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Relationship between humidity and physiology in warm and humid conditions: A literature review

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D2.3.2 – RELATIONSHIP BETWEEN HUMIDITY AND PHYSIOLOGY IN WARM AND HUMID CONDITIONS – A LITERATURE REVIEW

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1 Abstract

Change in precipitation patterns caused by global warming will likely increase humidity in some areas of the world. Moreover, populations in tropical climates with already high humidity levels can experience an added stress on their health and thermal comfort due to an amplifying effect of heat and moisture. Humidity is a generic term commonly used to describe moisture in the air. However, there are numerous variables that describe different properties of humid air that can be used in scientific studies. While relative humidity remains the most used, it has several shortcomings associated with its high correlation with air temperature. Thus, it is important to understand the differences between the variables that describe atmospheric moisture and their proper applications in scientific studies. Furthermore, to maintain outdoor thermal comfort in warm and humid world, the effect of atmospheric moisture on human physiology must be explored. This report will first provide definitions and descriptions of the main atmospheric moisture variables and their proper application. Then, it will explain the human heat balance and how it is achieved through physiological body systems, and provide the overview of scientific studies to date exploring how warm and humid conditions affect human physiology and heat perceptions depending on the activity levels and demographic characteristics. Lastly, it will provide the summary of findings and identify the pathways for future research.

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2 Variables of atmospheric moisture

2.1 Introduction

Human health and thermal comfort is influenced by a combination of environmental variables, such as air temperature, short and long wave radiation, wind, and atmospheric moisture (Epstein & Moran, 2006). Among these, the impact of atmospheric moisture is the most contested one due to the inconsistencies in how this variable is measured and interpreted, as well as the lack of studies that concentrate on the effect of atmospheric moisture in particular (Davis et al., 2016; Maughan et al., 2012a). The impact of atmospheric moisture on human health and comfort is especially important in warm and humid climates like Singapore, as it can amplify the effect of rising air temperatures due to global warming and urban heat island effect (Chen et al., 2019). This section will provide an overview of the variables of atmospheric moisture, explain how they relate to each other, and provide information that can aid in decisions about selection of appropriate variables based on the question of interest.

2.2 Definitions

The term *humidity* is commonly used to describe how much moisture is in the air. However, it is a generalized term that does not have a scientific definition. In fact, there are several terms, and each of them describes particular properties of the humid air (Camuffo, 2014). Variables that describe atmospheric moisture can be broadly categorized as pressure- or mass-based and saturation-based. Pressure- and mass-based variables examine the ratios of the pressure or mass of atmospheric moisture to the mixture of air; saturation-based variables show how much more moisture the air can hold to reach saturation. Definitions and equations for humid air properties are based on the ideal gas laws (Legg, 2017). Atmospheric moisture variables as they are commonly used in meteorology and human health and comfort studies are described below.

1. ***Partial pressure of the water vapour*** (e) is the partial pressure of water vapour in the air (*American Meteorological Society Glossary*, n.d.). Considering the mean sea level pressure of 1013hPa, partial pressure of the water vapour can very between zero for cold and dry climates to 40hPa in hot and humid climates. Partial pressure of the water vapour variable is not commonly used in scientific studies related to human health and thermal comfort (Davis et al., 2016); however, the relationships of other variables can be more easily understood through their relationships with partial pressure of the water vapour.

2. ***Mixing ratio*** (w or r) is a mass of water vapour to the mass of dry air. Mixing ratio is related to partial pressure of the water vapour accordingly:

$$w = \frac{0.622e}{p-e} \tag{1}$$

where p is air pressure; 0.622 is the above ratio between the molar masses of water and dry air.

3. ***Specific humidity*** (q) is a mass of water vapour per mass of air. The relationship between partial pressure of the water vapour and specific humidity is as follows:

$$q = \frac{0.622e}{p - 0.378e} \qquad (2)$$

Both mixing ratio and specific humidity show the actual amount of water vapour in the air and are independent of temperature variations since the denominator is in the units of mass. These two measures are often used interchangeably as they are almost equal (Camuffo, 2014; Davis et al., 2016).

4. ***Absolute humidity*** (also called *vapour density*) (ρ_v or H) is a mass-based variable that relates the mass of water vapour to the total volume of the air at a given temperature and pressure (Parish & Putnam, 1977). This variable is directly proportional to the partial pressure of the water vapour and inversely related with air temperature (Camuffo, 2014) and, according to the General Gas Law, relates to the partial pressure of the water vapour as follows:

$$e = \rho_v R_v T \qquad (3)$$

where R_v is the gas constant for water vapour; T is the air temperature.

5. ***Saturation vapour pressure*** (e_s) is when the vapour pressure is at equilibrium with that substance in the liquid or solid phase, in this case water (*American Meteorological Society Glossary*, n.d.). Saturated vapour pressure is equal to the atmospheric pressure (Legg, 2017).

$$e_s = 6.108\exp\left[\frac{17.27T}{T+237.3}\right] \qquad (4)$$

6. ***Saturation mixing ratio*** *(w_s)* is the ratio of the mass of water vapour in a given volume of saturated air to the mass of the dry air (Camuffo et al., 2006). Saturation mixing ration is related to saturation vapour pressure as follows:

$$w_s = 0.622\,\frac{e_s}{p - e_s} \qquad (5)$$

Saturation vapour pressure and saturation mixing ratio show how much moisture air can potentially hold, which depends on the temperature, but does not give information about the actual amount of moisture in the air, unlike the mixing ratio and the partial pressure of the water vapour.

7. ***Relative humidity*** *(RH* or u *or* ϕ*)* is the ratio of water vapour to the saturated water vapour at the same temperature. It can be calculated from any of the mass-based variables, or from dry and wet bulb temperature measurements using the psychrometric equation, or measured directly with instruments (*American Meteorological Society Glossary*, n.d.; Davis et al., 2016; Legg, 2017). Relative humidity relates to partial pressure of the water vapour accordingly:

$$e = 0.0611RH \times 10^{aT/(b+T)} \tag{6}$$

where a = 7.5 and b = 237.3°C are the Magnus-Tetens coefficients derived to describe properties of water vapour (Camuffo, 2014).

Relationships between the variables in terms of relative humidity are as follows:

$$RH = \frac{e}{e_s} \times 100 \approx \frac{w}{w_s} \times 100 \approx \frac{q}{q_s} \times 100 \approx \frac{\rho_v}{\rho v_s} \times 100 \tag{7}$$

As can be seen from the equation, relative humidity is inversely related to the air temperature and does not provide information about the actual amount of moisture in the air. Moreover, it is influenced by seasonal and diurnal variations (Davis et al., 2016). Relative humidity is derived from mass-based variables and temperature through non-linear relationships, thus, a mean value obtained by averaging relative humidity observations during certain period of time would not be accurate. When two air masses with different relative humidity mix, the final relative humidity does not equal to the arithmetic mean of the two, but it is the outcome of the final temperature and amount of vapour in the air. Thus, monthly averages of relative humidity should be calculated from the averages of mixing ratio or partial pressure of the water vapour and the air temperature (Camuffo, 2014).

8. ***Dew point temperature*** (*Td* or *DP*) is the temperature to which the air must be cooled to reach saturation at the same pressure. It is a humidity variable independent of air temperature expressed in °C. If air is saturated to 100%, the dew point temperature will equal the air temperature and partial pressure of the water vapour will equal the saturation air pressure (Camuffo, 2014).

9. ***Wet bulb temperature*** (*Tw*) is the temperature that air would have if it were cooled to saturation at constant pressure by evaporation of water (Camuffo, 2014). It can be measured by a thermometer with a bulb covered in a moist cotton cloth exposed to the moving air and without impact from radiation. This variable is especially important for human comfort studies in tropical climates, since body capacity to cool through evaporation may be inhibited by high wet bulb temperature (Davis et al., 2016).

Although dew point and wet bulb temperature are both achieved through cooling at constant pressure until the saturation is reached, dew point is achieved without a change in the amount of water vapour, while wet bulb temperature is achieved through adding water vapour. Thus, dew point is a typical temperature of condensation and wet bulb temperature is typical for evaporation (Camuffo, 2014).

To illustrate the relationships between the atmospheric moisture variables let us consider an example at two temperature conditions (Fig. 1). Cases A and B both have a mixing ratio of 5 grams of water vapour, represented with shaded dots, per 1 kilogram of dry air. The hollow dots show how much more moisture the air can hold before it reaches saturation. Since warmer air can hold more moisture, the saturation mixing ratio at 25°C is 22 grams, whereas at 10°C saturation mixing ratio is 8 grams. Using the mixing ratio and the saturation mixing ratio, the relative humidity for case A can be calculated as follows: $RH = 100\% \times \frac{5g}{22g} = 23\%$; and for case B: $RH = 100\% \times \frac{5g}{8g} = 63\%$. So, even though both cases have the same amount of atmospheric moisture, the relative humidity is much higher at 10°C since the air at 10°C is much closer to saturation. In case C, both cases A and B reach saturation at dew point of 0°C while relative humidity is at 100%.

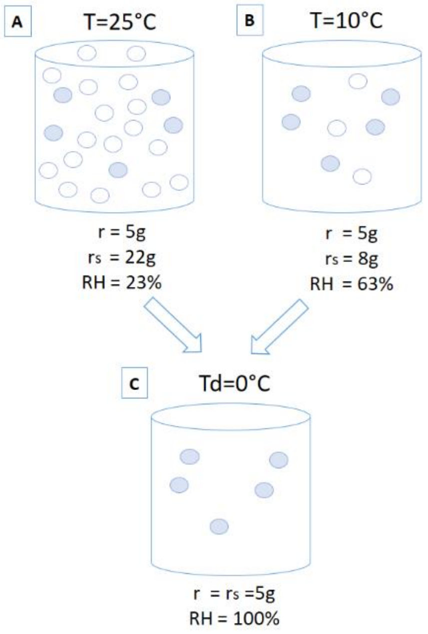

Figure 1. Example of the relationships between atmospheric moisture variables

Davis et al (2016) examined relationships between the variables of atmospheric moisture, air temperature and several thermal comfort indices for Singapore at 7:00 and 13:00 from January 1, 1992 through September 24, 1994. Pearson's correlations between mass-based variables were very strong, making them interchangeable regardless of the time of day. Relative humidity was negatively correlated with thermally based variables such as air temperature and wet-bulb temperature and weakly positively correlated with mass-based variables. Air temperature was highly correlated with all variables except relative humidity in the morning but had a weaker relationship in the afternoon, since in Singapore air temperature is close to dew point in the morning. With the increase of air temperature during the day, the inverse correlation with relative humidity became stronger, illustrating the diurnal nature of relative humidity and its strong relationship to air temperature.

2.3 Choice of the appropriate variable

As was previously discussed, different qualities of humid air are represented by different variables of atmospheric moisture, thus, careful consideration should be given to select the variable best fitting the goals of the study. For instance, pressure- and mass-based variables, such as absolute humidity, dew point temperature, mixing ratio, specific humidity and partial pressure of the water vapour are applicable for studies that examine the effects of the human exposure to the environment, effects on respiratory processes and microorganism development. Relative humidity, currently the most prevalent variable used in scientific studies, should be used with caution since it is strongly influenced by air temperature and varies diurnally and seasonally. Relative humidity and dew point depression are applicable when proximity to saturation is of interest, for instance to assess the dampness and mould development. Wet-bulb temperature and human comfort indices that include atmospheric moisture are suitable for studies of human comfort in hot climates where evaporative cooling is important (Davis et al., 2016).

3 Human thermoregulation and physiological responses

3.1 Introduction

Human heat exposure depends on the environmental conditions (air temperature, wind speed, long and short-wave radiation, and atmospheric moisture) and individual activity level that results in metabolic heat production (M) by the body. Human heat balance is achieved through convective (C), conductive (K), radiant (R), and evaporative (E) exchanges (N. A. Kenny et al., 2009). The first three are called dry heat exchange while the latter is wet heat exchange (Fig. 2) (Tawfik, 2020).

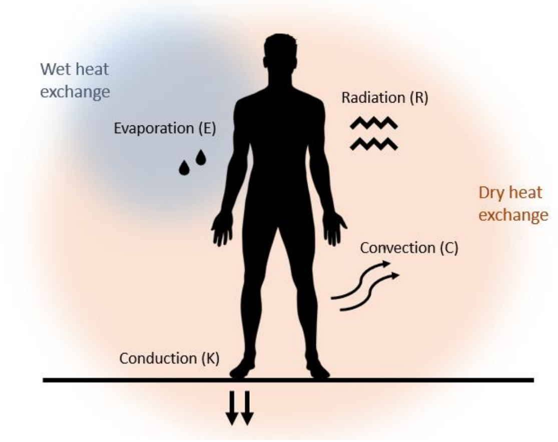

Figure 2. Human body heat balance mechanisms

The heat balance equation considering heat gains from the environment that is widely used in scientific studies is as follows (McGregor & Vanos, 2018):

$$0 = M + R + K + \Delta S \pm C - E \tag{8}$$

where ΔS is the change in body heat storage. Convectional heat gain ($+C$) occurs when air temperature is higher than skin temperature; when air temperature is lower than skin temperature, convectional heat loss ($-C$) occurs.

Once environmental heat gain by the body cannot be offset by the heat loss mechanisms, body core temperature rises resulting in the heat strain. When that is combined with intensive physical activity, an exertional heat stress, catalysed by rapid rise in the core temperature, may occur and can lead to heat exhaustion and heat illness. Thus, metabolic gains together with clothing level are essential in determining human heat balance (McGregor & Vanos, 2018).

Body temperature is regulated through the neural feedback from sensors on the skin and internal organs into the central nervous system. The hypothalamus receives sensory information and sends neural and hormonal signals that initiate physiological body responses aimed to gain or dissipate heat (Tawfik, 2020). Physiological reactions responsible for conductive, convective, radiative, and evaporative exchanges are controlled by the cardiovascular, sudomotor and metabolic systems (Fig. 3). Cardiovascular system controls body heat exchange through skin blood flow, particularly vasodilation in case when excess heat must be dissipated. While in a normal state skin blood flow uses around 5% of cardiac output (the amount of blood heart pumps per unit of time), it can rise to 60% when exercising in the heat. Sudomotor system controls heat exchange through evaporation of sweat. The amount of sweat and its sodium content depends on the quantity of activated sweat glands and their capacity, which varies based on the body fitness, level of acclimatization, age, and genetics. While performing intense activities, sweat production can vary between 1.5 litres/hour for unfit and not acclimatized to above 5 litres/hour for fit individuals. Intensity of sweating reduces after several hours. Evaporation is one of the most important heat dissipation mechanisms, especially when ambient temperature is higher than body temperature and heat dissipation through other mechanisms is not possible (Tawfik, 2020). As previously noted, metabolic activity is a significant contributor to body heat gains; while this might be beneficial in cold climates, where produced heat can help to achieve heat balance, in warm climates additional heat needs to be dissipated through dry or wet heat loss mechanisms. Common metabolic rates range from about 60 W/m^2 for light intensity activities such as sitting up to 500 W/m^2 and above for running and high intensity exercise (*ANSI/ASHRAE Standard 55-2010*, 2010; McGregor & Vanos, 2018).

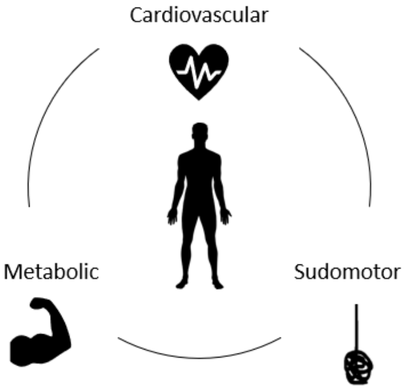

Figure 3. Human body systems responsible for heat balance

To track physiological changes resulting from environmental influences and physical activity, several cardiovascular, respiratory, and thermoregulatory variables are typically measured or estimated. Measured variables include skin and core temperature, heart rate, blood pressure, skin blood flow, respiratory rate, respiratory exchange ratio, pulmonary ventilation, oxygen consumption, sweat rate, sweat gland activation, and percent body mass change. Calculated calorimetry variables are evaporative capacity, evaporative heat loss, required rate of evaporative cooling, heat storage, metabolic heat production, convective heat transfer, radiative heat transfer, evaporative respiratory heat loss, and convective respiratory heat loss (Moyen, Muendel, et al., 2014). Core temperature is usually expressed as rectal temperature or ear (tympanic) temperature which is slightly lower than rectal temperature (Somboonwong et al., 2012). Another way to measure core temperature is with ingestible temperature sensors (Dougherty et al., 2009). Normal body temperature is between 36°C and 37°C and can vary between 33.4°C and 38.2°C (Tawfik, 2020). When exercising in hot conditions, core temperature can reach or exceed 38°C which is often considered as a threshold indicating heat strain (Seo et al., 2019).

It is known that the human body can adjust to changes in the environmental conditions through acclimatization and acclimation. Acclimatization is defined as body adaptation to the new environmental conditions through prolonged exposure; while acclimation is adaptation though intentional repeated short-time exposure to stressful environmental conditions, usually through intense exercise in laboratory settings. In response to acclimatization and acclimation to hot climates, the body adapts its physiological performance through reductions of core temperature, heart rate, skin temperature and earlier onset of sweating at higher intensity and reduced sodium level (Dougherty et al., 2009; Anita M. Rivera-Brown et al., 2006). Adaptations through acclimation occur between 4-14 days with fitness level being an important factor determining the level of acclimation (Brearley et al., 2016). Earlier studies have found that residents of tropical climates are better adapted to warm and humid conditions showing significant differences in sweat rate and sodium concentration and rectal temperature (Ihzuka et al., 1986). However, lifestyle changes and prevalent use of air conditioning is likely to affect natural adaptations. For instance, a study across humid temperate climates did not find physiological adaptations between the beginning and at the end of summer (Bain & Jay, 2011).

When air temperature remains within the comfort range, the effect of humidity on human heat balance is negligible, however, in warm environments a high amount of moisture in the air can cause discomfort by limiting evaporative capacity (McGregor & Vanos, 2018; Tawfik, 2020) and causing extra moisture on skin (Jing et al., 2013). The following section will review the studies of physiological responses in warm and humid conditions. Even though it is the actual amount of water vapor that drives evaporative capacity and affects thermoregulation, relative humidity is the dominant variable used to represent atmospheric moisture in the scientific literature to date. Thus, the majority of discussed-below studies concentrated on the relative humidity as representation of atmospheric moisture. The following section will review relationships between humid and warm conditions on a range of activity levels, from low to high, as well as potential gender and age differences in physiological responses. In the view of the global pandemic, the impact of masks on physiology and heat perceptions will also be investigated.

3.2 Review of studies on the atmospheric moisture and human physiology

3.2.1 Low-intensity activity

Jing et al. (2013) conducted a study involving ten healthy men and ten healthy women in their twenties. Authors explored the influence of humidity and air temperature on physiological body responses and heat perceptions. Participants experienced three different environmental conditions with relative humidity (RH) 40%, 60% and 80%, and three different air temperatures (T), 26°C, 28°C and 30°C, while sitting in a climate chamber for one hour. Every participant was subjected to nine trials with a different combination of RH and T. The study found that skin temperature (Tsk) was the highest at the highest T and RH combination, 30°C and 80%, and there were significant differences between Tsk at different RH levels within the same temperature condition in most experiments. At 80% RH, participants started to feel hotter faster than at the lower RH levels, and many respondents preferred RH to be lower at all temperature conditions. Over 80% of subjects wanted RH to be reduced at 30°C and 80% RH condition expressing feeling discomfort. Thermal comfort was the lowest at 80% RH at all three temperature conditions. Neutral temperature, defined as thermal conditions when people feel neither warm or cool (Nikolopoulou & Lykoudis, 2006), reduced from 26.7°C at 30°C T and 40% RH to 23.9°C at the same T and 80% RH (Jing et al., 2013).

3.2.2 Moderate intensity activity

Moyen et al. (2014), studying young and healthy men walking for 90 minutes in a climate chamber at 35°C T and 40%, 55%, 70% and 85% RH, found that men started to experience thermal strain at RH above 55%. Time of exposure had a significant influence on a majority of physiological variables. Tsk sharply increased after about 10 minutes and then continued to rise at high RH levels reaching 37°C at 85% RH. Tsk at low RH levelled off and kept constant at about 35.5°C. Rectal temperature (Tre) also increased after 30 minutes and was significantly higher at higher levels of RH. Rectal temperature reached 38°C after about 45 minutes for 85% RH and after about an hour for 70% RH and continued to rise until the end of the experiment (Moyen, Ellis, et al., 2014). Similarly, in another study Kamon & Belding (1971) looking at young males walking for two hours in hot conditions (36-37°C) with varying partial pressure of the water vapour (e), found that at e above 24mmHg for clothed subjects, rectal temperature continued to rise until the end of the trials. At lower e an equilibrium in Tre was reached between 40 and 60 minutes at the level above 38°C. Studies found that heart rate was affected by the duration of the experiment, RH (Moyen, Ellis, et al., 2014) and had a linear relationship with Tre (Kamon & Belding, 1971). Evaporative heat loss and maximum evaporative capacity decreased with each 15% in RH increase to the point when evaporative heat loss was equal to maximum evaporative capacity. At this point, skin moisture was at the maximum level. Body heat storage increased considerably after 30 minutes and was higher at RH above 70%; this was reflected in increased pulmonary ventilation and absolute oxygen consumption, as well as thermal sensations, rate of perceived exertion and thirst. However, non-evaporative and respiratory heat loss could not compensate for decreased evaporative loss. Thermoregulatory responses were non-linear, and were caused by Tre surpassing the balance point (Moyen, Ellis, et al., 2014). Kamon & Belding (1971) found that conductance was inversely related to the temperature gradient between core and skin temperature. With higher e, there was a steeper increase in Tsk over time than in Tre. Conductance increased with the need of the body to transfer heat from the core to the periphery.

In a similar experiment on women, Moyen et al. (2014) found that women experienced thermal strain at RH above 70% at 35°C T, however, their core temperatures remained at safe levels even after 90 minutes of low intensity exercise. Heat storage increased with the rise in RH and elevated Tre after 35 minutes due to limited evaporative heat loss. Higher body heat storage and Tre at 85% RH resulted in a higher Tsk to increase heat dissipation through dry heat loss which is reflected in higher heart rate and higher skin blood flow. Rate of perceived exertion followed Tre. At 85% RH, rate of perceived exertion increased after 30 minutes, while there were no differences between the rate of perceived exertion at 55% and 70% RH. Also, thermal sensations were similar for 55% and 70% RH, but were higher at 85% RH. The rise in thermal sensations occurred before the rise in Tsk and Tre that could be possibly associated with the increase in skin wettedness that is known to affect thermal sensations. Change of Tre in men was twice higher than in women. Men had 1°C higher Tre at the end of the trial exceeding the 38°C threshold, while Tre for women remained within the safe limits, reaching 38°C only at the end of the trial. Men also had a higher heart rate at 55% and 70% RH trials, which explained higher temperature rise compared to women (Moyen, Muendel, et al., 2014).

3.2.3 High-intensity activity

Maughan et al. (2012b), studying young men cycling at 70% of their maximum oxygen consumption until volitional exhaustion at 30°C T, and 24%, 40%, 60% and 80% RH, found that there was a distinct effect of RH on the time to exhaustion. While performance at lower RH was similar, it started to reduce at 60% RH and above with time of the exercise consistently decreasing from 68 minutes at 24% RH to 45 minutes at 80% RH. Tre at the end of the exercise was similar for all trials, but it rose with a higher rate at high RH, the same as body heat storage. Tre continued to rise for the whole time of the exercise and did not reach equilibrium. It exceeded 38°C shortly after 20 minutes of exercise and reached 39°C at the end of all trials. Tsk rose in the first half hour and then levelled, being significantly higher at 60% and 80% RH. Oxygen consumption, heart rate, skin blood flow, plasma volume and composition did not differ between trials. Sweating rate was higher at 60% and 80% RH. Rate of perceived exertion and thermal stress were affected by the RH. Rate of perceived exertion was not significantly different at 40% and 60% RH but was higher at 80% RH comparing with 24% RH. Similarly, thermal stress was higher at 60% RH and at 80% RH comparing to 24% RH (2012b).

Wakabayashi et al. (2011) compared young Japanese and Malaysian men exercising in hot and humid conditions (32°C T, 70% RH) for one hour at 55% maximal exercise intensity of peak oxygen consumption. Sweat rate increased for the first 20 minutes and then levelled for both groups, no differences between the groups were observed. Tre was constantly rising with the duration of the exercise and exceeded 38°C in both groups. Even though initial Tre was lower in Japanese men, it increased with a higher rate and both groups had similar Tre at the end. Tsk was rising at a slightly higher rate for Japanese men. A significantly higher skin to core temperature gradient in Malaysian men signified a better ability to transfer heat from core to skin. This was also reflected in a smaller heat storage in Malaysian men and lower increase in Tre.

3.2.4 Older adults

Epidemiological research shows a higher incidence in heat-related morbidity and mortality in elderly (G. P. Kenny et al., 2013) and heat vulnerability studies indicate that elderly are among the high heat vulnerability groups (Cutter & Finch, 2008). Thus, it is important to understand whether changes in physiological responses cause higher sensitivity to heat and how these responses are affected by higher atmospheric moisture. Comparison of physiological responses to high T and RH between different age groups involving older adults is explored below.

Smolander et al. (1990), looking at younger (28-37 years) sedentary men and older (55-60 years) healthy and moderately active men exercising at 30% of their maximum oxygen consumption for up to 4 hours in thermoneutral (21°C T, 43% RH), hot dry (40°C T, 20% RH) and warm humid environment (30°C T, 80% RH), did not find significant differences in oxygen consumption and heart rate between the two groups. Heart rate continuously increased for both groups in both hot dry and warm humid conditions. In the younger group, Tre increased during the first hour and then levelled in both hot dry and warm and humid conditions reaching 38°C. In older group Tre increased more gradually. In hot and dry conditions, it remained below 38°C threshold, but reached it in the warm humid conditions after more than three hours. Total body evaporation was significantly lower in humid environment comparing to the dry. Evaporation rate in the warm and humid environment followed a similar pattern as Tre for younger and older men. Thermal sensations and ratings of perceived exertion did not significantly differ between the groups, but for older men ratings were initially lower and increased more sharply during the exercise. Tsk increased but did not differ between the age groups for both hot dry and warm humid trials. The study showed that physiological responses of active older men did not differ from younger sedentary men. However, maximum oxygen consumption was lower in older men, which could result in more heat strain if participants were exercising at the same absolute intensity instead of the percentage of the maximum oxygen capacity. Nonetheless, this study showed that physical fitness can aid in improved heat and humidity acclimation for older men.

Notley et al. (2017) comparing younger and older women cycling at moderate intensity in dry and humid hot conditions (35°C T, 20% and 60% RH) also found that both groups had a lower heat loss capacity in humid conditions. In addition, older women stored 26% more heat in dry and 16% more heat in humid conditions. This could be associated with lower Tsk in older women, which could result in higher heat gain from the environment. However, Tre and percentage heart rate reserve was similar in both groups. Tre increased in both groups but did not exceed 38°C threshold.

Havenith et al. (1995), looking at 56 men and women with the age range between 20 and 73 years exercising for one hour at a low intensity absolute workload of 60W at 35°C T and 80% RH, did not find relationships between rectal temperature and age. Tre and heat storage were significantly influenced by the absolute maximum oxygen consumption. Sweat was best explained by the level of fitness and percentage of body fat. Significant relationships with age were found in heart rate, mean arterial pressure, forearm blood and vascular conductance flow, as well as with variables related to body composition. Hence, results showed that age had an influence on cardiovascular responses, but thermoregulatory responses were more related to maximum oxygen consumption and physical activity.

Similarly, Beatty et al. (2015), examining younger and older men exercising at a fixed rate of heat production of 400W for an hour in hot and humid conditions (35°C T and 60% RH) under varying wind speed of 0.5-3 m/s, found that heart rate, maximum heart rate, skin blood flow and skin conductance differed between the age groups and also changed with the duration of exercise. Duration of exercise and wind speed affected Tre, skin temperature, heart rate, sweat rate, skin blood flow and percent of maximum skin conductance. Heart rate and maximum heart rate increased more in younger adults, but percent of maximum skin blood flow and percent of maximum skin conductance increased greater in the older group. This could be due to an increase in heat storage resulting from impaired evaporative capacity in the older group. At low wind speed, Tre exceeded 38°C for both age groups, however, higher wind speed helped to keep core temperature within safe limits.

Presented-above studies showed that age by itself may not be the determining factor affecting thermoregulation, but rather associated factors with age such as increase in body fat percentage, and lower activity level can reduce thermoregulatory performance for older adults. Nevertheless, older subjects may be more susceptible to cardiovascular strain, due to age related decrease in heart rate. In addition, chronic diseases can have a significant influence on the body metabolic, cardiovascular, neurological, and thermoregulatory systems. For instance, type 2 diabetes was found to decrease vasodilation processes, resulting in additional body heat storage (G. P. Kenny et al., 2013).

3.2.5 Children

Several studies pointed out that children can be more prone to heat exhaustion due to physiological differences, such as larger skin surface area in relation to their body weight, reduced sweating capacity, and reduced cardiac output comparing to adults. Higher skin surface to body mass area can result in increased absorption of heat; and limited evaporation capacity can lead to reduced capacity to dissipate heat. Children might also be limited in their ability for prolonged high intensity exercise due to increased metabolic energy required for activities like walking and running and reduced cardiac output. In addition, children divert a higher proportion of cardiac output to the skin, which is reflected in higher skin blood flow. This leaves less available output for muscle activity and smaller venous return, which would result in lower exercise capacity, especially in high heat (Falk & Dotan, 2008). Studies suggest that these differences may lead to faster heat exhaustion in children (Anita M. Rivera-Brown et al., 2006). U.S. emergency room reports between 1997 and 2006 found that the highest proportion of exertional heat-related illness was in children engaged in outdoor sports or exercising. However, 10-year records in Queensland, Australia, did not show differences in heat injury reports between children and adults (Brun & Mitchell, 2006). No information on children heat related illness reports was available for Southeast Asia (Somboonwong et al., 2012). Nevertheless, other studies point out that higher incidences of heat illness occurring in some areas could be attributed to behavioural and lifestyle differences of children, such as regular exercise and play outdoors, and lack of hydration (Somboonwong et al., 2012). Furthermore, a review of studies on child physiology and thermoregulation suggested that due to the physiological differences explained above, children rely on different thermoregulation mechanisms than adults. For instance, higher skin surface to mass ratio allows dissipating more heat through dry heat exchange in mild or warm climate when air temperature is below the skin temperature. This could be advantageous in warm humid climates, where evaporative capacity is limited (Falk & Dotan, 2008). In this section, several studies comparing children and adults, as well as children with varying body types performing activities under warm and humid conditions, will be examined.

Rivera-Brown et al. (2006) compared girls (9 to 12 years old) and women (20-34 years old) cycling outdoors (33.4°C T, 55.1% RH, 41-43°C Tg) until fatigue between 10:00 and 14:00 while exposed to sunlight in tropical Puerto Rico. Subjects were physically active and matched for aerobic capacity. Results showed that girls exercised for less time comparing to women, but the difference was not statistically significant. Girls exercised between 30 and 95 minutes while women did so between 38 and 115 minutes. The majority of subjects stopped due to leg fatigue. Both groups perceived conditions as hot while, at the end of the exercise, girls perceived the environment as very hot. Sweating rates adjusted for body surface area were similar between the groups. Changes and absolute values of Tre and Tsk were also similar. Tre rose during the first 30 minutes and levelled for both groups. Exhaustion temperature for girls was between 37.8°C to 38.9°C while for women it was 38.0°C to 39.3°C. Girls had higher Tsk during exercise but final values did not significantly differ between the groups. Heat storage was also similar between the groups. There were no differences in cardiovascular performance; heart rate increased in the first 10 minutes and then levelled off while skin blood flow increased during the exercise but did not differ between the groups. The study showed that physically active and acclimatized girls had similar thermoregulatory and cardiovascular response as adult women in sunny, hot, and humid conditions. Shorter exercise duration for girls could be due to their higher perception of heat, which might be a protective mechanism to prevent exhaustion.

Somboonwong et al. (2012) conducted a longitudinal study in Bangkok, observing school children exercising outdoors during two semesters in the morning and afternoon. The authors found higher levels of heat stress during the afternoon session. Sweat rate was higher in the afternoon and about 4% of students experienced rise in tympanic temperature above 38°C. Overweight students were twice as likely to pass 38°C threshold than lean children, however, no students experienced heat related illness during the study. Overall, students were able to maintain thermoregulation even in the afternoon with sufficient hydration, thus, school boys had sufficient thermoregulatory and cardiovascular capacity to exercise for 30 minutes in hot and humid climate.

Dougherty et al. (2009) examined 9 to 12 years old lean and obese boys going through six 70-minute acclimation sessions of low-intensity exercise in hot and humid conditions (38°C T, 50% RH) in a climate chamber. The authors found that obese subjects were significantly less acclimatized to hot and humid conditions, which was indicated by their higher initial Tre. By the end of the trial on the sixth day, both groups achieved significant reductions in Tre, however, obese boys had a similar Tre at the end of the trial to lean boys on the first day. Reductions in core temperature for obese boys occurred slower than for lean boys. In addition, there was a significant reduction in heart rate for lean boys between the first and sixth day, but not for obese boys. Obese boys had a significantly higher relative sweating rate, but not the absolute rate comparing to the lean boys. The rate of perceived exertion was significantly higher for obese boys at the second half of a 6-day trial period. Lean boys had a significant reduction in the rate of perceived exertion at the end of the trial and lower thermal sensations during the second half of the six-day trial. The rate of perceived exertion and thermal sensations did not change for obese children. The study showed that children had similar physiological adaptation as adults for 6-day heat acclimation trials. For obese boys, the range of Tre reduction was 0.21°C -0.06°C, and for lean it was 0.23°C to 0.04°C. While core temperature exceeded 38°C on the first day of the trial, it was below the threshold on day six for both groups. The fact that heart rate did not decrease for obese children was likely associated with higher stroke volume, meaning that obese children did not have a reserve to further increase stroke volume that could decrease their heart rate.

Docherty et al. (1986), looking at 23 boys between 10 and 13 years old with different body composition walking on a treadmill at the same absolute intensity at 30°C T and 80% RH, found that oxygen consumption rose in the first five minutes by 4.5 times comparing to pre-exercise levels and then stabilized. Heart rate rapidly increased during the first 10 minutes and then continued to increase until the end of the exercise at a slower rate. Tsk increased during the first 25 minutes and levelled off. Tre increased consistently reaching 38°C after 20 minutes and continued to rise until 38.3°C at 60 minutes. Tympanic temperature also increased rapidly during the first 15 minutes and then rose at a slower rate, increasing by 0.2°C more by the end of the exercise. Comparisons of subjects' thermal responses and body type did not reveal significant differences. However, there was a weakly significant relationship between obesity and maximum oxygen consumption signalling that obese children could be at a higher risk of thermal strain. Study showed that boys were able to exercise in hot and humid conditions and successfully thermoregulate for one hour.

Overall, these studies showed that children can effectively thermoregulate in warm and humid conditions with low or moderate exercise up to an hour. Children showed similar acclimation patterns to adults. Obese children were at a higher risk to suffer from heat illness.

3.2.6 Masks

COVID-19 pandemic has resulted in face mask wearing enforcements in indoor and outdoor public settings and workplaces in most of the world. Surgical masks were first used in the 19th century in Germany by medical staff to protect patients during surgeries. Since then, surgical masks have been used more widely to protect users by creating a barrier from accidental body fluid of others during speech, coughing, sneezing, etc. (Lipp and Edwards, 2005). Respirators, such as N95 masks, became widespread among general public and workers in protecting from harmful airborne contaminants, infectious diseases, wildfires, and air pollution (Lin & Chen, 2019).

The face has a crucial role for body thermoregulation, accounting for 20% of the total impact from the skin due to more receptors and higher sensitivity (Scarano et al., 2020). The face is up to five times more sensitive compared to limbs. An increase of the facial skin temperature by 4°C results in a 50% increase in body sweating. Similarly, cooling of the facial skin has up to five times stronger effect on reducing body sweating comparing to the limbs (Tawfik, 2020). A mask traps exhaled air and moisture, hindering convection and evaporation of skin. This results in a microclimate inside the mask, which is called the dead space (Roberge et al., 2012b). Wearing face masks in hot and humid conditions can affect thermal sensations and cause heat stress, compromising thermal comfort, safety and reducing working time (Li et al., 2005; Roberge et al., 2012a). Moreover, discomfort associated with wearing a face mask, may result in poor compliance, incorrect use and, thus, compromise their efficiency. (Roberge et al., 2012b). The following section will review studies related to wearing face masks in warm and humid conditions and their effect on physiological body responses and thermal perceptions.

Li et al. (2005) conducted a study in a warm and humid environment (25°C T and 70% RH) with participants completing three 10-minute walking trials at different intensities. The authors found that the type of mask affected thermo-physiological responses of participants and overall discomfort. Participants wearing surgical masks had lower heart rate, facial Tsk covered by mask and dead space temperature in comparison to N95 masks. Surgical masks were more humid outside, which suggests that they are more effective in getting rid of the excess moisture from inside the mask. Shortage of oxygen and increased humidity in N95 respirators has likely impacted the increase in heart rate and perceived overall discomfort. Surgical masks were rated better for overall comfort in comparison to N95 respirators. Reports of masks being unfit, tight, itchy, odorous, salty, and causing fatigue were lower for surgical masks. Overall, perceptions of discomfort increased significantly with increased thermal stress and duration of wear, which can become a challenge if subjects are expected to wear face masks for several hours.

Lin & Chen (2019) looked at the impact of N95 respirators in various combinations of warm and humid conditions (25°C, 29°C, 33°C T and 55%, 75% RH) while walking on the stairs in an indoor environment. Tsk inside the respirators was significantly higher as well as T and RH inside the respirator comparing to the group not wearing a mask. Changes in the microclimate inside N95 respirator were rapid during the first 10 minutes and continued to rise slowly over time. Wearing a N95 respirator resulted in an increase of T (up to 1.3°C) and RH (up to 7%) of the dead space and nasal temperature. Heat index, an index derived from T and RH to convey 'feels like' temperature (McGregor & Vanos, 2018), inside the mask increased 30% to 62% comparing to the control group (Lin & Chen, 2019). Both physiological responses and heat perceptions increased with higher T, RH, and duration of the experiment. Transepidermal water loss increased by up to 85% in the forearm and up to 72% in the cheek after half hour of the trial. Thermal sensations increased with duration of the exercise, higher T and RH. Once heat index reached 38°C, there was a sudden increase in thermal sensations while water loss and Tsk levelled off, signifying that body reached the capacity to cope with heat which could result in thermal strain (Lin & Chen, 2019).

Scarano et al. (2020) compared discomfort from using surgical masks versus filtering respirators on males between 45 and 55 years old sitting and reading for one hour at moderate thermal conditions (22°C to 24°C and 50% RH). There was a significant difference in the mean temperature around the mouth after masks were removed (for surgical mask $\Delta T=0.7 \pm 0.5$ °C; for N95 $\Delta T=1.2 \pm 0.5$°C). Surface temperature in the surgical mask varied between inhalation and exhalation; however, for filtering respirator there was little variance. Participants wearing a surgical mask touched their face much fewer times than those wearing a filtering respirator, 8 and 25 times respectively. Intraoral temperature was above 37.5°C for participants wearing masks versus 37.3°C for the control group without a face covering. The surgical mask caused less discomfort and lesser temperature increase which shows that it could be more effective since there is a higher chance it will be used properly.

Discussed-above studies showed that face masks worn in warm and humid conditions result in elevated thermal sensations, increased sweating, and face temperature. Physiological responses and perceived discomfort increased with duration of wear, which can potentially decrease work efficiency and amplify thermal stress if masks to be worn for prolonged periods of time.

4 Conclusions and recommendations

Ongoing urbanization will likely continue driving environmental changes. At the same time, cities will be striving to maintain liveability in the changing climate. Increase in precipitation and atmospheric moisture can exacerbate the heat associated challenges caused by urban heat island effect and global warming. Choice of the variables that appropriately represent the amount of atmospheric moisture in the air is important for understanding separate and combined effects of climate variables on human physiology and thermal comfort. This report has shown that high atmospheric moisture adds an additional physiological stress in warm climates, primarily through inhibiting evaporative capacity of the body. Higher levels of relative humidity were associated with elevated physiological and perceptual responses.

Level of fitness is an important factor to tolerate heat. Moreover, heat acclimation practices showed success in improving heat and humidity tolerance in children and adults. Age was not specifically associated with impaired thermoregulation, it is likely that higher heat vulnerability of the elderly is related to lower activity levels, higher percentage of body fat, and chronic diseases. However, changes in cardiac output associated with age are likely to put additional cardiac strain in hot and humid conditions. Children can be more susceptible to heat due to differences in lifestyle as they regularly spend more time outdoors. Moreover, it was shown that children rely on dry heat dissipation mechanisms more than adults. Those findings have planning and design implications for outdoor urban environments in tropical climates:

- boost evaporative capacity of the body through urban canyon wind channelling and other design solutions that can increase wind circulation;

- develop urban spaces conducive for regular outdoor exercise to promote physical fitness and support acclimatization, especially for the elderly;

- provide ample shade at playgrounds and areas for child activity to support dry heat dissipation.

5 Future research directions and data needs

The majority of studies on the effect of warm and humid environment on human physiology and thermal sensations to date were done in climate chambers. While such approach allows a high degree of control over study design and execution, it ignores the effect of the complexity and variability of the urban environment on human physiology and psychology. Moreover, mean radiant temperature, one of the most influential variables of outdoor thermal comfort, was not tested in conjunction with high air temperature and atmospheric moisture in climate chamber studies.

Trials were mostly done on non-acclimatized individuals, which could mean that residents of tropical climates would experience less physiological stress to higher temperature and atmospheric moisture. However, it is not possible to assume that all urban dwellers in highly urbanized areas like Singapore are equally better adapted to the outdoor environment since many residents spend the majority of their time in climate-controlled spaces.

Finally, the effect of heat and atmospheric moisture on morbidity and mortality in Singapore is currently unknown due to data limitations. It is crucial to assess the risks of adults, as well as elderly and children to develop appropriate protective mechanisms.

Based on these arguments, future research directions are outlined below:

- conduct studies that evaluate physiological responses and thermal sensations in urban outdoor settings to identify design strategies most beneficial for outdoor thermal comfort;
- explore the relationships between the use of air conditioner, time of outdoor exposure and acclimatization level of residents in tropical climates;
- using heat-related mortality and morbidity data, analyse demographic, socio-economic, and spatial patterns of morbidity and mortality.

6 Glossary

6.1 Acronyms used

Variable	Description
e	Partial pressure of the water vapour
r or w	Mixing ratio
q	Specific humidity
ρ_v or H	Absolute humidity
m_v	Mass of water vapour
R_v	Gas constant for water vapour
e_s	Saturation vapour pressure
RH or u *or* ϕ	Relative humidity
a and b	Magnus Tetens coefficients

w_s	Saturation mixing ratio
q_s	Saturation specific humidity
ρ_{vs}	Saturation absolute humidity
T	Air temperature
Tg	Globe temperature
Tre	Rectal temperature
Tsk	Skin temperature
Td or DP	Dew point temperature
M	Metabolic heat production
R	Radiative heat exchange
K	Conductive hat exchange
C	Convective heat exchange
E	Evaporative heat exchange
ΔS	Change in body heat storage

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