean radiant temperature readings from the globe thermometers are governed by the heat exchange as indicated in Equation (6), the emissivity ε resulting from the coating and substrate of the sphere is crucial to obtaining accurate mean radiant temperature. Aside from traditional black/matte/flat paint, the grey coating was also widely investigated by researchers and found to be suitable in reflecting the radiant heat transfer by replacing the emissivity of an assumed black surface (0.97) with a grey surface (0.9) [72]. The use of Ping-Pong balls when investigating the optimal diameter of the globe thermometers also prompted discussions on what other materials could be considered when constructing globe thermometers beyond black-paint-coated copper spheres [59]. Celluloid [73], acrylic [74] were all investigated, including silver which was previously investigated as a material that was a nearly perfect reflector and only susceptible to the conductive heat transfer. Guo et al. have also demonstrated variability in the emissivity of coatings on black globes, depending on the number of layers of paint applied [71].

Despite the original definition of mean radiant temperature, the increasing application of globe thermometers in MRT evaluation has blurred the very concept of MRT from its relationship to the human body. It is important to point out, once again, that MRT is not something that can be measured without a degree of abstraction. Only a few research papers declared how the measured MRT from the globe thermometers is different from the definition of MRT [75], acknowledging the fact that there is no device that can replicate exactly the radiant heat exchange between the environment and the human body[76]. However, due to their inexpensiveness and simplicity of use [67], globe thermometers are considered the most accessible and convenient tool to evaluate MRTs in the field, such as in Post-Occupancy Evaluations (POE) requiring physical measurements [77]. Popular POE protocols such as BPET (also referred to as ICM [78]), NEAT [79] and PMP [80] consider mean radiant temperature one of the most fundamental IEQ parameters that needs to be measured, which was realized with globe thermometers for all three protocols.

3.1.2. Net radiometers

Net radiometers are used to determine MRT by integral (also known as six-direction) radiation measurements with view factors [81]. Originating from the human biometerology discipline where the incident radiant fluxes from different directions were measured, this method requires simultaneous measurements of shortwave K_i (via pyranometers) and longwave L_i (via pyrgeometers) radiation from six directions as was identified in Table 2 (i = 1–6, east, west, north, south, upward and downward). This is a total of 12 sensors needed for a net radiometer assembly. This allows the calculation of the mean radiant flux density by the body S_{str} following Equation (7).

$$S_{str} = \alpha_k \sum_{i}^{6} K_i F_i + \varepsilon_p \sum_{i}^{6} L_i F_i \tag{7}$$

where s is emissivity of the human body, σ is Stefan-Boltzmann constant, K_i is the shortwave radiation flux (Wm- 2), L_i is the longwave radiation flux (Wm-2), α_k is the absorption coefficient for shortwave radiation (standard value 0.7) and F_i is the view factor in one of the six directions. Inserting the resulting solid angle back to the expression from Table 2 as Equation (8), it is possible to obtain the MRT (T_r) with Equation (8):

$$T_r = \frac{\sqrt[4]{S_{str}}}{\varepsilon_p \sigma} - 273.15 \tag{8}$$

Interestingly, this allows climatologists to convert the incoming solar radiation into equivalent temperatures as if they arrive from a surrounding surface to the human body, such that it is possible for an outdoor environment to have air temperature at 20 °C with a 60 °C mean radiant temperature [82]. This method challenges the literal definition of the MRT in that it views the sky as a non-existing surface and converts both the direct and diffused solar radiation into hot surfaces surrounding the human body and yet proven to be very useful and intuitive in describing the outdoor radiant environment [83].

A simplified version of net radiometer was proposed by the German guideline VDI 3787 [84] where one pair of pyranometers and pyrgeometers are mounted on a movable axis to measure all six orientations within a 10 min measurement window. Other simplified methods measure incoming short and longwave radiation from two directions [85] or global shortwave radiation coupled with Rayman [72,86–89], or average out the surface temperatures with respect to surface areas [68].

3.1.3. Other instruments used in indoor MRT evaluation

Thermal comfort meter was developed by Fangers group and published in 1985 as a tool to provide corrected MRT readings from a grey globe thermometer reading [11]. The MRT output from a thermal comfort meter is a combination of an ellipsoid globe thermometer and a heated transducer where both the air temperature and the operative temperature can be measured. The resulting MRT could be calculated by subtracting the air temperature from two times the operative temperature measured by the transducer. This meter was further pushed to the market, although with Model 1212 from B&K was rarely seen referenced beyond the Denmark group that presented it.

Two-sphere radiometers have also been recommended by the ISO 7726 standards. The working mechanism of this device depends on heating two spheres (one black, one polished) with the same geometry and different emissivities to the same temperature and exposing them to the same radiant and convective environment. The known emissivity difference will allow for a correction of the convective heat loss and can be estimated using the corresponding equation in Table 2. Where the sensor temperature is T_s, P_p is the heat supplied to the polished sensor W/m^2, P_b is the heat supplied to the black sensor, epsilon by is the emissivity of the black sensor, while epsilon p and epsilon b are the emissivities of the polished/black sensors. Sigma remains to the be Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ [68].

The constant-air-temperature sensor was also proposed to be used for measuring the MRT by ISO 7726, where a sensor (sphere or ellipsoid) is controlled at the same temperature such that the surrounding air hence the convection heat loss/gain can be corrected. The heat added (or subtracted) to the sensor is, therefore, the same as the radiant heat loss (or gain). The resulting MRT can thus be calculated using the corresponding equation in Table 2: the MRT can be obtained with a known sensor temperature, heat supplied (W/m^2), the emissivity of the sensor with the Stefan-Boltzmann constant.

3.1.4. Infrared thermography

Infrared thermography developments have also provided unique opportunities within recent years to estimating MRT. There have already been demonstrated uses of an infrared camera as a 2D temperature sensor for building temperature distribution by Datcu [90], and to evaluate occupant thermal responses by Choi et al. [91], Koruku and Kilic [92], and Shastri et al. [93]. Encouraged by Fokaides et al. [94] and Cehlin et al. [95] to use an infrared camera to measure and visualize spatial air temperature distribution, Djupkep et al. [96] proposed a theoretical analysis of how an infrared camera multi-grid sensor setup can be used to predict mean radiant temperature. Djupkep et al. further perfected this model by proposing a full set of instruments: a grid, an infrared camera, a pair of stereoscopic cameras and a moving system [97]. This allowed them to compare thermographic results with measured results from a grid of 7 by 8 globe thermometers. The ultimate focus of both studies was on providing a robust system that determines the coordinates of each sensor on the measurement grid and improve upon the accuracy and robustness the system can achieve. However, this method was a highly-improved globe thermometer sensing system that essentially allowed for globe thermometer measurement within a 3D space since the specific locations of the sensors (a grid of small globe thermometers with the diameter of 12 mm, 0.2 mm thickness and a 0.96 emissivity surfaces) is known, meaning that the spatial distribution of mean radiant temperature can be measured.

Meanwhile, the possibility of including thermographic data acquisition with spatial and spatiotemporal thermal data analysis has also been proposed by Natephra et al. [98]. Albeit a rough framework, Natephra et al. discussed introducing periodic thermal image collection to the BIM model, but have yet to show any feasibility of real application.

Knowing the room geometry and fixing the thermographic image could be a solution to the issue of calculatimg exact view factors. New tools [99,100] have been used to provide spatially resolved thermal geometries, creating point clouds with each point tagged with a temperature, measured with a thermopile. The scans from this device, known as the SMART sensor, allow the creation of MRT maps of an environment from a single scan. These maps are fully spatially and temporally resolved, mapping to a BIM or other 3D model types.

Researchers have also arranged 8 thermopiles on the vertices of a cube to measure the average temperature of each direction [100], which can then all be averaged to provide an overall point average. The thermopiles are not sensitive to convection, as they measure internal temperature to convert the radiant flux measured about the sensing array with Equation (2) to extract the surface temperature in a 90° field of view.

3.2. Modeling of MRT

Computer simulation is also very commonly used to predict mean radiant temperatures. The computing power to account for the differential complexities between the human body geometry and that of the surrounding enclosure make simulation and modeling attractive for MRT view factors [101]. Even for computational tools completely resolving the geometry for all view factors between the human body and surrounding surfaces is not feasible and requires simplification. There are computational methods for surface subdividing, gridding, and ray tracing to compute the spatial relationship between complex surfaces in modeling and simulation. The most common simplification is to take the human body as a point, or series of points in space. In a numerical analysis from Chung et al. the MRTs were simulated in a test room following strictly Equation (2) to calculate point-specific MRT values [102]. Using the resulting MRTs, Chung et al. then calculated the corresponding PMVs and found considerable discrepancies between the PMVs calculated from actual MRTs and PMVs calculated by assuming MRTs are equal to air temperatures, showing how the point method can demonstrate significant impact of MRT, but also facilitating an interpretation that it represents reality.

It is also worth noting that there is a direct link between thermal radiation exchanges and radiosity [103]. This could indicate a potential connection between existing methods of calculating view factors and computer graphics research in characterizing the diffused thermal radiation that bounces off surfaces using radiosity algorithms, such as the Progressive or Full Matrix Radiosity algorithm, developed within the computer vision field [104]. There are many analogies between computer graphics and the tools used for calculating MRT and radiant heat transfer. The aforementioned difference between the indoor and outdoor understanding of radiant heat exchange is also clearly reflected by how mean radiant temperature can be simulated.

3.2.1. Indoor

For the indoor environment, a common tool is EnergyPlus, which has three calculation methods for mean radiant temperature, respectively the zone averaged, surface weighted and view factor MRTs. Among the three options, zone averaged MRT - averaged surface temperature with emissivities as Equation (9 - is set as default when estimating thermal comfort with PMV(or Predicted Mean Vote [45]). It can also be weighted to the surface closest to the person by taking the average of the closest surface T_{surf} and T_{r-avg}, which is known as the weighted surface option. Equation (10) is arguably the more accurate evaluation methods for MRT, and the most easily calculated zone-averaged MRT. The weighted surface option should be considered the least accurate since a prevailing surface near a person is usually vertical and cannot cover half a hemisphere completely. This is what the weighted surface expression suggests.

$$T_{r-avg} = \frac{\sum \varepsilon_i A_i T_i}{\sum \varepsilon_i A_i} \quad (9)$$

The last option, or the view factor option of MRT calculation, includes the view factors between a person and each surfaces in a space, as shown in Equation (10) (corrected from existing publication of Energy Reference for Energy Plus 8.9.0 [105]).

$$T_r = \frac{\sum \varepsilon_i F_i (T_i)^4}{\sum \varepsilon_i F_i} \quad (10)$$

EnergyPlus provides an option of view factor MRT by taking into account of the view factors of the surfaces surrounding the human body and obtaining the mean radiant temperature through Equation (2). This essentially calculates the point-wise radiant temperature [106]. As a computation engine that relies mainly on the weather file and the building geometry, it is often used as the backbone of various graphical user interface (GUI) such as OpenStudio, DesignBuilder, etc. As EnergyPlus was developed mainly for the indoor environment, its interpretation of MRT does not account for the incoming/reflected short-wave radiant heat fluxes, but rather only as Equations (9) and (10).

Other programs that also simulate indoor MRT include ESP-r, TRNSYS, as well as IDA- ICE. ESP-r was based on a semi-analytical tool from Laouadi in 2003 [107] with overt simplification on construction assemblies and evaluate the mean radiant temperature with Equation (6) operating on a variety of assumptions. Type 46 CRTF(full room transfer function) of the TRNSYS model is also capable of calculating the mean radiant temperature. It uses the surface temperatures as a result from energy simulations and the radiant heat exchange network proposed by Carlson [108]. IDA-ICE, according to its user manual, also provides MRT output [109]. The ICE user manual suggests that the MRT output will be a zone-average, seemingly comparable to the default in EnergyPlus. However, due to the lack of documentation and investigation on this particular tool, the actual method of calculation remains to be investigated [110]. ASHRAE has added to this with the Radiant Performance Explorer 1383 project and proposed simplified MRT distribution calculation model which later became a more detailed simulation algorithm [111]. Building on an existing ASHRAE Thermal comfort tool from 2011, this tool uses the projected human body surfaces and quantifies the geometrical relationship between the body and any arbi- trary space in the surrounding environment. A similar tool developed in association with the CBE uses a similar approach but with a rectangular box for surface temperatures ready for assignment [132], and can also be used to produce a distribution of mean radiant temperature in an in- door environment.

3.2.2. Outdoor

Since the outdoor environment is exposed to both short and longwave radiation, the resulting surface temperatures can be much higher than those indoors. This causes significant radiant asymmetry, and appeared to be more extreme than the indoor environment when accounting for the radiant heat exchange between a human body and its surrounding environment. Unlike indoors, outdoor mean radiant temperature simulation must always also consider shortwave radiation, and a comparison table of the methods is presented in Table 3:

A total of 7 tools were identified for the comparison. CitySim Pro uses detailed input of the human body and the surrounding environment to predict energy fluxes [112] and has been validated with both EnergyPlus and Building Energy Simulation Test [113]. The MRT is then calculated using Equations (7) and (8) with the integral radiation measurement. ENVI-met, on the other hand, simulates the interactions between the vegetated surfaces, building and ground surfaces with air in urban environment [114]. ENVI-met is equipped with an MRT calculation module through Equation (2). As was pointed out in Table 3, despite its simplified human body geometry and free-standing objects, it is capable of running detailed radiative heat exchange simulations for both shortwave and longwave radiations. Roth & Lim, for example, was able to verify that ENVI-met provides a moderately good simulation of temporal MRT shift for a tropical residential urban neighborhood [115].

Rayman was developed from a human-biometeorological model also based on radiant heat fluxes and has been verified with on-site measurements [39]. Their calculation of mean radiant temperature follows the method of Hoppe et al. [116], which essentially develops on Equations (7) and (8). Both the view factor and the sky view factor are obtained by analyzing fish-eye photographs.

Honeybee and ladybug were developed as plugins for Grasshopper using the EnergyPlus engine. To compute MRT with Honeybee, surface temperatures calculated with EnergyPlus simulation, and view factors derived through ray tracing, were used as inputs to Equation (2) to output MRT for a given location in the enclosure. The developers are yet to provide additional support for more detailed human body geometry models [117], but the inherent challenges for computation could be an obstacle as the geometrical relationship could significantly increase the computation time.

Autodesk CFD is a FEM(Finite Element Method)-based simulation software for Computational Fluid Dynamics. MRT can be calculated for a given geometry scenario as a by-product [118]. The view factors are calculated part-to-part while assuming diffuse grey bodies for all surfaces discretized to elements [119]. This software also has a series of limitations ranging from wavelength, directional dependencies to surface properties [101]. SOLWEIG was developed as a climate design tool first introduced in 2008 [120] and also produces detailed models evaluating the mean radiant temperature. SOLWEIG requires both of the global radiation data types to produce reasonable mean radiant temperatures. SOLWEIG has two crucial advantages over other tools: it produces horizontal 2-dimensional simulations for both SVF and mean radiant temperature, and it includes obstacle structure inputting capability. It is of note that its computational time could be reduced [121]. Recent developments for this software include its introduction into the QGIS suite as UMEP and the upcoming addition of a discrete solar radiation input for detailed urban modeling.

TUF3D was developed by meteorologists as a tool to better quantitatively understand the urban environment. Similar to creating a mesh for a finite volume method calculation, an urban geometry will be introduced to the algorithm with its topology sliced into meshes. At every cell of the mesh(or patch, as was defined in Ref. [122]), the short and long wave radiation can then be evaluated to calculate the surface temperature. The surface temperatures are then introduced in Equations (8) and (7) to produce the final mean radiant temperature output [123].

A new, somewhat less-popular, yet relevant tool named CityComfort + was also proposed explicitly to predict the mean radiant temperature in dense urban areas. Huang et al. proposed this tool to provide MRT as the output by accounting for all radiation components through raytracing [124]. The model does not have a detailed human body geometry but does use Human Body Projection Area factor, citing the formula from Underwood and Ward [125]. CityComfort + relies on the lighting simulation software to calculate the short-wave radiation [126]. The longwave simulation was modelled in two parts, i.e. the

Table 3
Evaluation of simulation tools that can be use to calculate mean radiant temperature with respect to human body geometry simplification, shortwave radiation and longwave radiation.

Tools	Body Geometry	Shortwave Radiation	Longwave Radiation
CitySim Pro	Detailed	Detailed	Detailed; Longwave radiation for free standing objects, local wind speed and direction unaccounted for.
ENVI-met	Simplified	Detailed	Detailed; Simplified long wave radiation for buildings and free standing objects.
RayMan	Simplified	Simplified; Fisheye SVF	Simplified:Simplified model for exchange with sky, buildings, vege- tation. Vegetation transpiration, ground evaporation unaccounted for. Uses Ray-tracing to compute the view factor.
Honeybee & Ladybug	Detailed	Simplified; Vegetation Reflection	Simplified model for exchange with sky, buildings and ground. Vegetation transpiration and ground evap- oration is unaccounted for.
AutodeskCFD	Simplified	Simplified, Diffused sky, No other diffusive sources	Detailed; Exchange with sky, vegetation, and evaporation unaccounted for. Simplified exchange with ground. Vegetation transpiration, ground evaporation unaccounted for.
SOLWEIG	Simplified	Detailed (Reflection simplified), SOLWEIG1D: Simplified calcula- tion of globe SVF	Detailed; No vegetation transpira-tion, ground evaporation accounted for.
TUF3D	Simplified	Detailed direct short-wave irradiance and inter-visibility determined with Ray-tracing	Detailed; Both shortwave (0.2–3.5 μm) and longwave (3.5–100 μm) assumed to be Lambertian.

atmospheric component and the surfaces. The atmospheric longwave radiation was calculated from the Angstrom formula [127], with measurements of the dry bulb temperature, the degree of cloudiness and relative humidity, and solar irradiance . The model appears not to have included capabilities of accounting shading and evapotranspiration from vegetation but accounts for the diffusion and reflection of radiation nonetheless. This model has yet to be implemented by other studies; and for the purposes of this review has been excluded from Table 3.

3.3. Common challenges for measuring and modeling MRT

3.3.1. Spatial distributions of MRTs

From both the indoor and outdoor simulation of MRTs, it is evident that there is a spatial distribution of MRTs across different types of indoor and outdoor typologies. For the outdoor simulation research communities, this variation is much more important and better evaluated, presumably due to the larger surface temperatures induced by incoming solar radiation. For the indoor environment evaluations, however, this variation is much smaller and is very often neglected. Researchers have demonstrated as early as in the 1960s that for spaces with a more substantial surface temperature differential, it is essential to use multiple globe thermometers to evaluate the resulting MRTs [8] experimentally.

DeGreef and Chapman simulated a small, radiantly heated bathroom with windows and found MRTs varying up to 4.18 °C [9]. Similar simulation studies from that of Chung et al. identified an MRT variation at the same height (1.5 m) of up to 6 °C with discrete transfer radiation model [128]. Simmonds et al. also researched understanding the MRT distribution in an indoor environment and produced MRT distribution in 1993 [129–131]. The ASHRAE Radiant Performance Explorer 1383 that Simmonds also contributed to produced the MRT variation in a 3D space [111].

The spatial variation of MRT has received more attention within the outdoor research communities where it is both computationally simulated and experimentally verified. For the outdoor environment, spatial MRT variation could vary from 10 to 20 °C for shaded and not-shaded locations in a residential environment [133] but could go as high as 38 °C [134] for surfaces that are significantly heated from incoming solar radiation.

Still, a precise measurement of MRT is a fundamental requirement of understanding and predicting how occupants feel in an environment [135] and in extracting maximal efficiency from thermal systems [58]. Recent attempts to provide spatially resolved measurements from thermal point clouds with the SMART sensor and a simpler cube sensor [99,100,136] begin to automate the process of extracting real-time MRT information for control of radiant systems.

3.3.2. Complexity caused by human body geometry

Accounting for thermal comfort could consider complex geometry and surface temperatures surrounding the human body, but the human body geometry complexity remains the primary challenge. The spatial variation of MRT described in the previous section is, as according to Equation (2), that of a point instead of for the entire human body. Fanger acknowledged the problem of this simplification very early in his publication, arguing that the shape of the human body is the factor that makes it difficult to measure MRT precisely [137].

Vorre approached this problem by comparing the calculated view factors from six different methods between a human body and the surrounding building surfaces [18]. In a rectangular room with a seated person, the view factors could first be obtained using the Rizzo et al. method given the location and posture of this person. A 3D laser scan of the seated person was then used to generate a mesh for ray-tracing. With no special attention paid to the reflectivity of the surfaces, secondary reflections were ignored in this study. The Rizzo method (an integrated Fangers Nusselt Analog interpretation from Rizzo) and three other geometrical (sphere, cube and tall rectangular box) simplifications were used to represent the human body. The Fanger-Rizzo integration was found to be the most accurate, assembling the view factors and the most time-consuming, while the sphere and geometric cube shapes were the least. Concerning the computation time, assuming geometric shape could cut the time needed by 50%, while the Rizzo method uses only 1% of the overall calculation time required by the Fanger-Rizzo integration. Vorre's research, together with other existing research on addressing the projected area factors of the human body [138,139] could contribute significantly to further quantifying MRTs according to its definition.

The geometric simplification of the human body very often involves dividing a complicated human form into individual spherical, cylindrical or rectangular parts. Miyanaga et al. proposed a 16-segment model that accounted for the entire body's radiative heat exchange and was able to provide information on both the core and the local skin temperatures [140]. By defining skin temperature and thermal resistance, it is possible to use their model to predict the effect of local radiant cooling on thermal comfort quantitatively.

Similarly, Schellen et al. constructed a more detailed thermo-physiological model by dividing the human body into 18 cylinders and a sphere [141]. This research mainly focused on comparing the Predicted Mean Vote (PMV) or Actual Mean Vote (AMV) resulting from asymmetrical boundary conditions. Comparing three different static thermal sensation models, Schellen et al. were able to identify a better agreement between the simulated PMV and the AMV a scenario where the radiant asymmetry happens at perpendicular surfaces instead of parallel ones. This points, according to the authors, to the possibility for a more individualized level of evaluating thermal comfort.

Even with the complex geometries taken into account, it is still very challenging to account for the different sensitivities of the various segments of human bodies to the thermal environment and to what extent these segments impact one's perception of thermal comfort. Many studies have demonstrated the different sensitivities towards radiation and convection on different segments of the body [142,143]. Among other assumptions, these methods treat the human body as a collection of 16 to 18 different segments [144] and attempt to identify the individual convective and radiative heat transfer coefficients for these segments [142].

Atmaca et al. used both simulation and experimental results to show the relationship between radiant temperature thermal comfort [145] and the reaction of different body part segments to different local radiant temperatures. Higher radiant temperature of surfaces heated by solar radiation close to the human body segments contribute to the warm thermal discomfort despite the fact that the walls and ceilings further away were not insulated and colder.

4. Utilizing MRT - building operation and environmental research

Despite the aforementioned challenge in understanding, measuring, and modeling the mean radiant temperature, its presence in recent and current research has never been more prominent. This is due in part to the significant role it plays in building energy efficiency, urban climate, and both indoor and outdoor thermal comfort. In this section, we will first review the role of MRT to efficiency and control for the indoor environment. We then compare the recent growth of MRT-related research for both the indoor and outdoor environments that span very different timeframes. What we found most interesting was not only the significant increase of usage of MRT, or the increasing interests from the human biometeorologists, but how important it is to understand and characterize the concept correctly, since it is the primary metric for characterizing the radiant environment and is widely used for comfort and system performance [146].

4.1. MRT related to building operation and efficiency

Despite the recent growth of radiant systems, they remain underutilized by the air-conditioning industry because of the challenges posed by MRT measurement and simulation we have discussed [147]. This is due in part to the lack of reliable and affordable devices for measuring and control of MRT.

A few studies have focused on possible energy savings from analyzing MRT. These often utilize the concept of operative temperature. It is a quantity that further simplifies MRT by averaging convective and radiant components of indoor environment heat transfer, and it is often calculated by simply averaging air temperature and MRT [21]. Halawa and Marquand proposed a control strategy that used the operative temperature as the controlled variable for a variable air volume (VAV) air-conditioning system and was able to demonstrate that it was not necessary to increase the air temperature setpoint to accommodate the change of control variable [148]. Niu and Burnett also suggested an operative temperature-based thermostat control to be used in building energy simulation so that the energy consumption of buildings is not underestimated [149]. Jain et al. argued that the resulting operative temperatures would be much higher during day time than the set point for air temperature, resulting in a potential underestimation of energy consumption exceeding 50% [150].

The energy saving potential of radiant heating and cooling systems has been analyzed in previous studies [15,54]. Radiant systems use hydronic piping systems. There is an energy saving potential from using a liquid working medium with larger heat capacity, and it therefore requires less energy to circulate per unit heating/cooling delivered. These savings are challenged by the complexities of MRT and its influence on radiant heat transfer and indoor thermal comfort [151].

Radiant systems have also been proposed in research applied to the separation of sensible and latent loads, allowing reduced fan power [152], and both system and room temperature setbacks [13]. In this context, energy efficiency is improved by allowing higher temperature cooling or lower temperature heating to be supplied to the radiant surfaces, which in turn enables a higher thermodynamic performance of any heat pump or chiller providing heating or cooling [153,154]. Radiant heat transfer has also been considered in some work as a key component in designing and implementing low exergy systems [155,156]. This work did not appreciate the spatial complexity of radiant heat transfer yet still claim to have experimentally evaluated thermal comfort performance[157].

Most of the operative temperature in applied research is measured by globe thermometers as an indicator of thermal comfort [158]. It is not common to use MRT or operative temperature as a control variable, but rather as a part of evaluating a building's overall system performance and resulting comfort delivery. A recent study on the cooling capacity variation of radiant floor systems under different solar radiations, air movements and carpeting is a good example where the operative temperature was used as an overall performance indicator. The aim of this particular study was to analyze radiant fluxes influenced by air, incoming solar radiation, and carpet-insulation on the radiant cooling capacity of the floor [159]. The selection of operative temperature, a concept that couples the effect of air and all incoming radiant fluxes, is an example of how the simplified term could limit isolation of independent effects . The cooling capacity of the radiant floors in the study increased from 32 to 110 W/m^2 when accounting for direct solar radiation, but spatial variation was not directly measured. This study is among a series of recent studies that focus on the comfort and energy consumption implications resulting from shortwave radiation within the indoor environment [19,160]. This may be related to the recent inclusion of the short-wave component in the ASHRAE standard [21].

A growing possibility to provide more localized thermal comfort has arisen with radiant heating and cooling systems. Comfort can be improved by affecting the thermal sensation of the human body by manipulating proximity, geometry, and surface emissivities/reflectivities, thereby influencing MRT independent of air temperature.

Radiant asymmetry defines the difference between radiant fluxes in opposing directions. The resulting discomfort cannot be described with the accumulated radiant fluxes defined by MRT. It is, therefore, also essential to be able to consider the directional variation of MRT, which can be done with radiometric tools mentioned above. ASHRAE regulated the radiant asymmetry to be less than 10 °C for the horizontal surfaces and 22 °C for the vertical [7]. In their simulation, Conceicao et al. placed two radiant surfaces close by to two experimental subjects and used three different methods to quantify the radiant heat exchange between the body and the surrounding surfaces [161]. Dividing the human body into 25 elements, the authors evaluated the three different methods of obtaining MRT (i.e. MRT, corrected MRT and radiosity method) and resulted in localized MRT differences of up to 6.0 °C.

Du et al. conducted another numerical simulation on a radiant panel suspended above a bed in an experimental room and were also able to demonstrate significant energy savings, in particular when the distance between the bed and the radiant panel can be optimized [162]. Validating the numerical results with previous experimental data, the authors concluded that including a radiant system could not only achieve energy savings but could also reduce the risk of cool drafts. There have yet to be studies that intentionally induce radiant asymmetry in the spirit of manipulating MRTs, which could partially be attributed to the lack of means to measure or control it accurately.

4.2. Past and current MRT-related research(insert 4.2.1 - Thermal comfort and MRT publication analysis)

Finally, we use reference data aggregation from research databases to consider more broadly how MRT has propagated through research and disciplines. This allows us to understand how accurately defining the mean radiant temperature has become increasingly important for researchers, and how it has evolved in different facets of the built environment, one primary set being indoor vs outdoor. We have compiled a dataset after performing a literature search attempting to characterize its importance in understanding the indoor radiant environment. The specific workflow the search followed is illustrated in Fig. 5.

We chose the keywords *mean radiant temperature*, *thermal comfort*, *convective heating/cooling*, *radiant heating/cooling*, *shortwave radiation* to identify existing literature in both Web of Science and Google Scholar. The checkpoint years were selected to correspond the checkpoints of standardization or publication on radiant systems and/or thermal comfort: respectively 1934 [4], 1966 [32], 1970 [24], 1985 [33], 1998 [163], 2007 [164] and present day. Special attention was given to using the Google Scholar database to eliminate an erroneous year of publication by filtering out publications that contain the years that are beyond the range of search so that the results returned were more likely to be the actual year of publication. As Web of Science keeps a record of more cited publications in comparison to Google Scholar, comparing Fig. 6 shows some interesting discrepancies, where the rate of publication for thermal comfort consistently increases in both databases over time. The Google Scholar results show a sharper increase from 1970 to 1985. Both databases appear to be experiencing a faster rate of publication on mean radiant temperature and shortwave radiation, while Web of Science appears to have a smaller rate of publication increase for convection during the last decade. This literature search may not have been comprehensive for all the literature that was published during the periods of interests. The number of the publications identified were nonetheless indicative of the change in research interests over time towards the respective topics: thermal comfort received more attention during the last twenty years. Radiant heating and cooling are beginning to play a much larger part in the total interest in thermal comfort, while convective heating and cooling appears to have either grown with the increase of thermal comfort (Google Scholar) or lost its significance (Web of Science). It is also worth noting that the

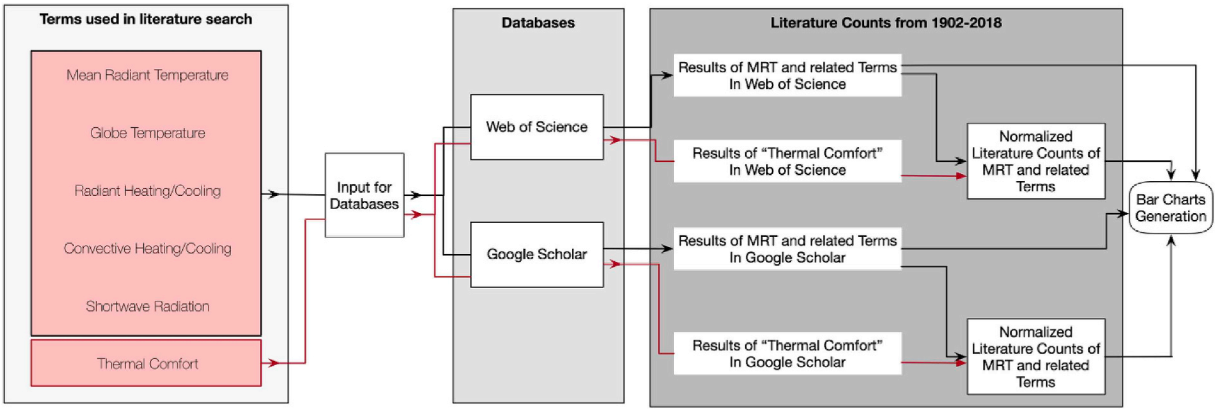

Fig. 5. Workflow of literature statistics collection on targeted keywords (black arrow) and thermal comfort (red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

increase of investigations towards shortwave radiation is also consistent across databases, potentially pointing to increased interest in outdoor thermal comfort, and expanded use of the mean radiant temperature as a concept. Although existing evidence suggests that radiant systems provide equal or better comfort than all-air convective systems [165], the growth of interests in radiant systems is unmistakable. This can be observed from Fig. 6 where we demonstrate the breakdown of growth in individual research topics normalized by the occurrence of discussions on thermal comfort. The brief increase of interest in convective heating and cooling may be due to interest in sick building syndrome. Research into radiant systems saw some increase. while other search terms saw a decrease over time. The relationship between the results obtained from Google Scholar and Web of Science point to an increase of interest among highly-cited researchers in the radiant environment during the last three decades, while the interests in the shortwave radiation see a steady drop over the years. Simultaneously, convective heating and cooling appears to be much more widely researched, as demonstrated by its rate of publication increase from Google Scholar, but considerably less cited from the numbers shown in Fig. 6 comparing to shortwave radiation from the 1980s with the 2000s.

4.2.2. Growth of MRT in characterizing the urban environment

Mean radiant temperature has become a widely used metric for outdoor thermal comfort according to the human biometeorologists, who borrowed the concept from the indoors[146, 166]. As can be observed from Fig. 7, there were very few mentions of mean radiant temperature for the outdoor environment before 2003, where the number of publications grew consistently over the last 10 years. We believe it is reasonable to speculate that the increase of mentions of MRT in the urban context is a result of the concept being carried over from the indoor environment, as well as an attempt to identify a metric that helps to capture the effect of incoming solar radiation on the street pedestrians. The earliest that we could identify when MRT was first introduced within proximity of the urban researchers was the VDI standard published in 1994 [84], where the net radiometers were also

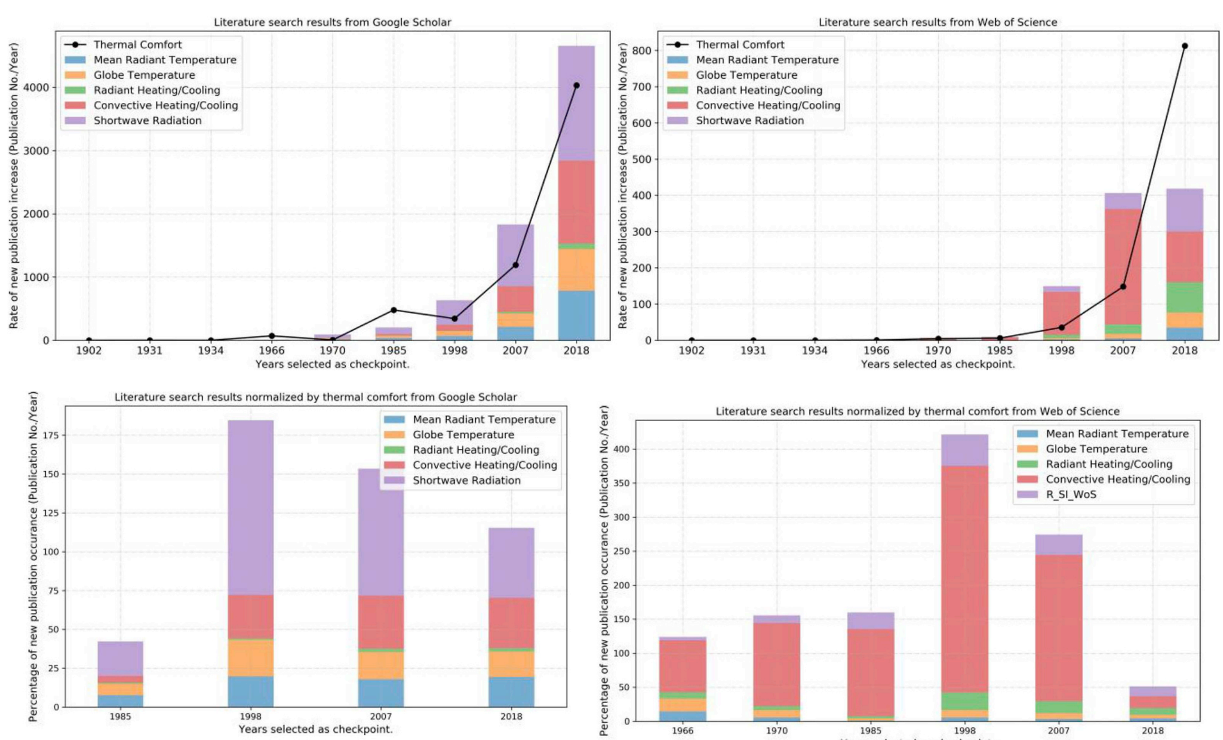

Fig. 6. Literature results returned from Google Scholar(left) and Web of Science(right), and the same results normalized by the count of thermal comfort.

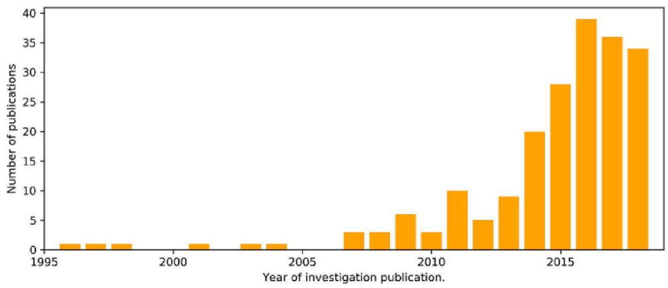

Fig. 7. Result of MRT hits within the urban context returned from a search for exact match on Web of Science catalog between the year of 1995–2018.

identified to be able to provide MRT measurement. Leveraging the strength of MRT, expressing incoming radiative heat exchange with a single temperature-like metric, this recent growth of interests towards MRT could be an interesting topic for future research. The actual origin of when MRT was formally introduced to the outdoor researchers could also be an interesting archival research task for aspiring researchers. With both the outdoor and the indoor research community working mostly in parallel, when/how MRT was first introduced to outdoor researchers is an issue outside of the scope of this paper.

5. Conclusions

This paper has presented a critical overview of MRT and its impact on understanding radiant heat transfer, building performance, and thermal comfort indoors and outdoors. Our current methods of modeling or measuring the MRT requires better precision/accuracy, yet it's the fundamental ambiguity of the concept that has caused the failings of our methods. We think this review is critical in clarifying the complexity of MRT and its determination. It is important that the simplifications and assumptions made in dispersed reserch activity are not passively accepted and forgotten, as this impacts the accuracy of MRT measurements and the consistency of MRT's scientific definition.

To begin with, researchers devised a very concise qualitative description of MRT, but for the quantitative measurements to match up with this description requires many assumptions and simplifications. Since only a small fraction of these assumptions are discussed and documented in engineering guidelines and textbooks, MRT is often remembered literally but understood through the many simplifications made in measuring and modeling. This may have led to the widespread obfuscation of its true definition, and may have partially contributed to the lack of proper evaluation of the concept, both numerically and experimentally.

The MRT definition effectively links the human body with the surrounding radiant environment and is, therefore, an important variable to accurately characterize. Existing methods of characterization simplify the human body into cuboid or cylinders, and only in rare cases, use an actual human body's geometry. To calculate the resulting mean radiant temperature from the surrounding environment is a computationally expensive problem that thus far lacks experimental investigation. There have yet to be studies that investigate the temporal variation of body-geometry-resolved MRTs.

Existing direct-measuring methods are not capable of capturing the total incoming radiant flux into the human body, using point-specific measurements to provide approximation can also be problematic as it can not reflect the full effects of larger radiant surfaces with more heterogeneity.

We also concluded that more advanced view-factor-based approximations of MRT is needed, in particular ones that can be analytically defined and modelled with computer-based simulations to characterize the indoor (and potentially outdoor) radiant environment. Such tools may prove valuable, not only to evaluating environments but in developing new sensing technologies once the analytical methods to calculate MRT are better understood.

Moreover, once the theoretical foundation of MRT evaluation and the inherent assumptions are better considered among researchers, further assessment of how a human body responds to the heterogeneous radiant environment is another exciting direction in which to conduct future research. Both the geometry and the sensitivity differentials between different body parts can result in different thermal sensation for an actual human body. Both could influence MRT.

The importance and usefulness of MRT will likely increase in the foreseeable future. Considering the economic benefits and improvements in system-robustness as well as thermal comfort, it has never been more important for us to understand, evaluate, and utilize MRT properly. Developing better modeling algorithms and measuring techniques beyond the status-quo is also important. There have yet to be any techniques that allow radiant systems to include real MRTs for feedback controls. Remaining cognizant of the complex role of MRT in the dynamic interplay of radiant heat transfer around the human body, therefore, remains critical for future investigations.

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Appendix A. Supplementary data

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