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Thermal comfort evaluation in residences with natural ventilation: an application in the Brazilian hot and humid climate

(**Avaliação de conforto térmico em residências com a ventilação natural:** aplicação no clima quente e úmido brasileiro)

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ABSTRACT

A recent approach to human thermal comfort under warm-to-hot conditions indoors includes dynamic airflows, whose mean air velocities vary in time. The dynamic airflow background is based on the features of the widely accepted natural wind, recognised as more pleasant than constant mechanical airflows. Natural wind-induced airflows may occur inside buildings if climatic and building design characteristics are favourable. Moreover, natural ventilation is a primary conditioning strategy in Brazilian residences – an optimal scenario to assess dynamic airflows. This research addresses natural ventilation and thermal comfort in hot and humid climates based on two main approaches: the impact of air velocity from dynamic airflows on households' thermal delight and satisfaction (1) and the routine adoption of natural ventilation at home based on preferences, motivations and economic background (2). The research methods involved an online national survey and a local field campaign conducted in São Luis, Brazil's Northeast, during the local wind regime. The field campaign started with a visit to residences (point-in-time surveys with air velocity measurements) and ended after long-term indoor air temperature and relative humidity monitoring. A thermal delight condition from natural ventilation was defined based on sedentary activity and light clothing in residential environments in a hot and humid climate. Households' optimal evaluation corresponded to air velocities of at least 0.4 m/s under an operative temperature range of 27-30 °C. The outcomes indicated that if the minimum air velocity threshold was maintained, the fluctuations in air movement intensity did not impair thermal delight, resulting in households' satisfaction with air movement at the end of the point-in-time survey. Households' routines, economic constraints and environmental conditions of indoor air temperature and outdoor wind speed were behind adopting a conditioning strategy at home. Air-conditioning usage and preference increased, whilst fan usage and preference decreased towards the highest income range. Nevertheless, income did not significantly affect the preference for natural ventilation only. Preference and usage patterns regarding a conditioning strategy were also aligned so that those who prefer natural ventilation at home are prone to use it more frequently. The results of this study indicate the relevance of air movement from natural ventilation to households' thermal comfort, particularly in well-ventilated homes. The relevance arises within the favoured adoption of natural ventilation in the Brazilian residential sector.

Keywords: natural ventilation; dynamic airflows; thermal comfort; Brazilian residences; hot and humid climate.

RESUMO

Uma abordagem recente de conforto térmico humano em condições de calor em ambientes internos inclui fluxos de ar dinâmicos, cujas velocidades médias do ar variam no tempo. Os estudos sobre fluxos de ar dinâmicos se baseiam nas características do vento natural, reconhecido como mais agradável do que os fluxos de ar mecânicos. Os fluxos de ar induzidos pelo vento natural podem ocorrer nas edificações se as características climáticas do sítio e de projeto forem favoráveis. Além disso, a ventilação natural é a principal estratégia de condicionamento utilizada nas residências brasileiras – um cenário favorável para avaliar os fluxos de ar dinâmicos. Esta pesquisa aborda a ventilação natural e o conforto térmico em climas quentes e úmidos com base em duas vertentes principais: o impacto da velocidade do ar de fluxos de ar dinâmicos na sensação de agradabilidade proporcionada pelo ambiente térmico (deleite térmico) e na satisfação dos residentes (1) e a adoção rotineira da ventilação natural nas residências com base em preferências, motivações e fatores econômicos (2). Os métodos de pesquisa envolveram uma pesquisa nacional on-line e uma pesquisa de campo local realizada em São Luís, no nordeste do Brasil, durante o regime local de ventos. A pesquisa de campo começou com uma visita às residências (pesquisas do tipo instantâneas com medições da velocidade do ar) e terminou com o monitoramento de longo prazo da temperatura do ar interno e da umidade relativa nas residências. A condição de agradabilidade sob ventilação natural foi definida considerando-se atividades sedentárias e roupas leves em ambientes residenciais situados em clima quente e úmido. A avaliação ótima dos residentes correspondeu a velocidades do ar de pelo menos 0,4 m/s sob temperatura operativa de 27 a 30 °C. Os resultados indicaram que, se o limite mínimo de velocidade do ar for mantido, as flutuações na intensidade do movimento do ar não prejudicariam a sensação de agradabilidade relativa ao ambiente térmico, resultando na satisfação com o movimento do ar no final da pesquisa instantânea. As rotinas das famílias, as restrições econômicas e as condições ambientais de temperatura do ar interno e da velocidade do vento externo influenciaram a adoção de uma estratégia de condicionamento nas residências pesquisadas. Na faixa de renda mais alta, o uso e a preferência pelo ar-condicionado aumentaram, enquanto que o uso e a preferência pelo ventilador diminuíram. No entanto, o fator renda não afetou significativamente a preferência pela ventilação natural apenas. Os padrões de preferência e uso com relação a uma estratégia de condicionamento também estiveram alinhados, de modo que aqueles que preferem a ventilação natural em casa estão propensos a usá-la com mais frequência. Os resultados deste estudo indicam a importância do movimento do ar da ventilação natural para o conforto térmico das residências, especialmente em residências consideradas bem ventiladas pelos seus ocupantes. Essa relevância ocorre em meio à adoção favorecida da ventilação natural no setor residencial brasileiro.

Palavras-chave: ventilação natural; fluxos de ar dinâmicos; conforto térmico; residências brasileiras; clima quente e úmido.

RESUMO EXPANDIDO

Introdução

O movimento do ar é uma das alternativas ao conforto térmico humano em climas quentes e úmidos, devido às trocas de calor por convecção e evaporação entre o corpo humano e o ambiente circundante. Uma abordagem recente de conforto térmico humano em condições de calor em ambientes internos inclui os fluxos de ar dinâmicos, cujas velocidades médias do ar variam no tempo. Os estudos sobre fluxos de ar dinâmicos se baseiam nas características do vento natural, reconhecido como mais agradável do que os fluxos de ar mecânicos. Tais estudos apontam que os fluxos de ar dinâmicos são eficientes ao promover melhores avaliações de sensação térmica (próxima à neutralidade) e conforto térmico em comparação aos fluxos de ar de velocidade média equivalente, porém constante ao longo do tempo, em condições de temperatura interna entre 27 a 30 °C. Concomitantemente, o movimento do ar incrementado (velocidade média acima de 0,8 m/s) é comumente empregado para mitigar o desconforto térmico por calor em ambientes internos, sendo constantemente associado a uma condição de aceitabilidade a qual não corresponde à avaliação ótima ou desejável pelos ocupantes. Nesse contexto, há uma lacuna referente à abordagem do movimento do ar sob a perspectiva do deleite térmico – o quanto a característica dinâmica do movimento do ar é agradável aos ocupantes e sob quais condições de temperatura e velocidade do ar. O setor residencial brasileiro oferece ampla possibilidade de investigação dos fluxos de ar dinâmicos em campo por ter a ventilação natural como estratégia primária de climatização. Deste modo, os fluxos de ar induzidos pelo vento natural podem ocorrer nas residências se as características climáticas do sítio e de projeto forem favoráveis. No entanto, não apenas fatores ambientais determinam a utilização da ventilação natural, uma vez que a penetração do ar condicionado no setor residencial é uma tendência crescente. Nesse sentido, a escolha por uma estratégia de climatização é pautada em determinantes relacionadas ao ambiente térmico interno e externo, mas também em fatores econômicos. Esta pesquisa aborda a ventilação natural e o conforto térmico em climas quentes e úmidos com base em duas vertentes principais: o impacto da velocidade do ar de fluxos de ar dinâmicos na sensação de agradabilidade proporcionada pelo ambiente térmico (deleite térmico) e na satisfação dos residentes (1) e a adoção rotineira da ventilação natural nas residências com base em preferências, motivações e fatores econômicos (2).

Objetivos

A tese tem como objetivo avaliar o deleite térmico dos residentes que experimentam o movimento do ar dinâmico e não uniforme proveniente da ventilação natural em ambientes residenciais de estar e repouso no clima quente e úmido brasileiro.

Os objetivos específicos da tese são:

- Associar as avaliações instantâneas do movimento do ar e de deleite térmico às variações temporais de velocidade do ar quantificadas em ambientes residenciais naturalmente ventilados;
- Delinear as condições de temperatura e velocidade do ar interno que proporcionam o deleite térmico em ambientes residenciais naturalmente ventilados;
- Comparar as avaliações atribuídas ao ambiente térmico experimentado pelos residentes quando ventilado naturalmente (com e sem ventiladores) e quando climatizado artificialmente;
- Associar a opção por uma estratégia de climatização nas residências à intensidade dos ventos externos e à temperatura do ar (externa e interna) vigentes;

- Investigar a associação entre renda familiar, frequência de uso da ventilação natural e preferência pela ventilação natural como estratégia de conforto térmico em residências.

Metodologia

Os métodos de pesquisa envolveram uma pesquisa nacional on-line, disseminada por todas as regiões do país, e uma pesquisa de campo local realizada em São Luís, no nordeste do Brasil, durante o regime local de ventos. A pesquisa nacional consistiu em um questionário abordando o uso da ventilação natural nas residências brasileiras: preferências, rotinas e motivações por trás de sua adoção ou não adoção. O questionário foi aprovado pelo Comitê de Ética em Pesquisa com Seres Humanos (CEPSH/UFSC) sob o número identificador CAAE 51459421.0.0000.0121. A estratégia de disseminação envolveu os cursos de pós-graduação públicos a nível nacional, visando à ampla divulgação em todo o território nacional e ao engajamento de participação da comunidade acadêmica. A disseminação ocorreu entre os meses de Outubro e Dezembro de 2021. A pesquisa de campo consistiu em visitas às residências e no monitoramento ambiental destas por aproximadamente um mês. A realização da pesquisa de campo permitiu o monitoramento das variáveis relacionadas ao ambiente térmico (temperatura do ar, temperatura de globo, umidade relativa do ar e velocidade do ar) e a realização de entrevistas com os moradores, complementando os resultados obtidos na pesquisa nacional. Os instrumentos de medição utilizados pertencem aos Laboratórios de Eficiência Energética em Edificações (LabEEE/UFSC) e de Meios Porosos e Propriedades Termo físicas (LMPT/UFSC). A amostra de residências foi definida, em princípio, a partir da rede de contatos da pesquisadora, complementada pela rede de contatos dos primeiros participantes. A proposta de pesquisa de campo foi apreciada e aprovada pelo CEPSH sob o número identificador CAAE 58653622.8.0000.0121. A pesquisa de campo foi iniciada com uma visita da pesquisadora às residências e finalizada com o monitoramento ambiental de longo prazo nos cômodos de ocupação mais frequente daquelas residências. Na ocasião da visita, os moradores participantes foram entrevistados e preencheram um questionário de avaliação instantânea do ambiente térmico (IQ) em intervalos pré-determinados, ao mesmo tempo em que as variáveis ambientais térmicas foram mensuradas. Essa parte da pesquisa é denominada pesquisa instantânea e possibilitou a associação entre as avaliações instantâneas e as variações de velocidade do ar no decorrer do tempo. Ao finalizar a visita, iniciou-se o monitoramento ambiental na ausência da pesquisadora, no qual a temperatura e a umidade relativa do ar interno foram medidas continuamente ao longo de aproximadamente um mês. Neste intervalo, os moradores foram convidados a responderem esporadicamente a um questionário rápido de avaliação do ambiente térmico (QL) pelo celular. Esta pesquisa, denominada monitoramento de longo prazo, possibilitou a avaliação do ambiente térmico em diferentes estratégias de climatização e a investigação acerca das motivações por trás da escolha de uma estratégia na rotina dos residentes. O tratamento de dados envolveu a associação entre categorias de dados qualitativos (teste de qui-quadrado), a regressão logística multinomial e a inferência estatística não paramétrica em linguagem R na interface RStudio.

Resultados e Discussão

O questionário da pesquisa nacional obteve 1.348 respostas válidas de todas as regiões do país. A pesquisa de campo realizada em São Luís contabilizou 597 e 629 respostas válidas aos questionários QL e IQ, respectivamente. A pesquisa nacional abordou a associação entre frequência de uso, preferência por uma estratégia de climatização e fatores econômicos (renda familiar e preocupação com a economia de energia para refrigeração). A frequência de uso da ventilação natural nas residências pesquisadas foi diretamente proporcional à preferência pela ventilação natural e inversamente proporcional à renda familiar e à preocupação com a economia de energia. A associação entre renda e preferência mostrou que a escolha por ventiladores é maior na faixa de menor renda (menos que 4 salários mínimos) e que a escolha por ar condicionado é maior na faixa de maior renda (mais que 10 salários mínimos), deixando clara a influência dos fatores não relacionados ao conforto térmico sobre a preferência declarada pelos residentes. Entretanto, a preferência pela ventilação natural como estratégia de climatização não se alterou pelo fator renda. Adicionalmente, o julgamento dos residentes em relação à ventilação natural disponível (residência bem ou mal ventilada) tem relação com a frequência de uso da ventilação natural, sendo que esta é maior na vivência dos participantes que julgam ter uma boa ventilação em casa. As principais estratégias de climatização, as motivações por trás dessa escolha e as avaliações do ambiente térmico foram investigadas durante o monitoramento de longo prazo da pesquisa de campo. A ventilação natural é a estratégia primária e sua ocorrência esteve essencialmente relacionada à rotina dos moradores. No entanto, os participantes também perceberam as alterações no ambiente térmico ao optarem pela ventilação natural. Participantes que justificaram sua escolha com base em “temperaturas amenas” e em “dia ventilado” estiveram expostos a temperaturas do ar interno ligeiramente menores (mediana próxima a 29 °C) e tiveram suas respostas correlacionadas a velocidades do vento externo ligeiramente maiores (mediana próxima a 3 m/s) do que as demais justificativas. Por outro lado, aqueles que justificaram a escolha da ventilação natural com base em “economia de energia” e “limitações ao uso de ar condicionado” experimentaram temperaturas do ar interno ligeiramente maiores (mediana próxima a 30 °C) e recorreram com mais frequência aos ventiladores. A avaliação de conforto térmico dos participantes em ambientes naturalmente ventilados com e sem ventiladores operando diferiu significativamente no monitoramento de longo prazo, refletindo as condições de temperatura do ar interno experimentadas. A avaliação em ambientes com ar condicionado foi apenas ligeiramente mais positiva do que a avaliação em ventilação natural, em que pesem as diferenças de temperatura e umidade relativa do ar interno experimentado (medianas de 29 °C/69% em ventilação natural e de 27,1 °C/57% em ar condicionado). A opção pelo ar condicionado esteve menos relacionada à condição do ambiente e mais relacionada à rotina dos participantes que possuem o equipamento, particularmente durante o sono. A pesquisa de campo instantânea, realizada durante as visitas da pesquisadora às residências, explorou a avaliação instantânea do ambiente térmico associada às variações de velocidade do ar provenientes da ventilação natural, culminando na satisfação ou insatisfação com a condição de movimento do ar ao final de 30-50 minutos de exposição ao ambiente naturalmente ventilado. A condição de deleite térmico foi definida considerando-se atividades sedentárias e roupas leves em ambientes residenciais situados em clima quente e úmido. A avaliação ótima dos residentes segundo esse critério correspondeu a velocidades do ar de pelo menos 0,4 m/s, experimentadas nos momentos de avaliação pontual, em condições de temperatura operativa de 27 a 30 °C. Mantendo-se tal limite mínimo, as flutuações de velocidade do ar não prejudicaram a sensação de agradabilidade relativa ao ambiente térmico. Ou seja, os participantes continuaram votando no lado positivo da escala de deleite térmico (levemente agradável, agradável e muito agradável) independente de aumento ou redução na velocidade do ar média, resultando na satisfação com o movimento do ar ao final da pesquisa instantânea. Para temperaturas operativas acima dos 30 °C, não foi verificada a influência da velocidade do ar sobre o deleite térmico dos participantes. Nessas condições, a utilização de ventiladores foi fundamental para manter a avaliação positiva de deleite térmico, uma vez que as velocidades do ar médias registradas nos ambientes naturalmente ventilados foram majoritariamente inferiores a 0,4 m/s.

Considerações Finais

As hipóteses estabelecidas neste estudo foram verificadas e confirmadas. Acerca da associação entre deleite térmico e variação temporal da velocidade do ar, verificou-se que as respostas mais positivas na escala de deleite térmico (ambiente agradável e muito agradável) estão associadas ao aumento da velocidade do ar em curtos intervalos (entre dois momentos de resposta consecutivos). Deve-se observar que o decréscimo da velocidade do ar entre intervalos não afetou a avaliação positiva de deleite térmico caso a velocidade do ar fosse superior a 0,4 m/s. Em relação à associação entre deleite térmico e satisfação com o movimento do ar, observou-se que a condição de deleite térmico levou à satisfação com o movimento do ar da ventilação natural, experimentado ao longo de um período de permanência prolongada. No que tange à adoção da ventilação natural e de estratégias complementares, as rotinas das famílias, as restrições econômicas e as condições ambientais de temperatura do ar interno e da velocidade do vento externo influenciaram a adoção de uma estratégia de condicionamento nas residências pesquisadas. Na faixa de renda mais alta, o uso e a preferência pelo ar-condicionado aumentaram, enquanto que o uso e a preferência pelo ventilador diminuíram. Os padrões de preferência e uso com relação a uma estratégia de condicionamento estiveram alinhados na pesquisa nacional e de campo, de modo que aqueles que preferem a ventilação natural em casa estão propensos a usá-la com mais frequência. Os resultados deste estudo indicam a importância do movimento do ar da ventilação natural para o conforto térmico das residências, especialmente em residências consideradas bem ventiladas pelos seus ocupantes. Essa relevância ocorre em meio à adoção já favorecida da ventilação natural no setor residencial brasileiro.

Palavras-chave: ventilação natural; fluxos de ar dinâmicos; conforto térmico; residências brasileiras; clima quente e úmido.

SUMMARY

1 INTRODUCTION

Air movement is one of the primary resources related to the human thermal balance due to the heat exchange between the human body and the surrounding environment following convection and evaporation (CÂNDIDO et al., 2010a). On the one hand, air movement tends to be uncomfortable and unpleasant when building occupants feel colder than thermally neutral (KABANSHI et al., 2019; MELIKOV et al., 2005) or have no control over local airflow (SCHIAVON et al., 2016b; ZHAI et al., 2017). On the other hand, air movement is generally welcome and pleasant when occupants feel warm or hot (CANDIDO; DEAR, 2012), thus being one of the leading passive or low-energy strategies to achieve thermal acceptability and comfort indoors.

The positive effect on thermal perception, resulting from increased air velocity beyond 0.8 m/s, is remarkable in hot and humid environments. Many studies have reported decreasing thermal sensations (towards neutrality) and increasing thermal acceptability and comfort due to the adoption of increased air movement (BUONOCORE et al., 2018; CÂNDIDO et al., 2010a; HUANG et al., 2013; ZHAI et al., 2017). Most investigations conducted since 2010 have aimed to define desirable, acceptable or required air velocity ranges to provide favourable thermal conditions for occupants in moderately warm or hot environments (CÂNDIDO et al., 2010a; HUANG et al., 2013; INDRAGANTI, 2010a; ZHANG; LIU; MENG, 2015).

Among the diversification of thermal comfort alternatives with minimum energy consumption, the approach to air movement indoors goes beyond the increment in mean air velocity and further considers the variability of air velocity in time. This approach to air movement comfort is presented in the literature as dynamic airflow. Dynamic airflows affect human thermal perception differently from constant airflows since the skin thermoreceptors receive stimuli of different proportions as the air velocity oscillates over time (DE DEAR, 2011; PARKINSON; DE DEAR, 2017). Dynamic airflows have an overall more significant impact on thermal perception under high indoor air temperatures (27-30 °C) experienced in chamber environments (CUI et al., 2013a; LUO et al., 2018; TIAN et al., 2019; ZHOU et al., 2006), compared to airflows with equivalent but constant mean air velocity (between 0.5 and 1 m/s).

From the dynamic airflow patterns assessed in the literature, those that simulate natural ventilation (true natural wind) were better evaluated regarding thermal sensation, preference and comfort than sinusoidal and intermittent patterns (ZHOU et al., 2006). The inherent characteristics of a breeze from natural ventilation are apparently more pleasant to humans due to their long-term history under natural ventilation and similar physiological frequency signs (GAO et al., 2022; KANG; SONG; SCHIAVON, 2013; OUYANG et al., 2006). However, the opportunities for natural ventilation in buildings are becoming increasingly restricted due to many factors. From the human thermal comfort perspective, the building code restrictions imposed on occupants, the climate unpredictability, the climate-change scenario and the rising occupants' expectations regarding the thermal environment may be highlighted as crucial challenges to adopting natural ventilation under warm-to-hot conditions.

At the same time, understanding the optimal thermal conditions for building occupants based on subjective assessment criteria is complex since they typically vary across seasons, locations, cultures and interpersonal differences (LIU et al., 2020; WANG et al., 2018b; XU et al., 2018). Furthermore, diverse ranges of thermal environmental conditions perceived as acceptable, neutral, preferred and comfortable within the same investigation have been reported in many studies (ANDRÉ et al., 2019; BUONOCORE et al., 2020c; FERIADI; WONG, 2004; SCHWEIKER et al., 2020b). More recently, a thermal delight assessment criterion has been adopted in the literature to measure a positive or negative perception of an environmental stimulus based on one's current physiological state (DE DEAR, 2011). This approach is based on alliesthesia, mainly addressed under contrasting air temperature conditions to elicit positive evaluations after facing a thermally uncomfortable condition (ARENS; ZHANG; HUIZENGA, 2006; PARKINSON; DE DEAR; CANDIDO, 2016; ZHANG et al., 2004). Nevertheless, thermal comfort studies have yet to address how air movement stimuli are evaluated under the thermal delight approach.

Two questions regarding air movement as a cooling strategy under warm-to-hot conditions arise in this context. The first refers to the optimal thermal conditions the strategy could provide based on pleasantness, in opposition to the acceptability (tolerance) achieved through its use. Increased air movement has been extensively adopted to mitigate occupants' thermal discomfort by heat when indoor temperatures exceed 28 °C. However, its cooling effect is commonly restricted beyond 32 °C, even if occupants can control the airflow around them (ZHOU et al., 2023a, 2023b). One of the drivers of this study is whether it would be possible to move from thermal acceptability to thermal delight following the dynamic characteristic of air movement from natural ventilation and under which thermal conditions.

The second question proposed is related to how long thermal delight evaluations can be maintained during occupants' exposure to the dynamic air movement from natural ventilation. From previous studies, the effect of an alliesthesia stimulus on physiological and subjective responses tends to be momentaneous as two minutes (PARKINSON; DE DEAR, 2017; PARKINSON; DE DEAR; CANDIDO, 2016) and associated with transitional conditions (ARENS; ZHANG; HUIZENGA, 2006), which means significant changes to indoor thermal variables in such short intervals. Nevertheless, supposing indoor temperature and humidity parameters are relatively stable hourly or daily. In that case, air velocity appears as a potentially time-dependent variable influencing the thermal delight assessment in naturally ventilated environments. The second driver of this study is whether it would be possible to achieve and maintain occupants' thermal delight for more extended occupancy and how the temporal variations in air velocity would be related to thermal delight.

The residential sector presents a valuable opportunity to assess the implications of dynamic airflows on occupants' thermal comfort, particularly thermal delight, in warm, naturally ventilated environments. Households are theoretically freer to adapt to the thermal environment at home compared to other building types, mainly by activity and clothing adjustments, window and curtain operations and the use of environmental controls. Natural ventilation, which can provide wind-driven airflows indoors, is already a default conditioning strategy in residences during summer (DANIEL, 2018; RAMOS et al., 2020a). Nevertheless, the cooling effect from air movement in residences has been mainly addressed as a fan-related adaptation, lacking an assessment of wind-driven airflow resources when available.

Despite the significant adoption of natural ventilation, households are susceptible to hot thermal discomfort in naturally ventilated dwellings mainly due to building characteristics and extreme climate events (BIENVENIDO-HUERTAS; SÁNCHEZ-GARCÍA; RUBIO-BELLIDO, 2020; INDRAGANTI, 2010b). Moreover, limited adaptive actions mainly related to economic constraints affect households' thermal comfort (MALIK et al., 2020; SOEBARTO; BENNETTS, 2014). The association between low income and poor energy performance driven by inappropriate constructive characteristics is the basis of the conceptualisation of energy poverty, an increasing concern at a global level (BIENVENIDO-

HUERTAS et al., 2022). Therefore, thermal comfort evaluations are essential in light of passive and low-energy strategies like natural ventilation in the Brazilian context.

Despite the influence of a natural breeze (wind-induced natural ventilation) on households' thermal comfort during summer conditions, some aspects concerning natural ventilation adoption at home should be deeply evaluated. The underlying reasons to keep homes naturally ventilated following the window-opening behaviour include thermal environmental, routine and economic-related aspects (LAI et al., 2018; MORI et al., 2020; YAO; ZHAO, 2017). However, the impact of outdoor wind parameters in adopting natural ventilation at home is underexplored in the literature that collected evidence from hot and humid climates, particularly when a local wind regime would favour its adoption. Furthermore, the rising residential air-conditioning ownership rates will likely affect how households choose among diverse conditioning strategies, including natural ventilation. Previous studies have shown how air-conditioning usage patterns relate to economic factors such as income and ownership (MORI et al., 2020; RAMOS et al., 2020a; SONG et al., 2018). Nevertheless, less attention has been paid to households' preferences under the perspective of natural ventilation adoption – the frequency of usage and the impact of economic factors.

This research addresses natural ventilation and thermal comfort in hot and humid climates under two general domains. The first refers to the impact of its dynamic aspects on households' thermal delight and satisfaction over a subjective evaluation interval; the second concerns the routine adoption of natural ventilation at home based on preferences and motivations. A hypothesis statement was proposed under the first domain (subsection 1.1), and the novelty aspects can be resumed as follows.

- Detailed airflow characterisation based on time-averaged air velocity in naturally ventilated environments;
- Analysis of successive subjective assessments in a point-in-time evaluation and its impact on overall satisfaction with air movement;
- Assessment of the environmental conditions needed to achieve and maintain thermal delight over the occupancy time in naturally ventilated environments.

1.1 HYPOTHESES STATEMENT

The following assumptions regarding the association between thermal delight and dynamic air movement from natural ventilation in a hot and humid climate were proposed.

- The most positive responses on the thermal delight scale are associated with increasing air velocity at short intervals.
- Thermal delight experienced over time in naturally ventilated environments leads to satisfaction with air movement at the end of an exposure time.

From the assumptions above, the researcher aims to understand whether achieving and maintaining optimal thermal conditions based on households' evaluation in naturally ventilated environments is possible. Furthermore, it is aimed to assess the dynamic air movement conditions based on air velocity corresponding to households' optimal thermal conditions.

1.2 RESEARCH AIMS

The thesis aims to evaluate households' thermal delight under the dynamic and non-uniform air movement from natural ventilation in residential living and resting environments in the Brazilian hot and humid climate.

The specific objectives of the thesis are listed as follows.

- To associate the point-in-time thermal delight and air movement assessments with the temporal variations in air velocity quantified in naturally ventilated environments;
- To report the indoor air temperature and air velocity conditions related to households' thermal delight in naturally ventilated environments;
- To compare households' thermal and air movement assessments under natural ventilation with and without fans and under air-conditioning climatisation;

- To depict the choice of a conditioning strategy at home based on the prevailing outdoor wind intensity and indoor and outdoor air temperatures;
- To investigate the association between family income, natural ventilation frequency of usage and preference for natural ventilation at home.

1.3 THESIS STRUCTURE

The thesis is structured into five chapters: Introduction (1), Literature Review (2), Research Methods (3), Results and Discussion (4), and Conclusion (5). The introduction section has presented the research gaps this study aims to address, the novelty and the objectives of the present study. The literature review was based on three main subsections. First, dynamic airflows in thermal comfort studies were assessed via a literature review article, from which the pertinent topics were highlighted in subsection 2.1. The subjective evaluation criteria adopted in thermal comfort studies were addressed in subsection 2.2. Subsection 2.3 summarises the findings from thermal comfort field studies conducted in the residential sector, emphasising air movement-related adaptations, methodological aspects of the studies, households' subjective evaluation and perspectives on adopting natural ventilation at home. Lastly, the final considerations on the literature review are presented in subsection 2.4.

The research methods are divided into two main subsections based on the study's scale. Subsection 3.1 describes the methodological procedures adopted in a national survey concerning natural ventilation in Brazilian residences. Subsection 3.2 addresses the methodological procedures adopted in a local field campaign conducted in São Luis, Brazil's Northeast. The results and discussions are presented in three subsections related to the methodological approaches. Subsection 4.1 follows 3.1 and presents the main findings of the national survey. Following the research methods presented in 3.2, the outcomes from the local campaign were divided into two: long-term monitoring of households' thermal comfort and chosen conditioning strategies (subsection 4.2) and a point-in-time survey on the dynamic aspects of air movement from natural ventilation (subsection 4.3). A conclusion chapter summarises all the findings, presents the limitations of the present study and gives insights into future studies.

Appendices A to H are presented following the abovementioned chapters. Appendix A contains the transcript of the literature review article. In contrast, appendices B to H complements the methods section by reporting a pilot study conducted before the field campaign, presenting the instruments of households' data collection and describing the instruments for physical measurements.

2 LITERATURE REVIEW

The literature review presented in this paper is structured into three main subsections. The first is related to the characterisation and evaluation of dynamic airflows in indoor thermal comfort research, emphasising the impact of such airflows on subjective thermal and air movement perception (section 2.1). The second concerns the subjective comfort assessment, particularly the criteria for evaluating the thermal conditions considered appropriate indoors (section 2.2). The third deals with natural ventilation for thermal comfort in residences (section 2.3), including (1) the primary adaptations to warm-to-hot thermal conditions through increased air movement, (2) the monitoring of environmental conditions and subjective assessment instruments, and (3) the perspectives for natural ventilation in the residential sector facing future challenges on a global scale.

2.1 DYNAMIC AIRFLOWS IN THERMAL COMFORT RESEARCH

This literature review subsection summarises the content published as a review article pertinent to this thesis. The review article topics related to the thesis are 3.2 THERMAL COMFORT EVALUATION (from dynamic airflows in controlled settings) and 4.2. TEMPORAL DIMENSION OF AIRFLOW CHARACTERISATION AND PERCEPTION. The full transcript of the publication is available in Appendix A.

- Title of article: From characterisation to evaluation: A review of dynamic and non-uniform airflows in thermal comfort studies (BUONOCORE et al., 2021).
- Authors: Carolina Buonocore, Renata De Vecchi, Roberto Lamberts and Saulo Güths.
- Published in: Building and Environment (ISSN: 0360-1323), Volume 206, December 2021, 108386.
- DOI (*Digital Object Identifier*): https://doi.org/10.1016/j.buildenv.2021.108386.

From experimental research in controlled environments, the thermal comfort evaluation (including thermal and air movement sensation, preference and acceptability criteria) is significantly affected by the dynamic characteristics of air movement under indoor air temperatures from 27 to 30 °C, standard summer clothing insulation and sedentary activity level (CUI et al., 2013a; LUO et al., 2018; TIAN et al., 2019; ZHOU et al., 2006). The dynamic airflow patterns that attempt to reproduce natural wind were more effective in improving the average thermal sensation and thermal comfort votes (CUI et al., 2013a; ZHOU et al., 2006) and were preferred by participants (LUO et al., 2018). In contrast, in most studies, the constant mechanical airflow patterns with equivalent mean air velocity could not perform as well as the dynamic ones (sinusoidal, intermittent and simulated natural) for thermal comfort purposes.

The natural wind characteristics include irregular distribution of air velocities (HUA et al., 2012; OUYANG et al., 2006) and changing intensity and direction over time (YU et al., 2022). However, spectral analyses of both natural and mechanical wind revealed that the main difference between them is the airflow energy distribution, which occurs in a low-frequency region in the natural wind (GAO et al., 2022; KANG; SONG; SCHIAVON, 2013; OUYANG et al., 2006). The authors emphasise a physiological background behind the preference for natural wind, which includes adaptability throughout human existence and similarities with spectral characteristics of the human body's physiological signals, such as blood pressure and heartbeat. Therefore, people tend to accept identical environmental conditions in a naturally ventilated environment more than in an air-conditioned or mechanically ventilated environment (OUYANG et al., 2006; ZHANG; ARENS; ZHAI, 2015a).

Despite the susceptibility of the indoor built environment to airflows from natural wind/ventilation, it is a challenge to address the airflow parameters due to temporal and spatial complexities. Air velocity is the primary variable representing air movement in space and time and is the most assessed in thermal comfort field studies. However, experimental studies with simulated airflows also addressed the turbulence intensity (Tu), fluctuation frequency and the negative slope of the double logarithmic power spectrum analysis curve (β value). In addition to air velocity, Tu is often assessed by adopting highly time-responsive anemometers (mainly hot-wire) in field studies. Thus, temporal variations in air velocity may be adequately represented following Tu: the lower values (<40%) are associated with more constant airflows and the higher values (>40%) with more fluctuating airflows (BUONOCORE et al., 2021).

Regarding subjects' assessment across time, it was observed that thermal perception might change rapidly due to air movement stimuli. At the same time, it is not always possible to record air velocity oscillations along a point-in-time survey in non-homogeneous environments. The subjective evaluation has been altered in the literature as a function of air movement at intervals ranging from 3 to 8 minutes (PARKINSON; DE DEAR, 2017; SCHIAVON et al., 2016a; ZHAI et al., 2019). Experimental evidence also showed that subjects could perceive even the fastest air speed fluctuations – 10 to 30 seconds – from dynamic airflow patterns (TAWACKOLIAN; LICHTNER; KRIEGEL, 2020; XIE et al., 2018).

These findings indicate that airspeed oscillations in time may be underestimated when an average air velocity value is assigned to a subjective assessment interval, which is usual in thermal comfort field studies. The maximum cooling airspeeds are usually limited in chamber experiments, and thus mean air velocities are also limited. The compiled data from the review paper indicated that mean air velocities across experiments and maximum airspeeds next to subjects were no greater than 1 and 1.5 m/s, respectively. In contrast, those values were significantly higher (2 and 3.5 m/s) in the field studies addressed in the review paper (BUONOCORE et al., 2021). Moreover, up to 5 and 7 m/s airspeeds were reported in multifamily housing and office environments from the ASHRAE II Global Database (FÖLDVÁRY LIČINA et al., 2018). Therefore, it is essential to account for shorter temporal variations when assigning air velocities to subjective perception responses under potentially higher airspeeds which can increase air velocity and induce a point-in-time evaluation.

Concerning the temporal dimension of dynamic airflow perception within the alliesthesia framework, previous studies suggested the air movement fluctuations as a driver of the thermal delight expressed by occupants in naturally ventilated buildings (DE DEAR, 2011; ZHANG; ARENS; ZHAI, 2015b). Two studies evaluated participants' thermal pleasantness related to air movement stimuli in the literature. The investigation conducted by Parkinson, de Dear and Cândido (2016) adopted a fan (constant airflow) during an upward ramping environment with an indoor temperature increase from 28 to 32 °C. In contrast, the study by Parkinson and de Dear (PARKINSON; DE DEAR, 2017) focused on the spatial alliesthesia – localised airflow stimulus – from dynamic airflow patterns. While a solid and momentaneous alliesthesial effect from the constant air movement was reported in the former, no significant effects from different airflow patterns on thermal pleasure were identified afterwards.

2.2 SUBJECTIVE ASSESSMENT CRITERIA IN THERMAL COMFORT STUDIES

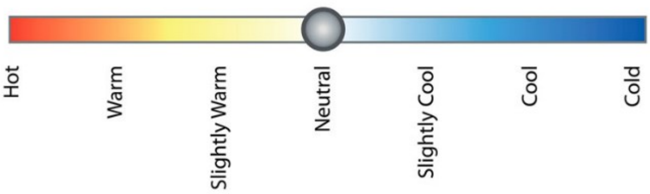
Thermal comfort research through subjective assessment criteria is one of the methods for studying the thermal environment, alongside objective physical measurements and performance simulation approaches. According to Wang et al. (2018a), subjective evaluation instruments involve binary questions (with two possible answers) and questions with response scales which can be multiple-point (also known as Likert scale) or visually graduated (continuous scales). In the literature, multiple-point and graduated scales are frequently employed in post-occupancy comfort assessment. Therefore, planning a subject survey entails defining the criteria that participants will evaluate besides the type of data collection instrument. A discussion on the main subjective evaluation criteria which are adopted in thermal comfort research is proposed in this subsection. Moreover, the appropriate indoor thermal conditions related to the criteria are discussed based on the available literature.

2.2.1 Thermal neutrality and neutral thermal sensation

ASHRAE 55 Standard defines thermal comfort as “the state of mind that expresses satisfaction with the thermal environment” (ASHRAE, 2020a). From such a point of view, the definitions of comfort and satisfaction are approximated. By convention, people who feel slightly cold (-1), neutral (0) or slightly hot (+1) on the seven-point thermal sensation scale set out in the standard (Figure 1) are considered thermally comfortable in a point-in-time comfort survey. However, the statement is arguable as sensation should refer to the detection of thermal stimuli, which differs from how people interpret such stimuli – their perception (DE DEAR, 2011). The studies conducted by Schweiker et al. on the assumptions for thermal sensation scales concluded that sensations are not judged as equidistant, resulting in different sensations regarded as “comfortable” and a non-linear relationship between indoor temperature and subjective sensation (SCHWEIKER et al., 2019, 2016). The findings also affect the common sense of neutral indoor temperatures, which usually result from linear regressions between thermal sensation and temperature.

Moreover, evidence collected in field surveys indicated that the proportion of perceived discomfort in each thermal sensation vote is not necessarily symmetrical around the neutral sensation vote (BUONOCORE et al., 2020c; SCHWEIKER et al., 2020a). Thus, thermal discomfort rates may increase or decrease depending on certain factors. As an example, the seasonal variations which are typical of winter and summer in high latitude locations lead to overall dissatisfaction with the thermal sensations of “slightly cold” and “slightly hot”, in that order, and enhance the preference for being warmer and colder, respectively (LU et al., 2018; MISHRA; RAMGOPAL, 2014; NEMATCHOUA; TCHINDA; OROSA, 2014). Therefore, neutral and slightly cool thermal sensations are deemed the most comfortable and preferred by inhabitants from hot and humid climates (BUONOCORE et al., 2020a; FERIADI; WONG, 2004; MALIK; BARDHAN, 2021; XU et al., 2018).

Figure 1 – ASHRAE seven-point thermal sensation scale



Source: Parkinson, de Dear and Cândido (2016)

The dissatisfaction with specific thermal sensation responses was disclosed based on a set of questions in the subjective survey. The survey may include a direct question about comfort status on the Likert scale (from “very dissatisfied” to “very satisfied”) or a binary question (“Are you comfortable or uncomfortable at the moment?”) in addition to the ASHRAE seven-point thermal sensation scale. Thus, it is usual to include more than one evaluation criterion in the survey to cross-analyse – despite the longer response time devoted by the participants. Post-occupancy evaluations often include thermal preference and perception of air humidity and air movement scales (DE DEAR; BRAGER; COOPER, 1997). Therefore, questions arise regarding which criteria would be more assertive about capturing the optimal thermal comfort condition in a subjective survey.

2.2.2 Acceptability and preference criteria

Besides the questions on comfort/satisfaction, acceptability is a criterion addressed in several subjective studies. Apart from the thermal sensation scale, ASHRAE 55 Standard states that comfort may be inferred based on a seven-point acceptability scale, in which "neutral" (0) to "very acceptable" (+3) responses are assigned as comfortable. However, a straightforward acceptability assessment ("acceptable" and "unacceptable" binary responses) is also adopted in thermal comfort studies. It was concluded that acceptability could be interpreted as a condition of tolerance to the thermal environment, probably far from the respondents' comfortable and preferred conditions. Therefore, acceptable indoor conditions were more critical than comfortable ones. In a hot and humid environment, it means notably higher indoor temperatures corresponding to acceptable ones (BUONOCORE et al., 2020b; MISHRA; RAMGOPAL, 2015).

The distancing between acceptability and comfort is mainly due to the low expectations regarding the thermal environment often experienced in these people's daily lives. Malik et al. (2020) cited an "unavoidable acceptance" of thermal heat conditions in low-cost housing linked to the residents' inability to pay for the operation of a climate control system. Some authors also cite acclimatisation to environmental conditions such as high humidity (HOSSAIN et al., 2019) or extreme cold and heat (YAN; MAO; YANG, 2017; YAO; LIU; LI, 2010) as a reason for high acceptance rates. Another approach discussed concerning acceptability is the influence of knowledge about "green" or low-energy buildings, in which occupants tend to better tolerate adverse conditions (identified as forgiveness factor in the literature) due to greater environmental awareness (BROWN; COLE, 2009; DEUBLE; DE DEAR, 2012).

On the one hand, acceptability is a criterion used to delineate the limits of conditions regarding the thermal environment (minimum and maximum acceptable operating temperatures). On the other hand, the neutral thermal sensation indicates an average condition corresponding to the neutral thermal sensation vote (0) on the seven-point scale. For instance, the neutral internal temperature is commonly referenced in field studies (see Table 1 in subsection 2.3.2.2). However, there is evidence of distance between neutrality and preference for a particular thermal condition (INDRAGANTI, 2010c; MALIK; BARDHAN, 2021). Analogously, the preference for being colder or warmer indoors may be expressive even among neutral thermal sensation votes (KUMAR et al., 2016a; MISHRA; RAMGOPAL, 2014). The outcome aligns with the assertion that being thermally neutral does not necessarily imply being in comfort (DANIEL; WILLIAMSON; SOEBARTO, 2016). In this sense, the preference criterion seems more incisive regarding the desired thermal conditions or those that meet the occupants' expectations in buildings.

The study conducted by Daniel, Williamson and Soebarto (2016) in Australian low-energy residences presented a model of thermal comfort based on the thermal preference criterion. The authors argue that residents did not necessarily want to feel neutral concerning the thermal environment. Moreover, preference could indicate people's tendency to act in order to change the environment. In the same line of reasoning, Kim et al. (2018) adopted preference as a criterion for assessing comfort in air-conditioned office buildings in which occupants had access to customised systems. Preference can also be addressed concerning air movement, which is particularly common in environments where occupants are susceptible to heat discomfort. Similar to the relationship between neutrality and thermal preference, the environmental condition related to the preference for "no change" in air movement differs from the "acceptable" air movement condition in some studies (BUONOCORE et al., 2018; DANG; PITTS, 2021).

2.2.3 Thermal delight

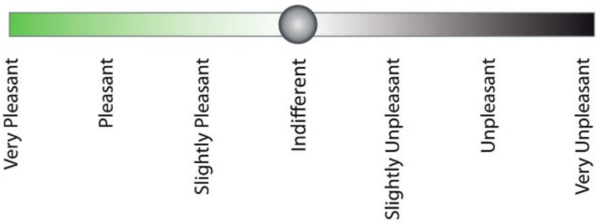
Thermal delight or pleasantness is a more recent approach to human thermal comfort in buildings. The discussion on thermal delight is initially related to the scope of non-steady indoor environmental conditions, where occupants may respond positively or negatively regarding their point-in-time perception of the dynamic thermal environment. Nevertheless, the subjects' overall thermoregulatory state is crucial to their physiological and subjective responses when experiencing diverse environmental conditions (PARKINSON; DE DEAR, 2015b). Thus, when the body is far from neutrality and receives a stimulus in the opposite direction (cooling, in case of a warm environment) to "correct" the initial thermoregulatory status, a positive feeling of pleasantness is expected — the alliesthesia background proposed by Cabanac (1971).

According to de Dear (2011), the result of this type of stimulus is perceived as thermal delight (CANDIDO; DEAR, 2012) and differs from neutrality and acceptability.

Unlike neutrality, which reflects a static thermal condition, the sensation of thermal delight is dynamic, resulting from a stimulus that decays over time and becomes indifferent to human perception (guided by cutaneous thermoreceptors). Moreover, the sensation of thermal delight is unique to each individual, as it depends not only on the intensity of the stimulus (e.g., increase in air velocity) opposed to the body's thermal balance state but also on the body's thermal balance itself - whether closer or further away from neutrality (DE DEAR, 2011).

In a series of studies on thermal perception (whole-body and local body parts) in transient and non-uniform environments developed by Arens, Zhang and Huizenga (ARENS; ZHANG; HUIZENGA, 2006; ZHANG et al., 2010), "very comfortable" votes were reported only when the local stimulus (a localised colder air jet) relieved the whole-body thermal stress (asymmetric environments). The authors reported that neutral thermal sensation was perceived only as "comfortable" by participants, not "very comfortable". Based on the findings, it was asked whether an initial condition of extreme discomfort was necessary for the corrective stimulus to be effective according to the alliesthesial approach (e.g., is heat discomfort a precondition for a breeze to be considered pleasant?)

Figure 2 – Seven-point thermal pleasure scale adopted in the literature



Source: Parkinson, de Dear and Cândido (2016)

Subsequently, further studies on human perception were conducted to study the alliesthesia under spatial and temporal thermal asymmetries (PARKINSON; DE DEAR, 2017; PARKINSON et al., 2021; PARKINSON; DE DEAR; CANDIDO, 2016). A thermal delight seven-point scale was adopted – from "very pleasant" (+3), through "indifferent" (0), to "very unpleasant" (-3) feelings, as illustrated in Figure 2. Combined physiological core temperature measurements and subjective evaluations have shown that thermal delight is also achievable in a close-to-neutral thermoregulatory zone (PARKINSON; DE DEAR;

CANDIDO, 2016), dismissing the thermal discomfort precondition to feeling thermally delighted.

Parkinson and de Dear (2017) referred to thermal pleasure as the qualitative component of subjective thermal perception, in opposition to thermal sensation (quantitative component). According to Schweiker et al. (SCHWEIKER et al., 2020b), thermal pleasantness evaluation expresses affective positive and negative feelings regarding environmental conditions. Thus, thermal comfort assumptions based on pleasantness and sensation are diverse. Their study goes beyond the notion of punctual, temporary thermal stimuli (temporal and spatial alliesthesia) by proposing a seasonal alliesthesia framework in which thermal pleasantness rates increase following long-term seasonal experiences – transitioning between summer and winter conditions. Moreover, a discrepancy between the optimal thermal conditions defined based on thermal pleasantness, sensation and straightforward thermal comfort assessment ("comfortable" or "uncomfortable" responses) was reported. Optimal thermal conditions defined based on thermal pleasantness were the widest, which calls attention to how mutable those conditions can be due to personalised demands and dynamic environmental stimuli.

2.2.4 Air movement evaluation

The air movement evaluation outside the scope of draught is particularly relevant in thermal comfort studies conducted under warm-to-hot thermal conditions (indoor temperatures above 27 °C). Such studies commonly adopt air movement sensation, acceptability, and preference assessments as evaluation criteria, similar to the thermal environment. Additionally, a summary of subjective criteria for air movement evaluation in thermal comfort studies is presented in Table 4 of Appendix A (literature review article transcript).

When analysing subjective feedback in such studies, combining thermal and air movement evaluation is a usual approach. On the one hand, there is evidence of independency between thermal and air movement assessments reported by participants, which means they can distinguish the air movement condition regardless of the thermal environment. The desire for increased air movement indoors was also reported by subjects voting on the cool side of the thermal sensation scale (MISHRA; RAMGOPAL, 2014; ZHANG et al., 2007). On the other hand, the impact of the thermal environment on air movement evaluation is solid in the literature. Thus, the hotter and more humid the environment, the worse the air movement evaluation – lower acceptability and higher desire for more air movement – under similar air velocity (DANG; PITTS, 2021; YAN et al., 2020; ZHOU et al., 2023a).

Cândido reported a combined thermal and air movement acceptability assessment in Brazil's Northeast, where minimal air velocity values required by occupants of naturally ventilated classrooms were established based on operative temperature (CÂNDIDO et al., 2010a; CÂNDIDO; DE DEAR; LAMBERTS, 2011). There is a limit to the cooling effect of increased air movement – airspeeds can no longer improve the overall subjective evaluation, even if occupants have control over air movement. The limit is related to indoor air temperatures around 32 °C in many studies (PARKINSON; DE DEAR; CANDIDO, 2016; ZHANG; ARENS; ZHAI, 2015b; ZHOU et al., 2023a, 2023b). Therefore, air movement acceptability rates and preference for more air movement get stable across increasing airspeed levels under such high indoor temperatures (BUONOCORE et al., 2018; YAN et al., 2020).

2.3 THERMAL COMFORT AND NATURAL VENTILATION IN RESIDENCES

Within the scope of thermal comfort research, residential environments are mainly investigated under the adaptive approach. The residential sector offers more adaptative alternatives to the indoor thermal environment than the commercial building sector (KIM et al., 2017; RYU et al., 2019). Occupants of office buildings face more restrictions related to dress codes, everyday activities, and access to thermal environment control devices. However, many studies have highlighted the constraints on households' thermal comfort and adaptive actions at home, mainly related to the economic aspect (BIENVENIDO-HUERTAS; SÁNCHEZ-GARCÍA; RUBIO-BELLIDO, 2020; INDRAGANTI, 2010c; MALIK et al., 2020; SONG et al., 2018). The quantity and quality of possible adaptative actions were widely evaluated in residences along with the residents' perspective on their thermal comfort (INDRAGANTI, 2010c; MALIK; BARDHAN, 2021; SOEBARTO; BENNETTS, 2014). Adaptive actions at home take place in several dimensions, including economic, socio-cultural and contextual (particularities of buildings and their surroundings).

This research addresses the adaptive actions involving airflows in the residential sector, such as operating windows, fans or air conditioning equipment when available.

Window operation connects indoor and outdoor environments, allowing natural ventilation. The adoption of fans increases air movement indoors and thus helps improve thermal conditions under natural ventilation. Air conditioning for cooling sets a more drastic change in the indoor environment, lowering air temperature and relative humidity. The abovementioned adaptations and motivations behind their use are addressed in the following subsection.

2.3.1 Air-movement-related adaptations

The operation of windows and doors (opening and closing) is one of the most studied behaviours in residential buildings due to its relationship with thermal comfort and performance (CARPINO; MORA; DE SIMONE, 2019). Many studies have depicted window-opening patterns driven by thermal environmental variables, mainly temperature parameters. The outdoor air temperature was the main driver for opening or closing windows at home. A well-defined pattern as a function of outdoor air temperature was presented for Sydney, Australia (KIM et al., 2017). The peak proportion of windows open occurred at around 25 °C, decaying towards higher or lower outdoor air temperatures in their study. The outdoor air temperature was strongly correlated to window opening in other investigations conducted in China (LAI et al., 2018; YAO; ZHAO, 2017).

In contrast, indoor globe temperature was the most relevant environmental parameter to describe window opening behaviour in the study conducted by Indraganti (INDRAGANTI, 2010b) in Indian apartments. The indoor air temperature was highlighted in the investigations conducted by Daniel (2018) in Australia and Rijal (2014) in Japan. The higher the indoor air temperature, the higher the proportion of open windows, getting stable around 80% for temperatures above 30 °C. The impact of temperature parameters may also be related to climate characteristics. A higher thermal amplitude could lead to more control over the windows, as Ramos et al. (2020b) suggested. In contrast, window operation could be less driven by temperature under lower thermal amplitudes from tropical regions.

Malik et al. (2020) reported that indoor relative humidity was the physical variable most associated with the proportion of windows and doors open in India. However, outdoor air and indoor globe temperatures could also be adopted as descriptors based on their study. Along with temperature and humidity parameters, Yao and Zhao (2017) addressed the influence of outdoor wind speed and direction on window-opening behaviour in residences in Beijing. Wind direction was insignificant in their study, whereas wind speed presented the most negligible influence among the significant influential factors.

Apart from the influence of thermal environmental variables, there is evidence of other determinant factors impacting window operation. Lai et at. (2018) reported a schedule and season-dependent operation in which the length of time for open windows was shorter in winter than in summer despite similar outdoor air temperatures. Daniel (2018) highlighted a significant proportion of windows open in naturally ventilated dwellings regardless of indoor air temperature. The author argues that residents do not perceive window opening as an adaptation but rather as a standard condition in dwellings planned to be naturally ventilated. The proportion of natural ventilation usage was not significantly altered by season in his study.

Aware of influential variables other than environmental ones, Mori et al. (2020) studied the influence of contextual factors and household attributes on window opening patterns in tropical cities of Malaysia and Indonesia. The authors showed the influence of income on window opening patterns after the preliminary study by Song et al. (2018) depicted the relationship between income and air-conditioning usage decisions. Mori et al. (2020) also reported a nighttime window-closing pattern, mainly among air-conditioning owners, and a short theoretical time of open windows as income increases, based on odds ratio analysis.

Besides bringing in natural ventilation, opening windows implies diverse intersections with the outdoors that may be desirable or needed but also undesirable. The research conducted by Ramos (2020) in Brazilian homes recently indicated that operating windows is standard behaviour and that 93% of respondents open their windows to obtain natural ventilation. Moreover, this behaviour was motivated by other factors, such as air renewal and the entrance of natural light (RAMOS, 2020). Most residents of social dwellings in the coastal zones of Southern Spain declared to open windows for multiple reasons at once: air quality, avoiding moisture and thermal comfort (BIENVENIDO-HUERTAS; SÁNCHEZ-GARCÍA; RUBIO-BELLIDO, 2020). Regarding closing windows in predominantly hot and humid regions, concerns with external factors such as climate change, insects, security and privacy are among the main reasons cited (INDRAGANTI, 2010b; MALIK et al., 2020; MORI et al., 2020; RAMOS, 2020).

The decision to open windows and doors is expected to be related to cross-ventilation (comfort ventilation) in warmer and more humid climates. However, little is known about the role of increased air movement among the primary motivations for operating windows and doors. In many studies, increased air movement is commonly related to turning on fans as adaptive action (DANIEL, 2018; INDRAGANTI, 2010c; MALIK; BARDHAN, 2021; SOEBARTO; BENNETTS, 2014). Households will likely not perceive the breeze from outdoors since airspeeds collected in naturally ventilated environments are generally negligible (less than 0.2 m/s) in hot and humid climates (DANG; PITTS, 2021; DE DEAR; LEOW; FOO, 1991; TOE; KUBOTA, 2015). Rijal (2014) argued that increasing air movement is one reason for opening windows at home during summer in the Kanto region of Japan. Nevertheless, this motivation was not directly assessed by households during his study.

In addition to operating windows, adopting fans is a fundamental adaptation in Brazil, India, China and Australia. Operating fans is directly related to increased air circulation and speed. It often complements the comfort ventilation from natural ventilation in the occupied room zones when the latter is insufficient to provide a cooling effect over the body. Both actions (opening windows and turning on fans) were the most chosen during the hottest periods of the year in many studies (INDRAGANTI, 2010c; RAMOS et al., 2020b; RIJAL, 2014; SOEBARTO; BENNETTS, 2014), particularly in the absence of an artificial climatisation system. Moreover, resorting to fans as a cooling strategy is not only climate-dependent and varies across individual habits, preferences and economic affordability.

Increased air movement is a significant demand in India, where indoor temperatures easily reach 35 °C (JAYASREE; JINSHAH; SRINIVAS, 2021; THAPA et al., 2020). A thermal comfort and occupant behaviour survey conducted in social housing reported a higher tendency to operate fans among all available adaptive actions (MALIK et al., 2020), which is in line with the general scenario in the country: controlling air velocity around the body (MALIK; BARDHAN, 2021). Concomitantly, households need to deal with power shortages and high operating costs in most residences, as noted by Indraganti (2010c) and Malik et al. (2020) in field studies conducted in the cities of Hyderabad and Mumbai. Soebarto and Bennets (2014) reported economic concerns among occupants of low to middle-income housing in South Australia as they deliberately resorted to air-conditioning the least as possible during summer. Turning on fans was the most chosen action in their study – more than operating windows and doors.

In hot and humid regions of countries such as Malaysia, Indonesia and Bangladesh, the fan adoption rate in residential surveys is 90% or more (ISLAM; AHMED, 2021; MORI et al., 2020). In Brazil, the overall percentage of fan use was around 65%, increasing as the climate gets hotter and more humid within the national territory (RAMOS, 2020). High adherence to fans (in use for approximately 50% of the occupancy time) was reported in naturally ventilated homes in Darwin, Australia (DANIEL, 2018). In contrast, a significant choice for opening windows (frequency of 39.5%) and a minor activation of fans (12.6%) and air conditioning (13.6%) was observed in homes with at least one air conditioning system in Sydney, Australia (KIM et al., 2017).

Resorting to a climatisation strategy to deal with hot and humid conditions indoors is associated with the current and typical seasonal thermal environment and the economic background (family income employed as a parameter). Nevertheless, other influencing factors arise in the literature. In many studies, the households' primary choice was natural ventilation, even under various temperatures and across diverse income levels. Daniel (2018) highlighted the consistent choice of natural ventilation associated with a high awareness of low-energy homes where participants live since some building improvements were related to increased air circulation from natural ventilation. Similarly, a higher comfort perception was reported in low-energy dwellings compared to 'standard-performance' air-conditioned dwellings in Victoria, Australia (MOORE et al., 2016).

High awareness of natural ventilation as a conditioning strategy was also reported in social dwellings in Spain (BIENVENIDO-HUERTAS; SÁNCHEZ-GARCÍA; RUBIO-BELLIDO, 2020). However, the authors argue that households' habits and daily rules (such as leaving home) are determinants of their minor perception of thermal discomfort under natural ventilation. Based on Ramos et al.'s (2020b) study in Brazilian residences, natural ventilation seems routine related to households' habit of opening windows. When asked about their preference at home, 89% declared to prefer naturally ventilated environments. Their preference also impacted their behaviour since those who prefer natural ventilation were more prone to operate windows and fans. In contrast, those who prefer air-conditioning resorted to it more frequently.

2.3.2 Thermal environmental monitoring and subjective evaluation

2.3.2.1 Instrumentation

Among the residential thermal comfort and occupant behaviour surveys, there is a predominance of long-term monitoring for months or even years. The primary approach involves thermal environmental monitoring with measuring instrumentation, which may occur concomitantly to point-in-time subjective evaluations (CARPINO; MORA; DE SIMONE, 2019). Households are usually interviewed before monitoring to characterise the residence (building construction features, climatisation systems available) and collect personal information, routines and adaptive actions at home.

The researcher's intrusiveness is one of the main concerns regarding participant field surveys, particularly in the residential sector, where keeping households' privacy is essential to obtain veridic and reliable information. Therefore, advances in two domains must be pointed out as possibilities for ensuring physical distance between the researcher and the participants for a long time without losing contact. The first is environmental monitoring, with the adoption of autonomous data-logging devices. The second is data collection, moving from in-person to online instruments.

Autonomous data-logging devices favoured non-intrusiveness due to smaller sensors that are portable and capable of monitoring for more extended periods. These are mainly HOBOs (DANIEL, 2018; ISLAM; AHMED, 2021; SÁNCHEZ-GARCÍA et al., 2018; TADEPALLI et al., 2021) and iButtons (KIM et al., 2017; RAMOS, 2020; SOEBARTO; BENNETTS, 2014; SONG et al., 2018). The thermal environmental variables monitored by those devices are mainly the indoor air temperature and the relative humidity. Air velocity measurements are presented in a few studies (DANG; PITTS, 2021; INDRAGANTI, 2010c; MALIK et al., 2020) and still require a more significant effort from the researcher to be taken. Therefore, air velocity measurements in the residential sector are restricted to the researcher's visit – and associated with the point-in-time subjective evaluation conducted by the researcher. Moreover, air velocity measurements are mainly addressed under a more significant possibility of increased air movement due to fan operation. Recently, the spatial mapping of air velocity by ceiling fans has been conducted in living rooms and bedrooms with different furniture layouts and openings configurations (JAYASREE; JINSHAH; SRINIVAS, 2021; TADEPALLI et al., 2021).

Long-term monitoring requires commitment and dedication from respondents throughout the survey period (MALIK; BARDHAN, 2021). The online questionnaire arises as an essential tool to reach an influential audience relatively cheaply despite the susceptibility to subjectivity and uncertainties during the completion (BALVEDI et al., 2018; RAMOS, 2020). According to Carpino, Mora and De Simone (2019), online questionnaire response rates may be increased when face-to-face interviews are conducted before long-term monitoring. Respondents' attention may be required at shorter intervals for in-person data collection. Ryu et al. (2019) studied the temporal dimension of adaptive thermal comfort mechanisms in residential buildings in South Korea. The instantaneous approach of the study demanded the collection of subjective feedback every five minutes. In any case, informing the respondents of such implications and obtaining their consent to participate is essential.

2.3.2.2 Subjective evaluation

Table 1 summarises the temperatures considered within the limits of acceptability or comfort by households in studies of thermal comfort and adaptive behaviour. Residents could undertake many adaptive actions to face the thermal environmental conditions per the relatively high mean and maximum temperatures observed. However, limitations to air conditioning usage (mainly unaffordability) were reported in some studies. When monitored, indoor air velocity was not correlated to acceptable or comfortable temperature conditions. Nevertheless, its influence on subjective evaluation was implicit since fans were commonly adopted. Some studies have addressed the influence of relative humidity on thermal comfort and actions. Rijal (2014) observed a linear relationship between the wet skin sensation expressed by residents and the deduced comfort temperature: the more intense the sensation, the lower the comfort temperature. Daniel (2018) observed that air conditioning activation was more related to the indoor relative humidity condition than the indoor air temperature – the higher the humidity, the higher the activation rate.

Table 1 – Acceptable/comfortable temperatures under natural ventilation at home during the warm season

Study information		Mean temperature condition		Maximum temperature condition	
Author(s)	City/Country	Variable	Criterion	Variable	Criterion
Indraganti (2010c)	Hyderabad, India	Neutral indoor temperature = 29.2 °C	Corresponds to the neutral thermal sensation vote (0)	Upper limit of comfort range = 32.5 °C	Corresponds to the thermal sensation vote slightly warm (+1)
Malik and Bardhan (2021)	Mumbai, India	Neutral indoor temperature = 28.3 °C	Corresponds to the neutral thermal sensation vote (0)	Upper limit of the acceptability range = 32.2 °C	80% acceptability - thermal sensation slightly warm (+1)
Rijal (2014)	Kanto, Japan	Indoor comfort temperature = 27.6 °C	Corresponds to the neutral thermal sensation vote (0)	Upper limit of comfort range = 30 °C	80% comfort
Kim et al. (2017)	Sydney, Australia	Optimum external temperature = 25 °C	Corresponds to the maximum use of open windows	Maximum outdoor temperature = 32 °C	Corresponds to approximately 50% of open windows
Song et al. (2018)	Tianjin, China	Neutral indoor temperature = 24.7 °C	Corresponds to the mean neutral thermal sensation vote	The upper limit for thermal acceptability = 27.3 °C	Upper indoor temperature limit corresponding to 80% thermal acceptability
Daniel (2018)	Darwin, Australia	Indoor comfort temperature = 27.9 °C	Not reported	-	-
Xu et al. (2018)	Nanjing, China	Neutral indoor temperature = 28 °C	Corresponds to the neutral thermal sensation vote (0)	Upper limit of the acceptability range = 30.1 °C	80% acceptability
Ryu et al. (2019)	South Korea	Comfort base temperature = 27.1–27.9 °C	Corresponds to the neutral thermal sensation vote (0)	-	-
Adaji et al. (2019)	Abuja, Nigeria	Neutral indoor temperatures ranging from 28–30.4 °C	Corresponds to the mean neutral thermal sensation vote	-	-
De Dear, Leow and Foo (1991)	Singapore	Neutral indoor operative temperature = 28.5 °C	Corresponds to the neutral thermal sensation vote (0)	-	-
Soebarto and Bennets (2014)	Adelaide, Australia	Neutral indoor temperatures ranging from 20.6–26.2°C	Corresponds to the neutral thermal sensation vote (0)	Indoor air temperature = 28 °C	Upper limit for thermal comfort
Dang and Pitts (2021)	Ho Chi Minh, Vietnam	-	-	Average indoor air temperature between 29.3–31.1°C.	Acceptability range

Source: elaborated by the author based on the literature review

There is a distinction between the mean and maximum temperature conditions observed in naturally ventilated homes (or homes where households have some restriction to air-conditioning) and mixed-mode residences with no apparent limitations to air-conditioning usage. In the latter case, neutral temperatures reported are usually below 28 °C. Accordingly, in many studies, the indoor temperature corresponding to air-conditioning activation was between 27-28 °C (DE DEAR; KIM; PARKINSON, 2018; RYU et al., 2019; SONG et al., 2018). In contrast, neutral and maximum acceptable temperatures following each study's criteria were above 28 °C and could reach 32 °C in naturally ventilated rooms. The situations Daniel (2018) and Xu et al. (2018) reported were exceptions due to the specific contexts related to low-energy and traditional old dwellings, respectively.

Concerning the thermal sensation votes, households often felt neutral at home. Nevertheless, the sum of slightly warm, warm and hot thermal sensation rates surpasses the neutral vote rate in many of those studies (DANG; PITTS, 2021; DE DEAR; LEOW; FOO, 1991; MALIK; BARDHAN, 2021; SOEBARTO; BENNETTS, 2014), indicating how susceptible to thermal discomfort by heat households can be if their adaptive capacity is limited in any dimension or their homes do not respond adequately to the outdoor thermal conditions.

2.3.3 Perspectives on natural ventilation adoption

One of the main challenges regarding building design and operation in warm-to-hot climates is the growing demand for air conditioning cooling in homes. This issue is cited as a long-term concern in Southeast Asian countries (MALIK et al., 2020; MORI et al., 2020; TOE; KUBOTA, 2015), in Australia (KIM et al., 2017) and in Brazil (RAMOS, 2020). Most countries facing such demand are emerging economies, and a considerable portion of their population is potentially growing in size and purchasing power (IEA, 2022; PAVANELLO et al., 2021). Concomitantly, there is a need to deal with a poorly efficient built stock in terms of thermal and energy performance. Adding this factor to the rising expectations and search for increasingly cold environments (DE VECCHI; CÂNDIDO; LAMBERTS, 2012), the global challenge involves building resilience, cooling energy consumption and greenhouse gas emissions. Kim et al. (KIM et al., 2017) cite "mutable" expectations regarding thermal comfort when referring to the increasing use of air conditioning in homes.

The association between various adaptation measures and the income factor is notorious in the literature. Such associations may directly impact air movement (from natural ventilation included) for thermal comfort. Following the latest National Electrical Appliances Possession and Usage Habits Research for the Residential Sector, Ramos (2020) reported a proportional relationship between family income and air conditioning ownership in Brazil, particularly in the hottest climates (PROCEL, 2019). The volume of adaptations (mainly low-energy ones) tends to be inversely proportional to households' purchasing power or income (INDRAGANTI, 2010c; RINALDI; SCHWEIKER; IANNONE, 2018). Therefore, the increasing ownership and more extended use of artificial climatisation systems following patterns or habits potentially lead to a preference for resorting to them more frequently.

Moreover, the climate change scenario challenges natural ventilation in buildings, given the more extreme outdoor thermal conditions and the occupants' reliance on active strategies for cooling. Energy poverty among the low-income population (PORRAS-SALAZAR et al., 2020) and frequent power outages (INDRAGANTI, 2010c) are crucial issues affecting some adaptative alternatives under natural ventilation. Furthermore, future climate scenarios are pessimist concerning the effectiveness of bioclimatic strategies such as natural ventilation in severe hot climates (BIENVENIDO-HUERTAS et al., 2022; SÁNCHEZ-GARCÍA et al., 2018). The occurrence of adverse climatic events associated with the difficulty of part of the population to pay for fuels and energy could even put human survival at risk (BIENVENIDO-HUERTAS; SÁNCHEZ-GARCÍA; RUBIO-BELLIDO, 2020). Therefore, designing buildings more responsive to local environmental conditions is urgent, along with national and global policies, to deal with the potential cooling addiction and mitigate the overall impact of human activities on the planet.

2.4 FINAL CONSIDERATIONS ON THE LITERATURE REVIEW

The final considerations and arising research questions from the literature review are summarised as follows.

- Whilst thermal sensation and comfort were the primary evaluation criteria for dynamic airflows in controlled environments, thermal delight is a relevant criterion to assess the tone (positiveness or negativeness) of environmental stimuli such as air movement fluctuations. In assessing thermal delight driven by diverse environmental stimuli, it must be highlighted that most alliesthesia studies were conducted under temperature ramps. However, very few focused on the dynamic characteristic of air movement, and none occurred in naturally ventilated environments, which are susceptible to such fluctuations. Does the increase in air velocity from natural ventilation relate to thermal pleasantness? If so, under which environmental conditions of air temperature and velocity?

- Apart from moving from optimal environmental conditions based on thermal sensation and acceptability to those based on thermal delight, the temporal dimension of thermal delight driven by dynamic air movement must be considered beyond a punctual assessment in thermal comfort studies. In other words, is it possible to feel satisfied with the air movement condition after an exposure time longer than in a single point-in-time evaluation? Is thermal pleasantness related to satisfaction with the air movement condition?
- The residential window-opening behaviour, allowing natural ventilation, is mainly driven by indoor and outdoor thermal environmental conditions, routines and economic factors. However, increased air movement from natural ventilation (a perceptible breeze) as a background for suitable indoor thermal conditions in hot and humid climates is underexplored in the literature. Do households from such locations perceive this air movement source? Apart from temperature parameters, does outdoor wind influence whether households resort to natural ventilation as a conditioning strategy in their home routine?
- The imminent increase in residential air-conditioning in hot climates such as Brazil potentially challenges the currently predominant passive natural conditioning on a long-term basis. The preference for air-conditioning as a cooling strategy in Brazilian homes is crucial to resort to it on a routine basis – personal preference leads to various adaptive actions. Nevertheless, more insights on this issue would be desirable to depict better the natural ventilation preference and routine backgrounds, particularly regarding economic indicators. Therefore, the association of natural ventilation preference with family income and energy-saving concerns should be evaluated.

3 RESEARCH METHODS

The research addressed natural ventilation and thermal comfort via two main approaches. An online survey spread nationally assessed the adoption of natural ventilation at home based on households' preferences and motivations (section 3.1). The impact of dynamic airflows from natural ventilation on households' thermal delight and satisfaction was evaluated in a field study conducted locally in São Luis, a hot and humid city in Brazil's Northeast (section 3.2).

The field study (field campaign) comprised point-in-time surveys and long-term monitoring in the residences, as depicted in Table 2. Point-in-time surveys assessed the impact of measured air velocities on households' thermal and air movement perceptions. The households' subjective evaluations, chosen conditioning strategies, and underlying reasons for resorting to each strategy were assessed during the long-term monitoring.

3.1 NATIONAL SURVEY ON THE USE OF NATURAL VENTILATION IN BRAZILIAN RESIDENCES

Considering the emphasis of this research on the perception of natural ventilation as a strategy for indoor conditioning and body cooling, the survey questionnaire included aspects of frequency of use, motivations and barriers related to adopting the strategy in hot seasons or climates. The questionnaire was widely disseminated (online) in the national territory. The national survey questionnaire was designed based on previous surveys on user behaviour and its impact on thermal comfort, adaptation strategies to environmental conditions, energy consumption and air conditioning usage patterns in the Brazilian residential sector (BALVEDI et al., 2018; RAMOS, 2020). However, the national questionnaire proposed in this thesis focuses on natural ventilation in the Brazilian residential context and what is behind its adoption: households' preferences, usage routines, motivations and impediments to resorting to it.

3.1.1 Survey design

The survey questionnaire was designed to prioritise objectivity when filling out the questions and analysing the answers. The questionnaire includes 15 close-ended questions. Thus, the time the audience spends filling it out is potentially shorter. Moreover, data treatment is based on counting the frequencies of answers to each option (quantitative treatment method for nominal variables). The first section includes participants' characterisation (location, gender, age, education and monthly income). The following parts present questions about the overall perception of natural ventilation at home (2nd), routines of use (usage patterns), motivations/impediments to adopting natural ventilation at home (3rd), and how the COVID-19 pandemic has affected the frequency of use of natural ventilation (4th).

3.1.2 Consideration by the Ethical Committee

Because it is research involving human beings, the thesis project was submitted to the Ethical Committee for Research with Human Beings (CEPSH-UFSC). At first, only the national survey questionnaire was submitted to appreciation (processing between August and September 2021). Regarding the committee's requirements, a presentation letter of the national research was prepared, containing the consent form to make the participants aware of the objectives and implications of the study. It is important to emphasise that this research had no specific target audience. Participation was conditioned to consent, willingness and availability of electronic devices in which households could answer the questionnaire. None of the participants was identified at any research stage (anonymous participation). The proposal, considered and approved in September/2021 under registration CAAE 51459421.0.0000.0121, is shown in Appendix B.

3.1.3 Disclosure strategy and goals

After an ethical assessment, the questionnaire was transcribed into the Google Forms interface (GOOGLE LLC, 2018). Because it is a survey with a broad audience and no restrictions on participation, a coordinated dissemination strategy was necessary at the national level. In the case of this research, the primary dissemination strategy took place via postgraduate courses inside and outside the Federal University of Santa Catarina (UFSC). In other words, the responsible people from courses were asked to forward the online questionnaire to the respective contact lists composed mainly of graduate students. Contacts within UFSC were obtained via institutional webmail. In contrast, contacts of postgraduate courses at the national level were obtained through the list contained in the Sucupira Platform (GOVERNO FEDERAL, [s.d.]). In this case, the courses from related areas were prioritised: Architecture and Urbanism, Engineering (Civil Construction) and Urban and Regional Planning.

In addition to the primary dissemination strategy, dissemination was requested through other representations (national networks of researchers and laboratories) to reach a more significant number of responses and a greater audience diversity throughout the Brazilian territory. The initial target for the national survey was about 500 responses to the questionnaire based on similar previous studies in the residential sector (CARPINO; MORA; DE SIMONE, 2019). By mid-November, a month before the end of the publicity campaign, the questionnaire received just over 500 responses. Given the availability of more time for disclosure, the campaign was expanded, aiming at the most significant possible number of responses until December 2021. This expansion included the other postgraduate courses in Brazil listed on the Sucupira Platform, obtaining 1,348 valid responses.

3.1.4 Methods of data treatment

The Google Forms output is a spreadsheet of the qualitative (non-metric, nominal) data defined in the survey design. Therefore, the selected data treatment methods were Pearson's Chi-squared test for count data in a contingency table and multinomial logistic regression. The Chi-squared test is adopted to check the association between two categorical variables and their respective levels. The significance level is assumed to be $\alpha = 5\%$. A post hoc adjustment to the significance level of the Chi-squared test was employed when multiple categories in a contingency table could lead to a Type I Error – rejecting the null hypothesis when it is true (MACDONALD; GARDNER, 2000). Standard residuals were also analysed after post hoc adjustment.

Multivariate analysis of multinomial logistic regression was adopted to model the relationship between a nominal dependent variable and more than one independent (explanatory) nominal variable. In this survey, the natural ventilation usage pattern is set as the dependent variable and assumed to be influenced by a set of independent variables representing households' perceptions, income, and motivations to adopt/not adopt natural ventilation at home. The primary purpose of multinomial logistic regression was to obtain the odds ratios (OR) that depict the strength of association between events A and B (e.g. "prefer air-conditioning" and "never adopt natural ventilation" at home). The significance level is assumed to be $\alpha = 5\%$ as well. All the above statistics were conducted using the R language (R CRAN, 2022) in the RStudio interface (POSIT, 2023). The "nnet" package (RIPLEY, 2022) was employed to conduct multinomial logistic regression. The details of the modelling process – including data cleaning, statement of the models, verification of assumptions and reviews – are described in section 4.1.

3.2 THERMAL COMFORT FIELD SURVEY IN RESIDENCES

After disseminating the national survey, a field survey campaign was conducted locally (São Luis city, Brazil's Northeast). The proximity between the researcher and the participants of the field survey allowed the environmental monitoring (thermal-related physical variables) at the residences, which was impossible in the national survey. Therefore, the field survey complements the knowledge addressed previously but adds the influence of the thermal environment on human perception.

The field survey is divided into two steps based on the methodological procedures applied. First, a point-in-time survey was adopted to evaluate the dynamic aspect of air movement from natural ventilation and its impact on thermal and air movement perception. Second, long-term monitoring addressed households' options for a conditioning strategy and its motivations. Both approaches are summarised in Table 2. Appendix C extends the field survey methods described in this subsection by depicting the practical research protocols and instruments for data collection tested in a pilot field study before the field survey.

Table 2 – Field survey research steps

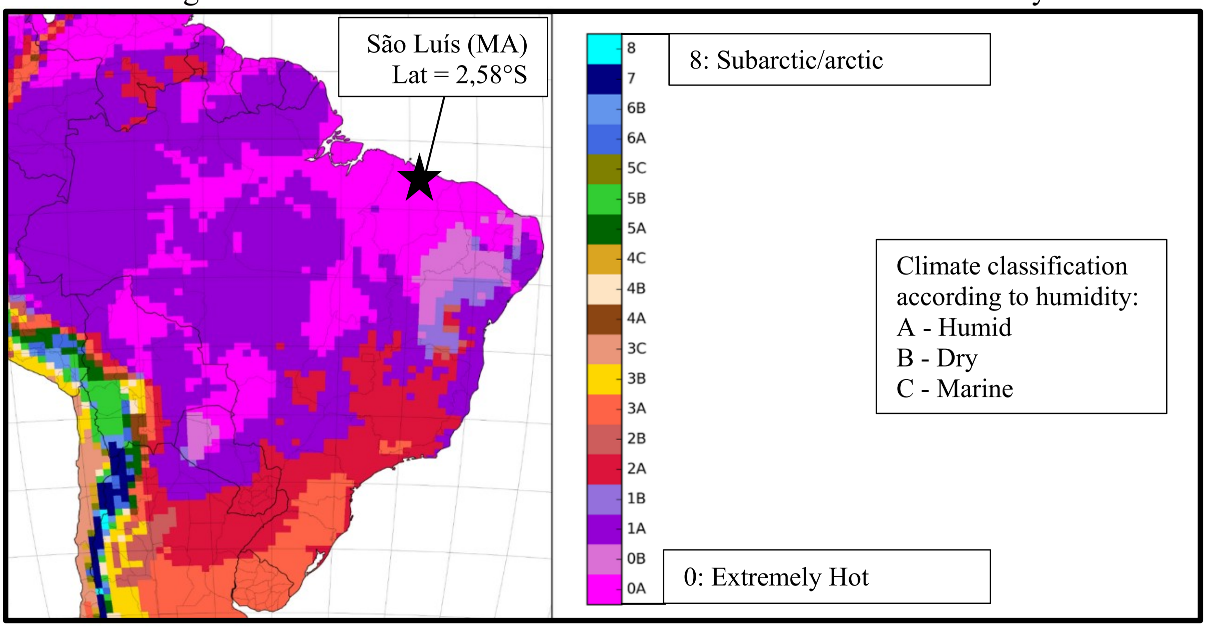
	Point-in-time Survey	Long-term Monitoring
Occasion	First visit to the residence	Starting from the first visit
Total duration	Maximum one-day shift	Approximately one month
Researcher	Present at homes	Absent from homes
Measuring instrument	Microclimatic station SENSU	HOBOs
Data collection instrument	Semi-structured Interview (I) + Point-in-Time Survey Questionnaire (IQ) Presented in Appendices E and F	Long-term Comfort Survey Questionnaire (Online) (QL) Presented in Appendix G

Source: elaborated by the author

3.2.1 Geographical delimitation and climatic data

The geographical delimitation for conducting the field survey within the Brazilian territory was based on the demand for air movement as a primary strategy for cooling the body, which occurs in tropical equatorial climates (hot and humid throughout the year). In this context, São Luis (MA) is a favourable site for conducting the idealised field survey. São Luis is within Bioclimatic Zone 8 (ZB8) of the current Brazilian bioclimatic zoning (ABNT, 2003) and Zone 0A of ASHRAE 169 climate classification (ASHRAE, 2020b), as shown in Figure 3. Such climate zones are the hottest and most humid locations in the Brazilian territory. Therefore, with greater susceptibility to thermal discomfort due to heat in most hours of the year.

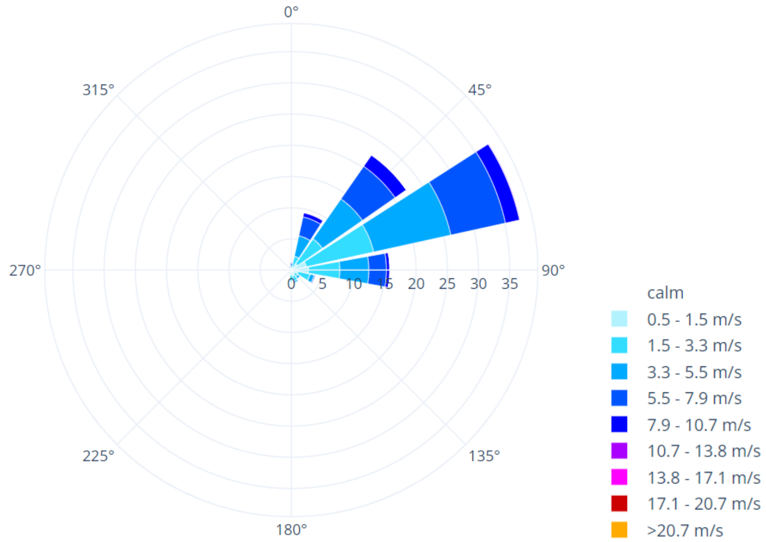
Figure 3 – Climate classification of São Luis in the Brazilian territory



Source: Adapted from ASHRAE 169 (ASHRAE, 2020b)

Besides its hot and humid climate, the city is on an island. Wind intensity is above 2 m/s yearly (annual average equals 2.4 m/s). From August to December, corresponding to the hot and dry season, wind intensity is above 3 m/s (INMET, 2021). By analysing the corresponding climatic data file[1], it is possible to identify the daily and hourly distribution of winds – intensity, in meters per second, and direction, in degrees – throughout the year. The representations obtained on the CBE Clima Tool[2] interfaces are illustrated in Figure 4, Figure 5 and Figure 6.

Figure 4 – Annual wind rose in São Luis

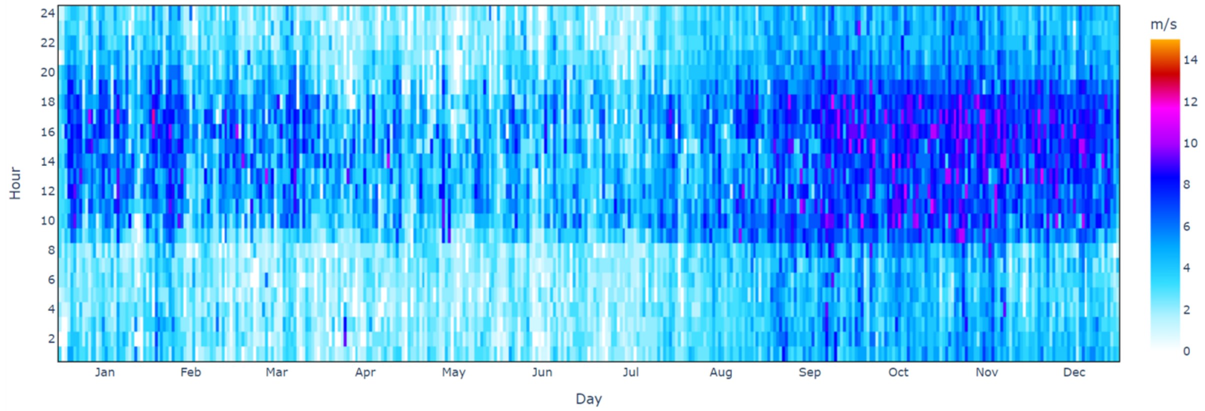


Source: Betti et al. (2021)

[1] Climate data file "BRA_MA_Sao.Luis-Machado.Intl.AP.822810_TMYx.2004-2018.zip". Available at: https://climate.onebuilding.org/WMO_Region_3_South_America/BRA_Brazil/index.html#IDMA_Maranhao-. Accessed on feb. 2022.

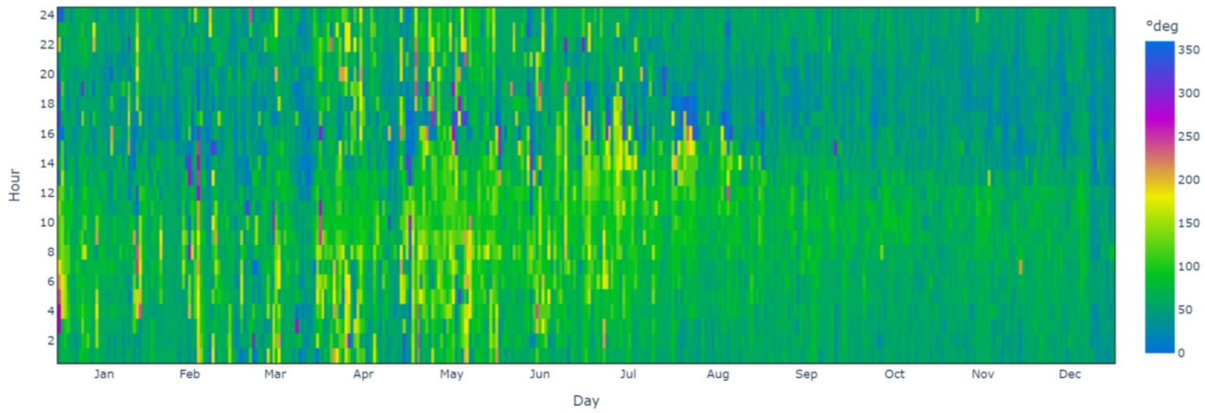
[2] Betti, G., Tartarini, F., Schiavon, S., Nguyen, C. (2021). CBE Clima Tool. Version 0.4.6. Center for the Built Environment, University of California Berkeley. Available at: https://clima.cbe.berkeley.edu/. Accessed on feb. 2022.

Figure 5 – Wind intensity over the year in São Luis



Source: Betti et al. (2021)

Figure 6 – Wind direction throughout the year in São Luis



Source: Betti et al. (2021)

The annual wind rose (Figure 4) indicates the predominance of winds from the North-East quadrant (0-90º), particularly from the Northeast and East directions. In the temporal analysis, winds are predominant with higher intensity (up to 10 m/s) from September to December. In the same period, there is less variation in wind direction - the predominant direction is well-defined. It is also possible to notice a time pattern in which the lower intensity winds (< 6 m/s) occur during the night/early morning and come from the North. In comparison, the winds of higher intensity (> 6 m/s) come from the Northeast and East directions throughout the day (particularly in the afternoon). Based on this analysis, the field study was conducted between July and November 2022.

3.2.2 Household sample selection

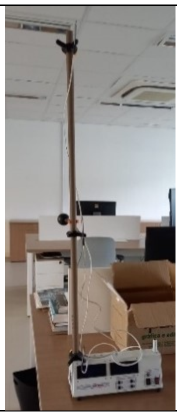
The researcher targeted a sample of residents who were willing to participate as volunteers once aware of the purposes and implications of the survey. Based on the recent residential survey experience by Ramos (2020) in Florianópolis, it was noticed that households were more receptive to participating in the study when there was the intermediation of someone known to both (the researcher and the resident). Thus, the initial strategy for selecting households was the network of the researcher's contacts, which was expanded from successive contacts. The researcher aimed to get a total sample of at least 100 participants, regardless of the number of residences. The field study reached 106 participants in the point-in-time survey (who were interviewed and answered the IQ form presented in Appendix F) and engaged 111 participants in the long-term monitoring (who answered the QL form presented in Appendix G). Fifty-six residences were visited, and all of them were included in this study's final sample.

3.2.3 Thermal environmental monitoring

The instrumentation from the Laboratory of Energy Efficiency in Buildings (LabEEE-ECV-UFSC) and manufactured in the Porous Media and Thermal Physical Properties Laboratory of the Mechanical Engineering Department (LMPT-EMC-UFSC) were used in the environmental monitoring of the residences. All measurement sensors were checked for accuracy (compliance with the margin of error) before, during and after the field survey. Information on the measurement instrumentation adopted in the field survey is summarised in Table 3. The instrumentation set includes:

- HOBOs: portable meters for air temperature and relative humidity;
- Hot wire thermal anemometers: portable meters for air temperature and air speed (unidirectional sensors);
- SENSU microclimatic stations: three air velocity sensors (omnidirectional), temperature, relative humidity and globe temperature sensors.

Table 3 – List of measuring instruments

Instrument	Photo	Manufacturer	Measured variables	Timestamp	Application
HOBO		ONSET	Air temperature (°C) Relative humidity (%)	10 minutes	Monitoring of long-stay rooms in the longitudinal survey
Hot Wire Thermal Anemometer		TESTO	Air temperature (°C) Airspeed (m/s)	1 second	Periodic calibration of the air velocity sensors in SENSU microclimatic stations
Microclimatic station SENSU		LMPT-EMC-UFSC	Air temperature (°C) Globe temperature (°C) Relative humidity (%) Air velocity (m/s)	1 minute (default when saving) or 2 seconds (copy-paste from the SENSU app)	Monitoring environmental conditions during the instantaneous survey (interview and IQ form) and possibly in other air velocity measurements during the visit to residences

Source: elaborated by the author

All the information on the application of measuring instruments in the pilot field study can be accessed in Appendix C (subsection C.3. Instruments for measuring indoor physical variables). Details on the measuring instruments (description, measuring range, accuracy) and the tests performed before, during and after the field survey are described in APPENDIX H – Measuring Instruments.

3.2.4 Instruments for participants' data collection

The instruments for data collection from residents were developed based on the national survey results and the existing bibliography. They were tested in the pilot field study as described in Appendix C (C.2. Instruments for collecting data from subjects). After the pilot, instruments were defined as follows: an interview script (APPENDIX E – Semi-structured interview script); a form for quick assessment of the thermal environment during the interviews (APPENDIX F – Point-in-Time (Instant) Survey Questionnaire (IQ)); and an online questionnaire to assess the thermal environment at specific moments during the long-term monitoring (APPENDIX G – Long-term Comfort Survey Questionnaire (Online)).

Additionally, a consent form (APPENDIX D – Consent Form for participation in the Field Study) was elaborated, tested in the pilot study and consolidated into the field study. The instruments were disseminated in Portuguese and transcribed into English in this Thesis document. As the national survey questionnaire, those instruments were submitted for approval to the Ethics Committee on Research with Human Beings (CEPSH-UFSC). The field study design was approved under registration CAAE 58653622.8.0000.0121. The application of instruments within the research protocols is presented in subsection 3.2.5 Execution of the field study and detailed in Appendix C (C.1. Practical research protocols).

3.2.4.1 Semi-structured interview

The semi-structured interview approach was selected as part of the field study, allowing more significant interaction with the participant and greater detail in the answers provided (see APPENDIX E). The interview script included an open conversation about households' overall perception of the thermal environment, particularly natural ventilation at home. Moreover, their thermal comfort and environmental adaptations (particularly air conditioning and fan usage) were addressed. The motivations to adopt and not adopt natural ventilation at home were included in the interview script based on the feedback from the 2021 national survey. Finally, the characterisation of the sample surveyed was included (gender, age, approximate income and level of education). The interview was the first in-person contact between the researcher and the household(s). Thus, information on the occupancy routine was applied to prepare the long-term monitoring, e.g. where to place the sensors inside the residences and when to send the QL form (Online Questionnaire).

3.2.4.2 Questionnaires

During the interview, participants were requested to fill in a form (see Appendix F) for thermal comfort evaluation concomitantly to the air temperature, globe temperature, relative humidity and air velocity measurements. The researcher requested answers to five subjective evaluation criteria (P1-P5) at indicated moments. As air velocity fluctuations could occur in the room, the answers were asked repeatedly (R1-R5, with intervals of 5-10 minutes) until the interview was finished. A final (F) air movement evaluation was requested after R5.

The form was offered printed only to avoid distractions for the respondents in other equipment such as smartphones, tablets or notebooks.

During the long-term monitoring of about a month, the researcher sent an online questionnaire to the residents requesting information about the thermal perception (P1-P5) in the occupied rooms, the running conditioning strategy and the primary reason behind it. This questionnaire is identified as a QL form due to its application throughout long-term monitoring. Because of the researcher's absence at this stage, information such as the location within the residence, the running strategy, the activity performed and the clothing used when filling out the questionnaire were requested. Those procedures were adopted by Ramos (2020) in long-term residential monitoring in Florianópolis, which favours further comparisons between two distinct Brazilian climates.

3.2.5 Execution of the field study

The summary presented in this subsection is based on the content of Appendix C – Pilot Field Study, C.1. Practical research protocols.

The researcher presented the consent form to the volunteers on their first contact. The consent form is a document that invites volunteers to participate and gives a brief presentation of the objectives and implications of the field study. This first contact was made in person (once the visit to the residence was authorised) or virtually, in the case of sending the document to the participant's knowledge. Once the invitation to participate was accepted, the researcher's first visit to the residence was scheduled. The participants' consent was obtained and documented during the visit. The researcher also sought permission to record the interview and photograph the current measuring equipment arrangement. The researcher offered a printed copy of the consent form signed by both if the participant preferred.

The semi-structured interview (I) and the form for the point-in-time survey (IQ) were applied on the first visit to the residence, concomitantly to the measurements of thermal environmental variables. This set of actions is referred to as a point-in-time survey, and the sequential procedures adopted are presented as follows.

- As the researcher entered the residence, the households present and willing to participate were asked to indicate a preferred location for the interview;

- Once it was determined, a SENSU microclimatic station was positioned on the floor, up to 1 meter from the respondent(s) (Figure 7). The current conditioning strategy (whether natural ventilation, air-conditioning or fans) was registered – there was no interference/imposition of the researcher on this issue;
- After obtaining consent, the researcher began conducting the interview and requested periodic responses (observing 5-10 minutes between responses) to the IQ form, according to the orientations in the interview script.

Figure 7 – Positioning of a SENSU microclimatic station during the interview

Source: elaborated by the author

After the interview, the researcher requested permission to visit the other rooms of the residence (guided tour). Once the researcher was aware of the rooms most occupied by the residents (from interviews), the HOBO measurement devices were placed preferentially on furniture surfaces inside the rooms where residents stayed longer (Figure 8). The HOBOs were adopted to record the indoor air temperature and humidity for approximately one month. They were placed away from heat sources (direct solar radiation, electronic equipment) and as close to the occupied area as possible.

Figure 8 – Placement of HOBOs for long-term monitoring

Source: elaborated by the author

If possible, measurements with SENSU were taken at places other than the interview site and which were listed by the resident(s) as the most frequently used during the home occupation (for example, near sofas, beds and workstations as illustrated in Figure 9). The objective of the measurements with SENSU in the presence of the researcher is to capture the air velocity profile in the rooms cited by the participant as frequently occupied. Each additional measurement should last at least 30 minutes, as should the measurement conducted during the interview. The additional measurement mainly occurred concomitantly with the interviews to save time for both researcher and the households. The researcher left the residence after all on-site measurements with SENSU microclimatic stations and placement of HOBOs.

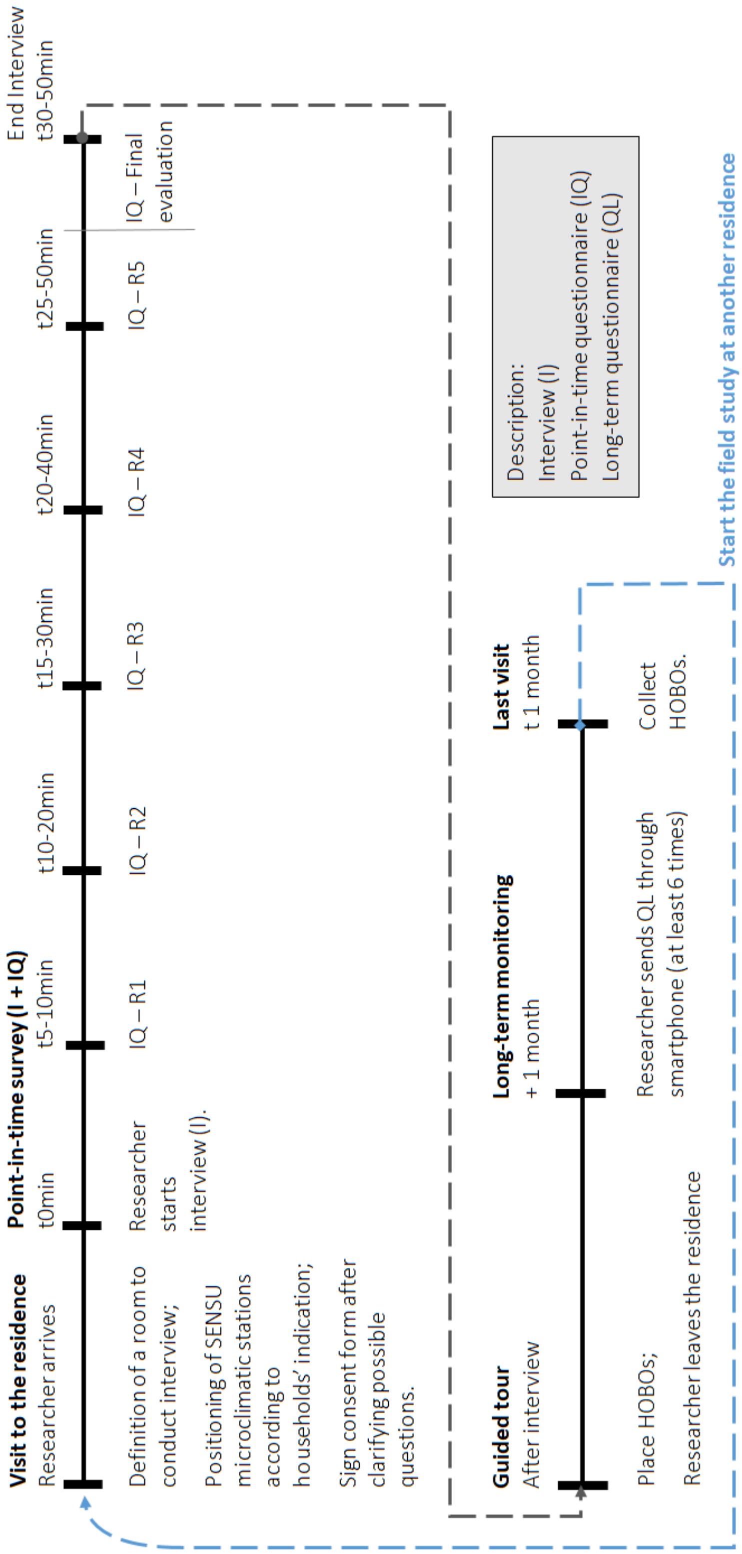
Figure 9 – Positioning of a SENSU microclimatic station for additional measurements

Source: elaborated by the author

After the researcher's first visit, long-term monitoring took place. The residence was continuously monitored for approximately one month in the absence of the researcher. The long-term questionnaire (QL) was sent online to residents. The researcher sent at least six QLs to each participant to obtain at least 500 valid responses from all participants. Two events guided the times of sending. First is the external wind condition indicated on the national weather forecast[3] (wind intensity: moderate). The coincidence between the response moment and the incidence of higher-intensity winds (> 3 m/s) was expected. The other event is the occupancy routine of residents, which was obtained in the interviews. At the end of the long-term monitoring, the researcher scheduled a new visit to collect the HOBOs. The HOBOs removed from one residence were moved to another to start new monitoring. A summary of the research procedures is shown in Figure 10.

[3] INMET :: Previsão. Available at: https://previsao.inmet.gov.br/.

Figure 10 – Diagram of field survey development in each residence



Source: elaborated by the author

3.2.6 Methods of data treatment

3.2.6.1 Data cleaning

The treatment stage comprises the data transcription into specific spreadsheets with categories (categorical qualitative variables) and numerical values (continuous quantitative variables – measurements of environmental parameters). Three spreadsheets were developed: interview, IQ responses and QL responses.

The researcher transcribed the interview data by listening to the voice recordings and adding the pseudonym code EC assigned to each residence (EC1 to EC56). The number of participant households per home (interviewed and who answered to IQ form) was identified by the additional pseudonym code IQ followed by a number (e.g., IQ1 and IQ2 if there were two interviewees). Therefore, households were not identified by their names at any stage of data transcription. Essential information from interviews was highlighted to be linked to the IQ and QL spreadsheets: air-conditioning (AC) availability at home, conditioning strategy preference at home, family income and personal perception of cooling energy cost at home.

The IQ responses spreadsheet was elaborated with data from the SENSU microclimatic station (indoor air temperature, globe temperature, relative humidity and air velocity) and the IQ form (thermal and air movement perception responses; participant characterisation of gender, age range, education level and family income). The metabolic rate and clothing insulation parameters were estimated according to the procedures presented in ASHRAE 55 Standard (ASHRAE, 2020a). The information was organised by EC and IQ in a temporal order so that the IQ form responses were linked to the indoor measurements conducted during the interview.

The temporal order is identified by the moments of voting from R1-R5. Air velocity, mean radiant temperature and operative temperature were calculated according to the procedures presented in ASHRAE 55 Standard (ASHRAE, 2020a). The instantaneous airspeed readings were averaged in 1-minute, 5-minute and 10-minute intervals prior to the moment of responding to P1-P5. Moreover, the differences (Δ) in air velocities and voting scales between R timestamps were quantified. The results of the point-in-time survey are presented in section 4.3.

The QL responses spreadsheet was elaborated based on data from the Google Forms output. The researcher manually added HOBO (indoor air temperature and relative humidity) and INMET measurements (outdoor instant air temperature, relative humidity and wind speed) by following the timestamp registered through Google Forms. Each response was assigned an indoor air velocity value based on the additional measurements (when available) conducted during the researcher's visit. The assignment of indoor air velocities was based on current running strategies and occupied rooms. Therefore, an additional air velocity measurement conducted under natural ventilation in a specific room during the researcher's visit should best represent the air velocity when households responded to QL under natural ventilation afterwards.

Outdoor measurements were obtained from the INMET weather system[4] by selecting data from the SAO LUIS A203 automatic station from June to November 2022. Therefore, QL form responses were linked to a corresponding environmental condition (indoor and outdoor). Moreover, when households reported the current use of AC, the researcher also collected the environmental parameters corresponding to the moment prior to its activation. The timestamp corresponding to the highest indoor air temperature and relative humidity before their drop in the room was selected to reference the outdoor conditions. Finally, the selected information from interviews was added to the QL responses spreadsheet. The results of the long-term monitoring are presented in section 4.2.

3.2.6.2 Statistical data treatment

Inferential statistical analysis was conducted by testing the significance of differences in groups (samples) of data. The assumption of normal distribution was verified for continuous numeric data such as physical measurements and derived calculations. Non-parametric tests were adopted when data were non-normally distributed or ordinal (GRECH; CALLEJA, 2018). The Mann Whitney U (Wilcoxon Rank-Sum) test is the non-parametric approach to the Student's T-test for the significance of differences between two independent groups (e.g. air velocities in NV and NV+FAN running modes). Similarly, the Kruskal-Wallis test is the non-parametric alternative to the One-way Analysis of Variance (ANOVA) for the significance of differences between more than two independent groups (e.g. air velocities

[4] INMET :: Tempo. Available at: https://tempo.inmet.gov.br/.

corresponding to the votes on the seven-point ASHRAE thermal sensation scale). Both statistic tests were conducted using the “ggpubr” package (KASSAMBARA, 2023) in R language (R CRAN, 2022) in the RStudio interface (POSIT, 2023). All analyses assumed the significance level as $\alpha = 5\%$.

The temporal analysis of R1 to R5 moments of voting also required a paired evaluation. The Friedman test (non-parametric approach to the Repeated-measures ANOVA, available as a native function in Rstudio) was adopted to check the significance of differences between more than two paired groups. The Dunn-Bonferroni post hoc adjustment on the Siegel test was applied to verify any significant intra-group differences (POHLERT, 2022).

4 RESULTS AND DISCUSSION

The results and discussions arising from the present study were organised into three sections. The outcomes from the national survey (natural ventilation at home based on households' preferences and motivations) are presented in section 4.1. The results from the long-term monitoring of the local field campaign (households' subjective evaluations, chosen conditioning strategies and motivations) are shown in section 4.2. The outcomes from the point-in-time survey of the local field campaign (the impact of dynamic airflows from natural ventilation on households' thermal delight and satisfaction) are presented in section 4.3.

4.1 NATIONAL SURVEY ON PERCEPTIONS, ROUTINES AND MOTIVATIONS BEHIND THE ADOPTION OF NATURAL VENTILATION AT HOME

The natural ventilation (NV) usage routine in Brazilian homes is assumed to be related to personal preference regarding a conditioning strategy, the households' judgement of NV at home and economic factors (affordability of active climatisation systems). The description of the variables[5] from the National Survey assessed in this analysis is presented in Frame 1.

[5] Only variables with statistical significance ($\alpha = 5\%$) in the multinomial logistic regression were depicted.

Frame 1 – Variables analysed from National Survey.

Variable description	Variable resumed name	Levels **(reference group in bold)**
Frequency and condition of use of natural ventilation in the hottest season of the year	NV_usage_ pattern	**always naturally ventilated (Always NV)**; natural ventilation mainly during the day (Daytime NV); natural ventilation mainly during the night (Night-time NV); natural ventilation depending on environmental conditions (Conditional NV); never naturally ventilated (Never NV)
Preference for a conditioning strategy in the hottest season of the year	StrategyPreference	**natural ventilation (NV)**; natural ventilation with fans (NV+FAN); air-conditioning (AC)
Judgement of the residence regarding natural ventilation	JudgementVent	**good ventilation (good)**; poor ventilation (poor)
Monthly income	Income	less than four minimum wages (<4); 4-10 minimum wages (4-10); **more than ten minimum wages (>10)**
Motivation "to save energy" as a reason to adopt natural ventilation at home	Motivation.Energy Savings	**do not cite energy savings as a top-three reason (No)**; cite energy savings as a top-three reason (Yes)
Motivation "good ventilation" as a reason to adopt natural ventilation at home	Motivation.Good Ventilation	do not cite "good ventilation" as a top-three reason (No); **cite "good ventilation" as a top-three reason (Yes)**

Source: elaborated by the author

Before the modelling, the following procedures were adopted: (1) Data cleaning, removing non-answered data (NA's) – 79 rows were removed, and a new sample of 1,269 observations was created. (2) Definition of reference groups (levels), highlighted in bold in Frame 1 – it was defined based on the choices that would favour the use of NV the most among the options available in the dataset. (3) Verify the assumptions of mutually exclusive categories, independence of observations, absence of multicollinearity, and independence of irrelevant alternatives (IIA).

4.1.1 Natural ventilation usage patterns and their influencing factors

The result of multinomial logistic regression for the NV usage pattern is depicted in Figure 11. A Nagelkerke's pseudo R^2 of 0.29 was reported, indicating a relationship of 29% between the investigated independent variables and the dependent variable. The interpretation of coefficients towards the lowest frequency of NV usage (NeverNV) points to increasing preference for a strategy other than NV – particularly AC. Accordingly, the odds ratios for

NV+FAN (2.1) and AC (76.4) compared to NV in the reference model (Figure 12) reinforce the association trend between personal preference and NV usage routines. In other words, those who prefer AC would be 76.4 times more likely to "never use" NV at home than those who prefer NV. The proportions of preference for NV and AC show inverse trends in Figure 13.

Figure 11 – Outcome of regression: coefficients, standard errors and significance values

Multinomial logistic model

	Dependent variable:			
	DaytimeNV	NighttimeNV	ConditionalNV	NeverNV
	(1)	(2)	(3)	(4)
StrategyPreferenceNV+FAN	0.201	0.378^{*}	0.759^{***}	0.743^{**}
	(0.167)	(0.207)	(0.168)	(0.356)
StrategyPreferenceAC	1.984^{***}	2.154^{***}	3.086^{***}	4.336^{***}
	(0.502)	(0.541)	(0.484)	(0.575)
JudgmentVentpoor	-0.526	0.056	0.502^{**}	2.878^{***}
	(0.326)	(0.314)	(0.243)	(0.344)
Income< 4	-0.714^{***}	-0.230	-0.597^{***}	-1.527^{***}
	(0.220)	(0.280)	(0.221)	(0.387)
Income4-10	-0.336	-0.141	-0.371^{*}	-0.608^{*}
	(0.217)	(0.284)	(0.222)	(0.364)
Motivation.EnergySavingsYes	0.563^{***}	0.726^{***}	0.714^{***}	0.764^{***}
	(0.164)	(0.204)	(0.162)	(0.289)
Motivation.GoodVentilationNo	0.171	0.853^{***}	0.839^{***}	0.912^{**}
	(0.174)	(0.241)	(0.189)	(0.459)
Constant	-0.373^{*}	-2.009^{***}	-1.291^{***}	-3.645^{***}
	(0.214)	(0.309)	(0.239)	(0.518)

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Source: elaborated by the author

Figure 12 – Outcome of odds ratio for the NeverNV usage pattern (worst case for NV)

Characteristic	OR[1]	95% CI[1]	p-value
NeverNV			
StrategyPreference			
NV	—	—	
NV+FAN	2.10	1.05, 4.23	0.037
AC	76.4	24.7, 236	<0.001
JudgmentVent			
good	—	—	
poor	17.8	9.06, 34.9	<0.001
Income			
>10	—	—	
<4	0.22	0.10, 0.46	<0.001
4-10	0.54	0.27, 1.11	0.10
Motivation.EnergySavings			
No	—	—	
Yes	2.15	1.22, 3.78	0.008
Motivation.GoodVentilation			
Yes	—	—	
No	2.49	1.01, 6.13	0.047

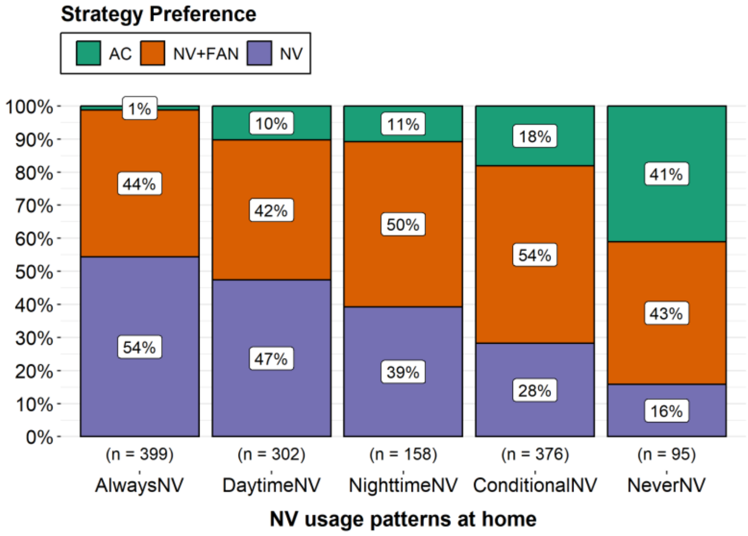
[1] OR = Odds Ratio, CI = Confidence Interval

Source: elaborated by the author

Regarding the association between income and usage patterns, the impact on NV frequency at home is significant only for the lowest income level (<4 minimum wages) compared to the highest income level (>10 minimum wages). The frequency of NeverNV and the odds ratio for Income<4 decreases compared to Income>10. Those with Income<4 have 0.22 times the chance (less chance) of "never using" NV compared to those with Income>10. The energy-saving concern is also related to how households use NV, as depicted in Figure 14. The group of participants who consider "energy savings" as a top-three reason to adopt NV at home (Motivation.EnergySavingsYes) is less likely to use NV frequently than the group who does not consider it as a top-three reason (Motivation.EnergySavingsNo). However, in contrast to the assumption of income influence, there was no statistical difference in the distribution of Yes/No samples across income ranges (χ^2=0.017 · df=2 · Cramer's

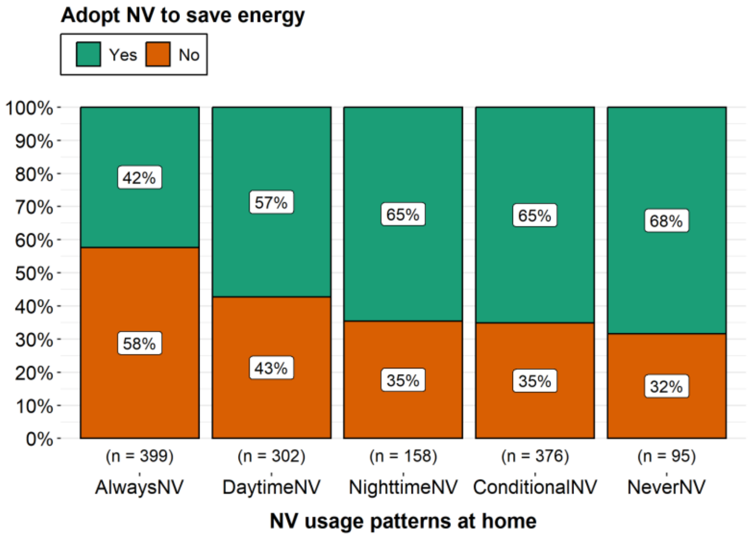
V=0.004 · p=0.991). The outcome indicates similar energy-saving concerns among survey participants despite income ranges and overall low probability of economic constraints behind that motivation to influence NV usage patterns.

Figure 13 – Strategy preference among NV usage patterns



Source: elaborated by the author

Figure 14 – Energy saving concern among NV usage patterns



Source: elaborated by the author

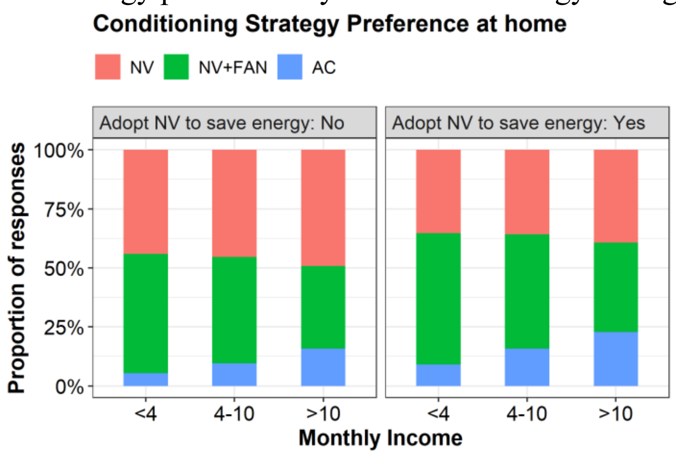
It was assumed that households' judgement regarding NV at home (JudgementVent) would reflect the perceived performance of NV and thus influence the usage pattern. According to Figure 12, people who judge their home as poorly ventilated (JudgementVentpoor) are 17.8 times more likely to "never use" NV compared to those who judge their home as well-ventilated (JudgementVentgood). Also, the interpretation of coefficients towards the lowest frequency of NV usage (NeverNV) points to an increasing judgement of poor ventilation at home compared to good ventilation (Figure 11). A similar conclusion can be drawn from the analysis of "good ventilation at home" as a top-three reason to adopt NV (Motivation:GoodVentilation). Therefore, the chance of "never adopting NV" is more significant for the group that does not consider it a top-three reason (Motivation:GoodVentilationNo). This outcome probably reflects the NV panorama in which the more well-ventilated, the more NV is adopted frequently (AlwaysNV and DaytimeNV patterns, with associated residual p-values < 0.005 from post hoc adjustment).

4.1.2 Depicting the preference for a conditioning strategy at home

The primary objective of the National Survey is to investigate how financial aspects relate to households' preference for a conditioning strategy. The association between strategy preference, monthly income and energy-saving concern is illustrated in Figure 15. The proportion of NV preference has increased towards the highest income level (>10), although it is not a statistically significant trend (residual p-values for NV > 0.0056 from post hoc adjustment). In contrast, the higher the income, the lower the preference for NV+FAN at home. This outcome is statistically significant for the lower and the higher income levels (residual p-values for NV+FAN < 0.0056 from post hoc adjustment). The preference for AC also increases towards the highest income level for both energy saving concerning groups, except for a difference in income <4, which was significant to the "Yes" group but not significant to the "No" group. It can be inferred that energy saving is a concern affecting the preference in choosing a conditioning strategy, particularly for the households with the lowest monthly income.

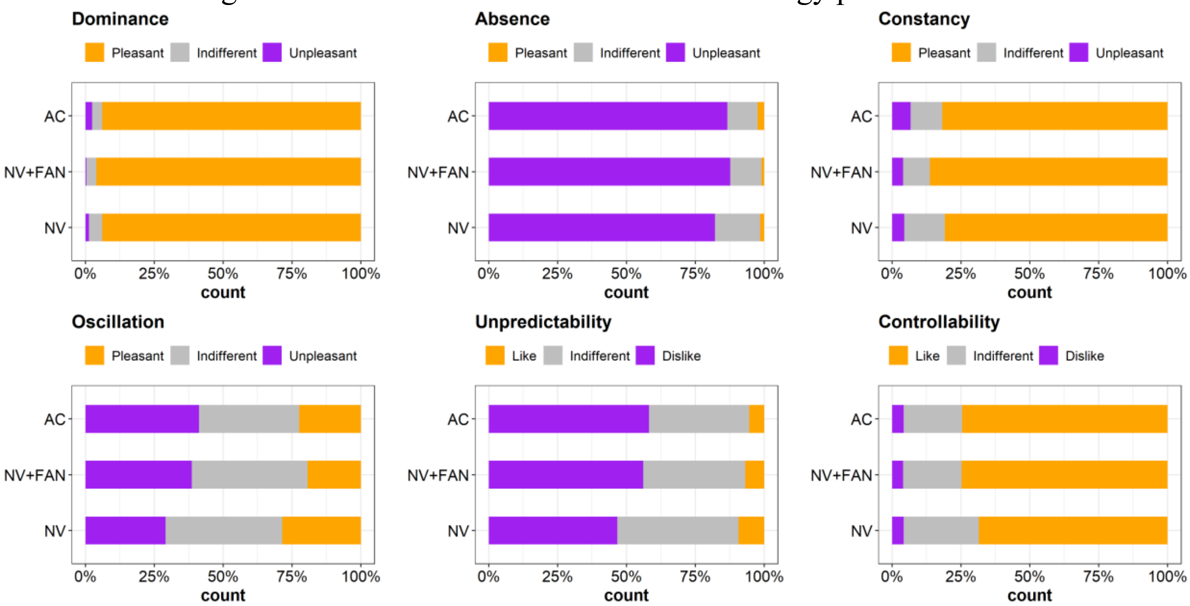
Low income (<4 minimum wages) constrains households' preferences and routines at home. The low-income level is related to a higher frequency of preference for natural ventilation assisted by fans and a lesser frequency of "never adopting" natural ventilation. The alignment between preference and routine outcomes indicates that participants consider other criteria when pointing out their strategy preference – e.g. choosing fans to support natural ventilation instead of air-conditioning. Apart from the energy saving concern, "air renewal" was one of the most cited reasons to adopt natural ventilation at home, which can also influence one's preference judgement – i.e. preferring NV as a conditioning strategy because of air renewal. Moreover, the status of natural ventilation performance at home is related to households' choice to adopt natural ventilation more or less frequently. Participants who judged their home as poorly ventilated were prone to use natural ventilation less frequently and mentioned "poor ventilation" as one of the main barriers to adopting it.

Figure 15 – Strategy preference by income and energy saving concern



Source: elaborated by the author

Figure 16 – Breeze characteristics versus strategy preference



Source: elaborated by the author

Considering the ordinary operation of openings and fans to provide air movement in Brazilian residences in summer (RAMOS, 2020), the thermal comfort implications of air movement from natural ventilation (referred to as breeze) were addressed in the National

Survey. “Thermal comfort” from air movement was the fourth most-voted reason to adopt NV at home during the hottest seasons, while “thermal discomfort” due to lack of air movement was the second most-voted reason not to adopt NV. Therefore, the absence of air movement representing thermal discomfort caught more attention from participants than its availability to provide thermal comfort. Diverse preference profiles can be found according to the investigated breeze characteristics, as shown in Figure 16.

Dominance and absence were evaluated as opposite characteristics, with a slight increase in “indifferent” to the absence of air movement among the group who prefer NV as a conditioning strategy. “Constancy” (constant air movement from a breeze) was appreciated mainly by those who chose NV+FAN. From all characteristics, oscillation (alternating between high and low air velocity) was the one which divided opinions the most. It was considered slightly more pleasant by the ones preferring NV. The unpredictability of the breeze is generally disliked, especially among those who prefer AC. Instead, the possibility of controlling the breeze (controllability) is appreciated, particularly in NV+FAN and AC groups. Households who prefer NV were slightly more indifferent to breeze characteristics deemed unfavourable – mainly absence and unpredictability. They were also more indifferent to controllability and favourable to oscillation. Alternatively, absence, oscillation, and unpredictability were sensibly more disliked among those who do not prefer NV.

4.1.3 Discussion

As expected, economic constraints affected the households’ declared preference for a conditioning strategy and the natural ventilation use routines at Brazilian homes. Previous evidence has shown how income influences the availability and frequency usage of heating/cooling appliances (RAMOS et al., 2020b; SONG et al., 2018) and shapes the adaptive comfort behaviours at home (INDRAGANTI, 2010b; MALIK et al., 2020; SOEBARTO; BENNETTS, 2014). Moreover, it is inferred that appliances’ availability and usage frequency (particularly air-conditioning in warm-to-hot environments) lead to increased preference for adopting them as climatisation, influencing households’ preference. The basis for this assumption is the cooling addiction hypothesis addressed in previous studies (BUONOCORE et al., 2019; CÂNDIDO et al., 2010b).

The main difference in strategy preference across income ranges is related to which active cooling strategy is chosen to complement or substitute the natural ventilation: resorting to fans to increase indoor air movement (1) or switching to air-conditioning to change the thermal environment (2). While the former is more frequent towards lower income levels, the latter is more frequent at the higher income level. This trend is aligned with the results of the latest National Electrical Appliances Possession and Usage Habits Research for the Residential Sector (PROCEL, 2019) and Ramos's (2020b) findings regarding the Brazilian residential sector. Analogously, Simões, Leder and Labaki (2021) have reported constant use of fans in low-cost housing in Brazil's Northeast region, resulting from removing window openings. However, the preference for natural ventilation (without fans) is not significantly affected by income, suggesting the inclusion of other aspects that favour natural ventilation in the judgement of "preference for a conditioning strategy".

Having good natural ventilation at home is one of the aspects contributing to the frequent adoption of the strategy and is also associated with preference. Therefore, households' satisfaction with the available natural ventilation is an encouragement to maintain or incorporate a frequent use of the strategy. A similar trend was reported in studies conducted at traditional (ISLAM; AHMED, 2021) and low-energy (DANIEL, 2018) dwellings. Households acknowledged the adequacy of their homes to the local climate and showed overall satisfaction with the thermal environment under passive conditioning strategies such as natural ventilation in those studies. Controversially, having poor natural ventilation at home is a consistent barrier to its adoption and leads to the choice of either the fans or the air-conditioning to improve the thermal environment. According to participants' open comments in the questionnaire, poor ventilation at home is associated with either the local wind regime or the residence's design.

The possibility of getting fresh air from the outside to the inside through the windows (air renewal) is another relevant benefit of natural ventilation acknowledged by the participants of the National Survey. This aspect, also highlighted by Ramos et al. (2020b) among the reasons to open windows, is particularly relevant in Brazil since the national residential building stock lacks mechanical air renewal systems. The impact of the COVID-19 pandemic on the perceived frequency of natural ventilation use suggests the concern with air renewal, as this frequency was increased for 30% of the participants and diminished for only 3%.

The thermal comfort/discomfort motivation was also essential to adopt or not adopt natural ventilation under warm-to-hot thermal conditions. Although it was addressed from the perspective of air movement and its cooling effect, the impact of air movement (a breeze from natural ventilation) on thermal comfort seems not evident to all participants. Moreover, the absence of air movement impairs natural ventilation more than the occurrence of air movement favours it. The impact of air temperature over air movement determines the overall thermal sensation since households have mentioned hot outdoor conditions to resort to air-conditioning. Previous studies aimed at deducing the window-opening rates as a function of indoor/outdoor temperatures. In some studies, the warmer the environment (outdoor air temperature above 28 °C), the fewer windows/doors were kept open (KIM et al., 2017; MALIK et al., 2020). However, the proportion of open windows/doors across even higher temperatures is not diminished in other studies (DANIEL, 2018; RIJAL, 2014), disclosing a different relationship between the outdoor environment and the permissiveness of natural ventilation.

Regarding the air movement from natural ventilation under hot thermal conditions, some participants of the National Survey acknowledged their perception of discomfort and pointed out strategies like shading or simply closing the openings to cope with the undesired outdoor environment. Similarly, Indraganti (2010b) highlighted the negative effect of hot breezes from natural ventilation through the windows/balconies of Indian apartments during the hottest and driest season. The difference in heat gains between dry and humid climates/seasons could justify the acceptance of air movement against thermal discomfort since it is desired for comfort purposes in previous studies conducted in hot and humid regions (BUONOCORE et al., 2018; CANDIDO et al., 2010; RIJAL, 2014). The minor data from the driest climates (ASHRAE 169 “B” climate classification) in the National Survey did not allow further exploration of this issue in this study.

Despite the natural breeze, air movement from fans is a reliable and consolidated strategy to reduce thermal discomfort regardless of outdoor thermal conditions, mainly in low-to-middle-income dwellings (ADAJI et al., 2019; MALIK et al., 2020; MOORE et al., 2016). Soebarto and Bennetts (2014) reported that turning fans on was the primary response to feeling warm at home in Australia. Meanwhile, window/door operation was the leading choice when the environment was stuffy. Indeed, most people would rely on active strategies to achieve thermal comfort instead of expecting a natural breeze, especially when conditioning factors like seasonal variations, natural ventilation performance or hindrances to opening windows/doors at home take place. From the perspective of personal preference, the supporters of natural ventilation differed from those who would opt for fans or air conditioners in terms of the inherent breeze characteristics (mainly oscillation and unpredictability). The compiled outcomes of the National Survey suggest that ensuring a minimum natural ventilation performance (whenever the strategy is recommended or feasible to be implemented) is essential to households' awareness of natural ventilation, in accordance with previous studies in low-energy dwellings (DANIEL, 2018; MOORE et al., 2016).

4.2 THERMAL COMFORT AND CONDITIONING STRATEGIES: FINDINGS FROM A LONG-TERM RESIDENTIAL MONITORING IN BRAZIL'S HOT AND HUMID CLIMATE

The indoor/outdoor thermal conditions, the household subjective evaluation and the conditioning strategies adopted at home are discussed in this section. One hundred eleven residents from 56 homes in São Luis provided 597 valid (at-home) responses from the 10th of July to the 28th of November 2022. One hundred and six (106) of them participated in the interviews before, and five could not participate but agreed to join the long-term monitoring.

Table 4 – Summary of personal variables: metabolic rate and clothing insulation

Metabolic Rate (met)			**Clothing Insulation (clo)**		
Category	*n*	*% total*	*Category*	*n*	*% total*
<1 met	434	72.7	0.25 clo	441	73.9
~1.1 met	104	17.4	0.36 clo	114	19.1
>1.6 met	57	9.5	0.57 clo	32	5.3
>2 met	2	0.3	0.74 clo	10	1.7

Source: elaborated by the author

Households were mainly performing sedentary activities (resting, lying in bed, sitting) and wearing short clothes (e.g., a combination of sleeveless blouse and short shorts) at home, as depicted in Table 4. Regarding using different conditioning strategies when responding to the QL form, the classification shown in Table 5 was adopted. It is observed that the rooms were mainly operated without air-conditioning (N-AC), particularly with natural ventilation only (NV). The second most used strategy was NV supported by fans (NV+FAN), followed by fans only (windows closed – FAN). The free-running (FR) classification refers to no operating strategy in this study – windows were closed, and no equipment was turned on. Fans could also be turned on when AC was turned on (AC+FAN).

Table 5 – Data classification according to the current conditioning strategy

AC-turned-on classification			**Running strategy classification**		
Category	*n*	*% total*	*Category*	*n*	*% total*
AC (turned on)	43	7	AC+FAN	10	1.7
			AC	33	5.5
N-AC (not turned on)	554	93	FR	29	4.9
			FAN	54	9
			NV+FAN	73	12.2
			NV	398	66.7

Source: elaborated by the author

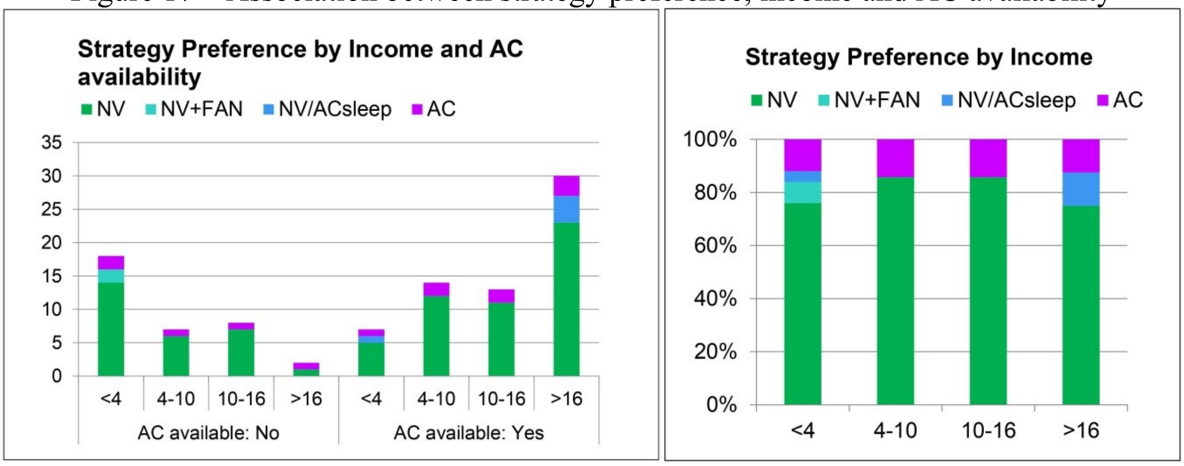
The sample characterisation by AC availability, income and perception of cooling energy cost from the interviews (106 participants) are presented in Table 6 to contextualise those aspects in the discussion. The perception of cooling energy cost refers to how high or low this specific consumption would be compared to the total energy consumption of the residence. It is worth noting that despite most households having AC available in this sample (~60%), NV was adopted the most during the long-term monitoring. Moreover, most households preferred NV over other (mainly AC) strategies at home, regardless of income and AC availability (Figure 17).

Table 6 – Interview sample characterisation of AC availability, income and perception of cooling energy cost

AC availability			**Family income (min. wages)**			**Perception of cooling energy cost**		
Category	*n*	*% total*	*Category*	*n*	*% total*	*Category*	*n*	*% total*
Yes	67	63	<1	5	4.8	very high	14	14.3
No	39	37	1-2	10	9.6	high	32	32.7
			2-4	12	11.5	neither high nor low	32	32.7
			4-10	22	21.2			
			10-16	21	20.2	low	18	18.4
			>16	34	32.7	very low	2	2
Total	106	100	Total	104	100	Total	98	100

Source: elaborated by the author

Figure 17 – Association between strategy preference, income and AC availability



Source: elaborated by the author

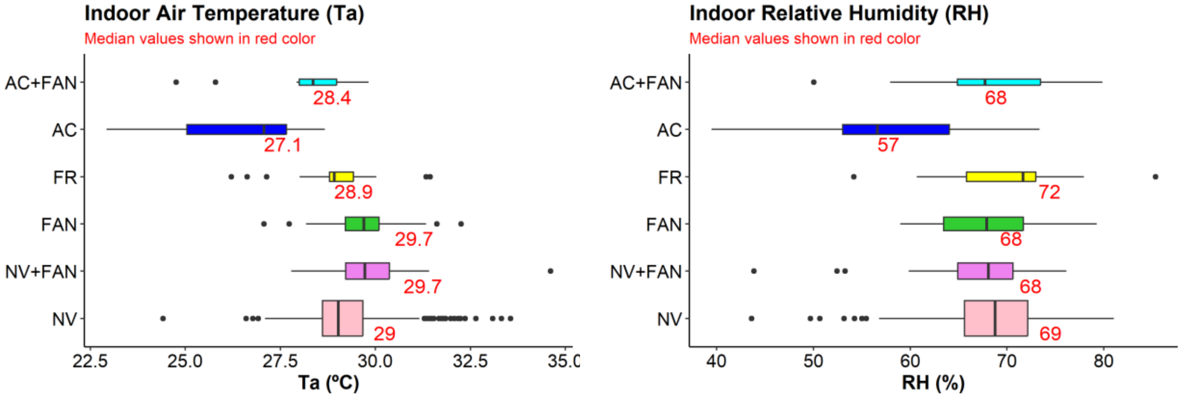
Although the lowest income ranges are not numerous in this sample (26% below four minimum wages), the proportion of households without AC available is relatively high (~40%), particularly in a hot and humid climate. As expected, the higher the income, the higher the AC availability (Figure 17). Most interviewees acknowledged that the residential cooling energy consumption is "high" or "neither high nor low" following their appliance usage.

4.2.1 Thermal comfort evaluation and corresponding indoor conditions

The indoor air temperatures and the relative humidities corresponding to the moment of responses to QL form are summarised in Figure 18. The NV environment presented the broadest range of air temperatures, while the AC had the most significant variability in relative humidity. As expected, the lowest values of both variables (including the lowest medians) were recorded in the AC. The air temperature in rooms with fans on was slightly higher than the air temperature corresponding with no fans on. The difference is valid for AC+FAN compared to AC and NV+FAN or FAN compared to NV, suggesting that higher air temperatures lead to the use of fans to mitigate thermal discomfort.

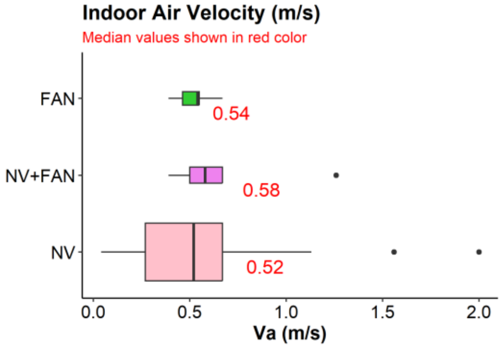
The assumed air velocities (measured during the researcher's first visit to each residence) were assigned to 261 occurrences in NV, 20 in NV+FAN and 14 in FAN strategy (Figure 19). As expected, the broadest range of air velocities was previously measured in NV (0-2 m/s). Meanwhile, the air velocity measurements with fans turned on were slightly above 0.5 m/s with a slight variation.

Figure 18 – Current indoor air temperature and relative humidity readings from HOBOs



Source: elaborated by the author

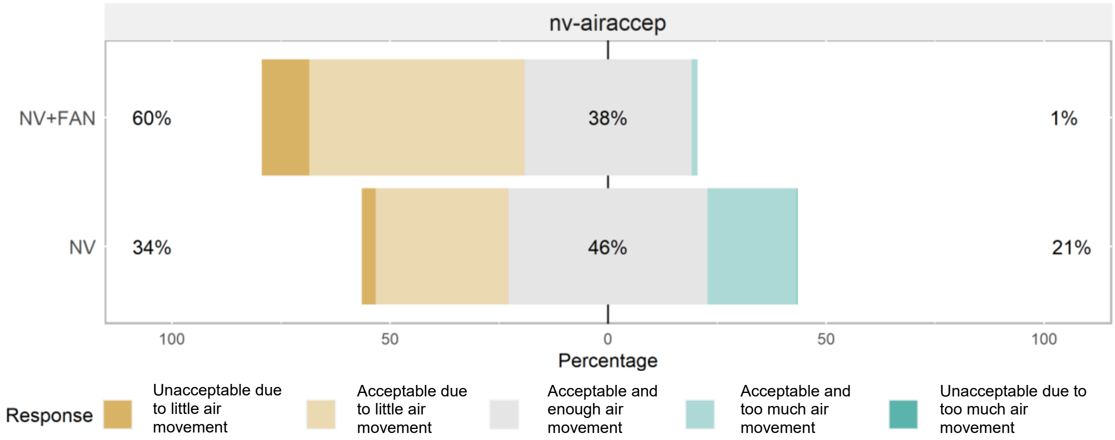
Figure 19 – Assumed indoor air velocities by running strategy



Source: elaborated by the author

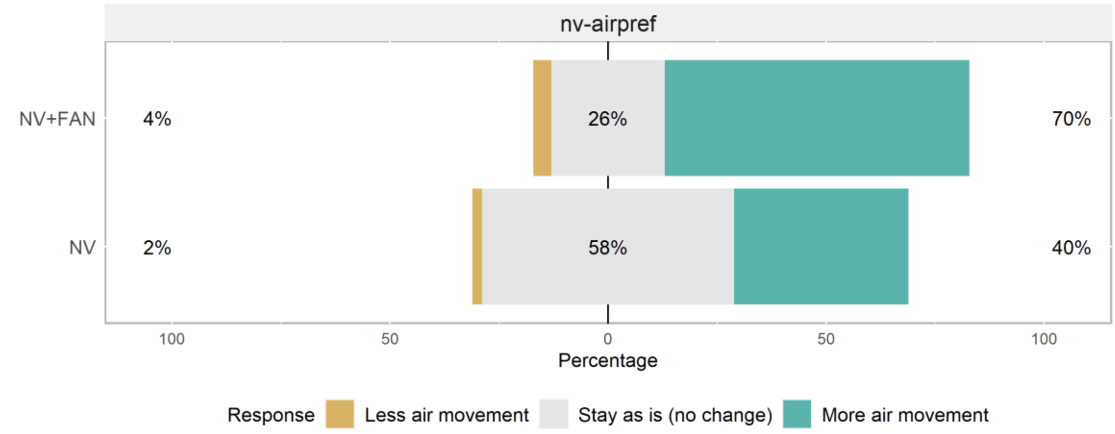
Figure 20 and Figure 21 illustrate the air movement evaluation under NV conditions. Households gave more optimistic feedback in NV rather than in NV+FAN for both acceptability and preference criteria. The proportions of “acceptable and little air movement” and “acceptable and too much air movement” differed significantly among NV and NV+FAN samples (Figure 20). Moreover, the unacceptability rate due to low air movement is higher in NV+FAN. In the same line of reason, the proportions of preference for “more air movement” and “stay as is” were inverted in both samples. A significant proportion of “stay as is” was observed in NV, while the massive preference in NV+FAN was to have more air movement (Figure 21).

Figure 20 – Air movement acceptability under NV strategies



Source: elaborated by the author

Figure 21 – Air movement preference under NV strategies

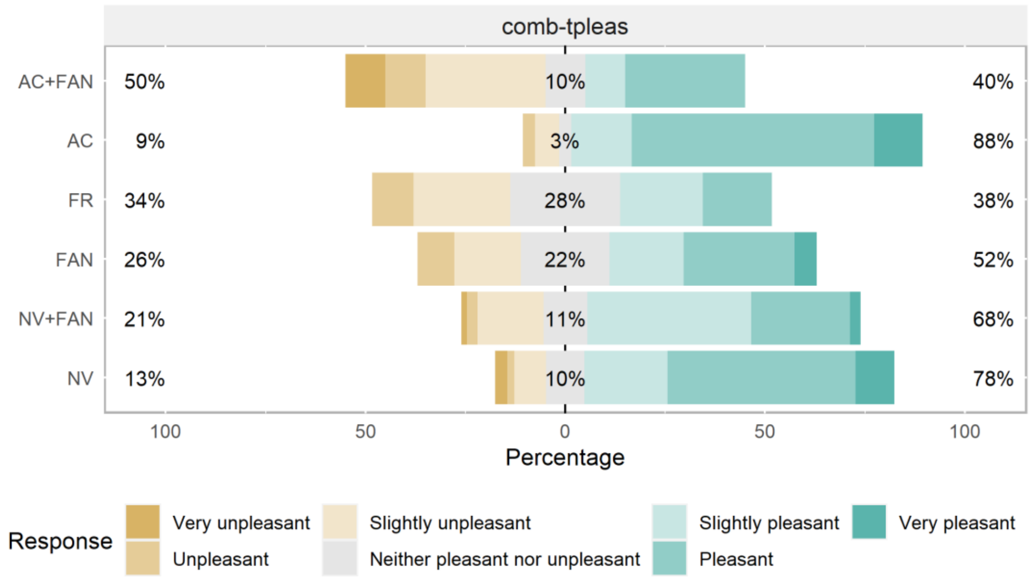


Source: elaborated by the author

The more positive air movement evaluation in NV compared to NV+FAN does not seem to reflect the assumed indoor air velocities or the relative humidity since their distributions (median values and interquartile ranges) are similar among the running strategies. Nevertheless, the influence of indoor air temperature on air movement evaluation can be discussed. However, it should be noted that the highest air temperatures of the long-term monitoring (> 31 ºC) were recorded under NV. Thus, the corresponding evaluation has been considered so far.

The thermal comfort evaluation comprises pleasantness (comb-tpleas), sensation (comb-tsens) and preference (comb-tpref) responses illustrated in Figure 22, Figure 23 and Figure 24, respectively. The more significant proportions in the positive scale of thermal pleasantness ("slightly pleasant", "pleasant", and "very pleasant") were recorded in AC – 88%, followed by NV – 78% (Figure 22). The proportions of "very pleasant" responses are also greater under AC. Similarly, the more significant proportions of preference for not changing the thermal environment were registered in AC – 85% and NV – 65% (Figure 24). It can be concluded that even if the thermal environment is pleasant, some households would prefer to feel colder in NV. Although AC and NV samples are similar regarding the neutral thermal sensation, AC responses are skewed towards the colder side of the thermal sensation scale (Figure 23). In comparison, NV responses are skewed towards the warmer side, following the environmental conditions depicted in Figure 18.

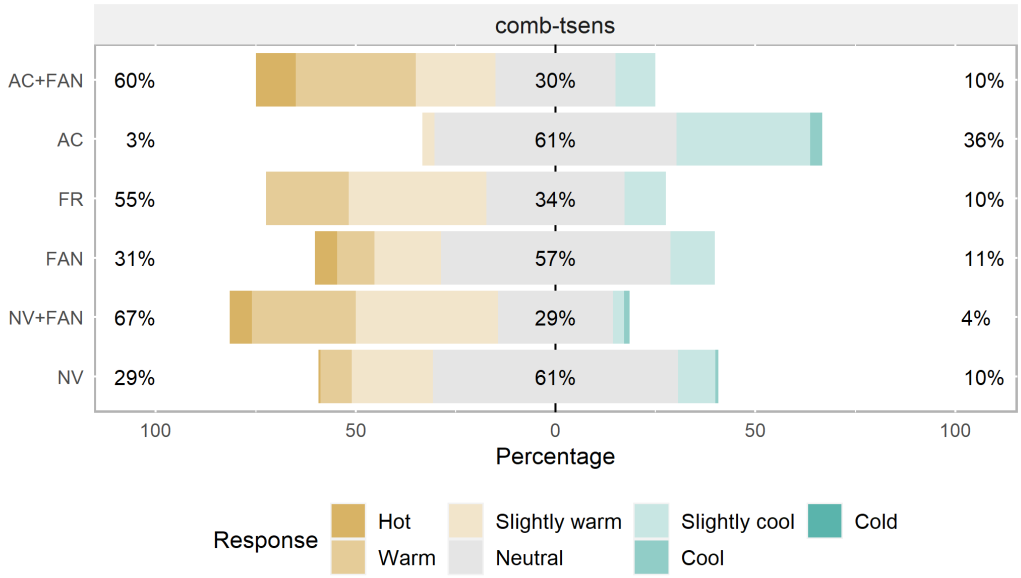
Figure 22 – Thermal pleasantness responses by running strategy



Source: elaborated by the author

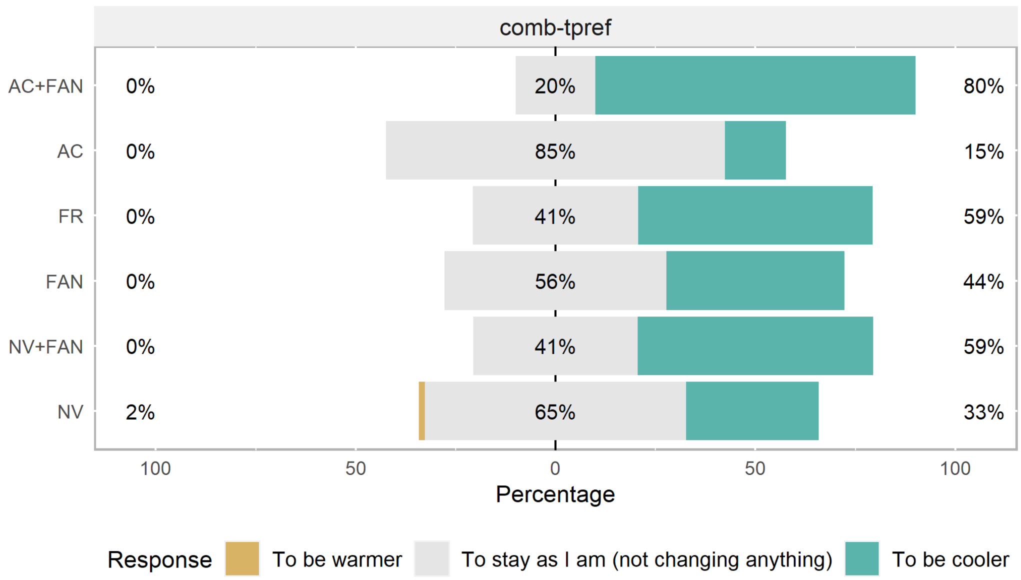
The differences in indoor air temperature and relative humidity between AC+FAN compared to AC and NV+FAN or FAN compared to NV (Figure 18) reflected on households' subjective evaluation. Therefore, the overall evaluation under AC+FAN is worse than under AC – and NV, with similar air temperature and relative humidity distribution. Similarly, the overall evaluation under NV+FAN and FAN is worse than under NV, except for the thermal sensation responses (Figure 23). The thermal pleasantness, sensation and preference responses under free-running (FR) mode are also unfavourably compared to NV despite similar environmental conditions. Thus, more significant unpleasant responses, slightly warm to hot sensations and preference to be colder rates were recorded in FR.

Figure 23 – Thermal sensation responses by running strategy



Source: elaborated by the author

Figure 24 – Thermal preference responses by running strategy



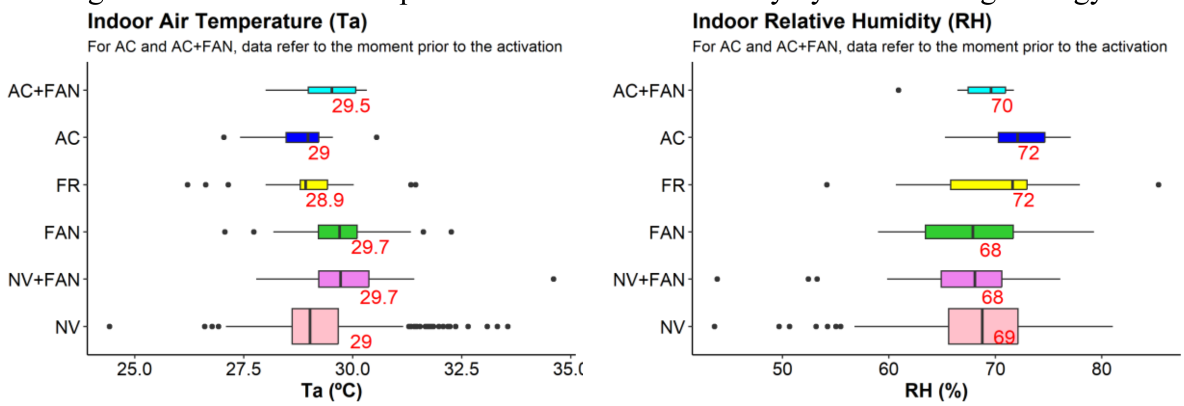
Source: elaborated by the author

4.2.2 Exploring the influence of indoor and outdoor thermal environments on choosing a conditioning strategy

Considering that NV is a primary conditioning strategy in most Brazilian homes, the occurrence of complementary strategies with fans turned on (FAN running) and or AC could be motivated by some factors. This subsection is dedicated to examining the impact of indoor and outdoor thermal environmental variables on the current room operation mode – mainly when AC is activated. It is observed in Figure 25 that the indoor air temperature conditions registered prior to the AC activation are similar to those recorded under NV. Therefore, households might have motivations to resort to AC other than those related to the thermal domain. However, indoor air temperatures were slightly higher under AC+FAN, suggesting a thermal comfort motivation behind fan operation concomitantly to AC.

Compared to the indoor variables currently recorded under AC and AC+FAN in Figure 18, it is observed that the drops in temperature and humidity were more significant in AC (1.9 °C and 15% in median values) than in AC+FAN (1.1 °C and 2% in median values). Resorting to fans in NV rooms is also related to thermal discomfort caused by heat – the median indoor air temperatures were 0.7 °C higher under NV+FAN and FAN operating modes. Nevertheless, the highest air temperatures (> 31 °C) reported as outliers in the NV sample from Figure 25 suggest non-thermal constraints to adopting a complementary cooling strategy.

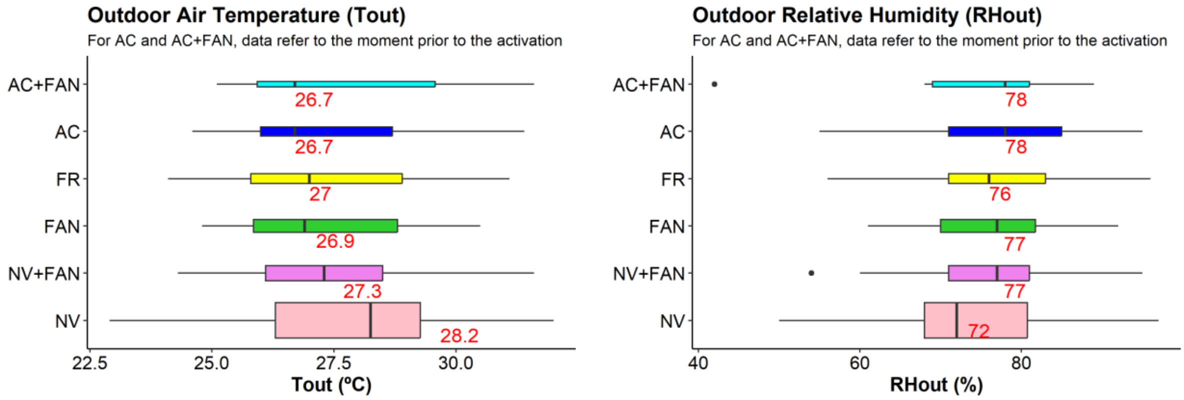
Figure 25 – Indoor air temperature and relative humidity by conditioning strategy



Source: elaborated by the author

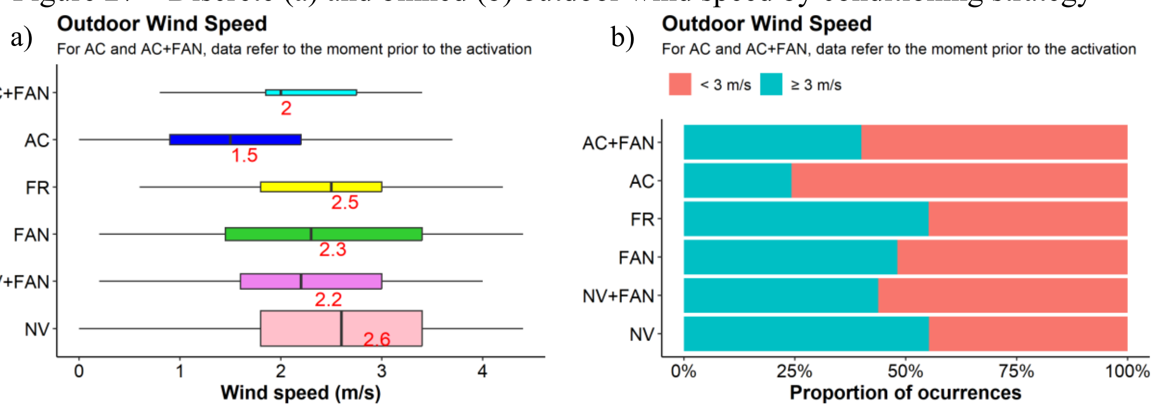
In contrast to the air temperature and relative humidity recorded indoors, the respective outdoor variables corresponding to the moments before AC activation were similar between AC and AC+FAN samples (Figure 26). The most diverse outdoor conditions among all running strategies came from NV – the operating strategy with the broadest environmental conditions. Compared to current conditions under NV, the lower air temperatures and higher relative humidities when turning AC on suggest no evident influence from those outdoor thermal variables when resorting to AC strategies.

Figure 26 – Outdoor air temperature and relative humidity by conditioning strategy



Source: elaborated by the author

Figure 27 – Discrete (a) and binned (b) outdoor wind speed by conditioning strategy



Source: elaborated by the author

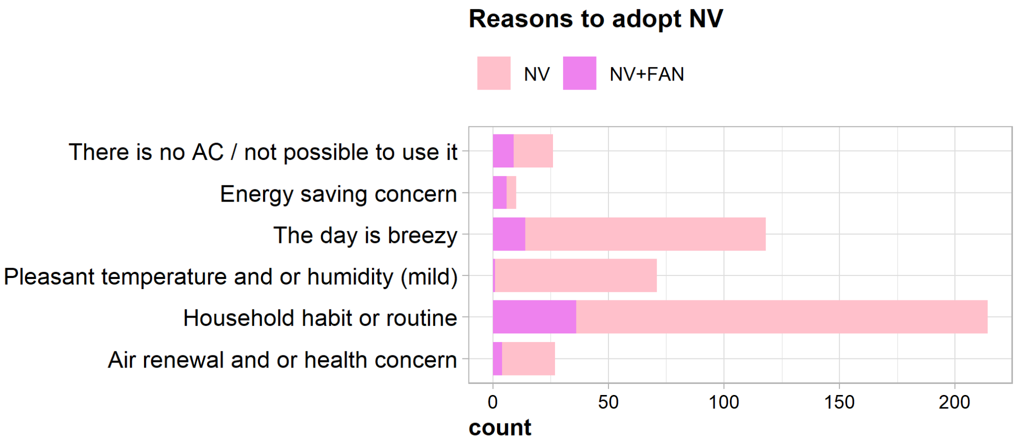
The outdoor wind speed was adopted to analyse the impact of air movement from natural ventilation (breeze) on the current conditioning strategies (Figure 27). The highest wind speeds occurred under NV, closely followed by FR – when windows were closed. In contrast, the lowest wind speeds were linked to AC, indicating an association between low wind speed and resorting to AC. The same association is verified when resorting to fans to increase indoor air movement, despite the slight difference in wind speed values in NV+FAN, FAN and AC+FAN samples compared to NV. Moreover, the highest median values of indoor air temperature were recorded in those samples, corroborating the option for turning on fans and or AC.

4.2.3 Exploring the reasons to adopt and not to adopt natural ventilation at home

As seen in subsection 4.2.2, the indoor and outdoor thermal environments partially explained households' choice of conditioning strategy at home. Therefore, the reasons to adopt and not adopt natural ventilation at home are depicted in the present subsection to further address this issue. Households currently under NV or NV+FAN (running strategies with windows open, n = 471) responded with a primary reason to adopt natural ventilation. Instead, households in rooms with windows closed (n = 126) responded with a main reason not to adopt natural ventilation at that moment.

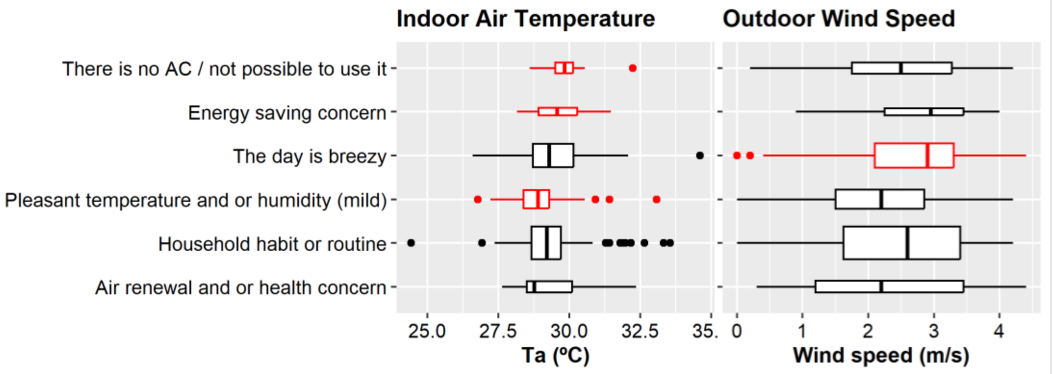
The quantitative reasons for adopting NV are presented in Figure 28. The most cited is the household habit or routine, indicating that households are not bothered by the current thermal environmental conditions (mild, hot or breezy) in most occurrences. However, those conditions were cited as motivations mainly on two occasions: breezy day (second most cited) and pleasant temperature or humidity (third most cited). The indoor air temperature and the outdoor wind speed are depicted in Figure 29 to confirm the association between those reasons and the respective variables. Households reporting NV usage due to pleasant temperatures or humidity experienced overall air temperatures lower than in other samples. In the same line of reason, the overall wind speeds linked to "the day is breezy" responses were slightly higher, except for households reporting energy-saving concerns. However, those have also experienced slightly higher air temperatures. The use of fans to increase indoor air movement is minor for households reporting a breezy day or a pleasant temperature.

Figure 28 – Reasons to adopt NV and the running strategies



Source: elaborated by the author

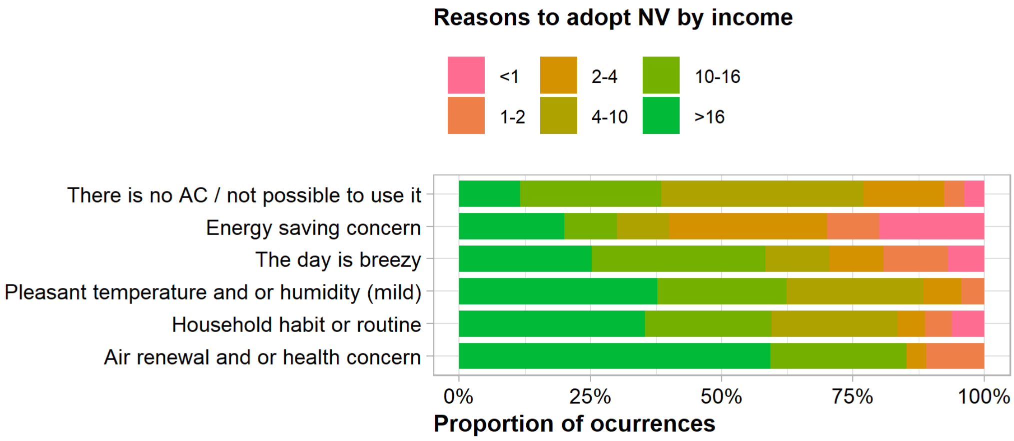
Figure 29 – Indoor air temperature and outdoor wind speed by the reasons to adopt NV



Source: elaborated by the author

The use of NV due to limitations in AC usage (not having AC or being unable to afford its usage) is associated with more frequent use of fans (proportion of NV+FAN samples in Figure 28) and high indoor temperatures (~30 °C, highlighted in red colour in Figure 29). By analysing the family income distribution in Figure 30, a concentration of low-income ranges (<4 minimum wages) is observed among households concerned with energy savings, despite the predominance of high-income ranges in the surveyed sample (Table 6).

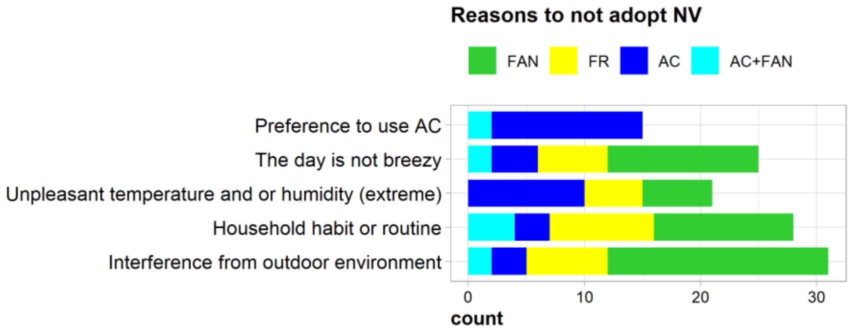
Figure 30 – Family income distribution by the reasons for adopting NV



Source: elaborated by the author

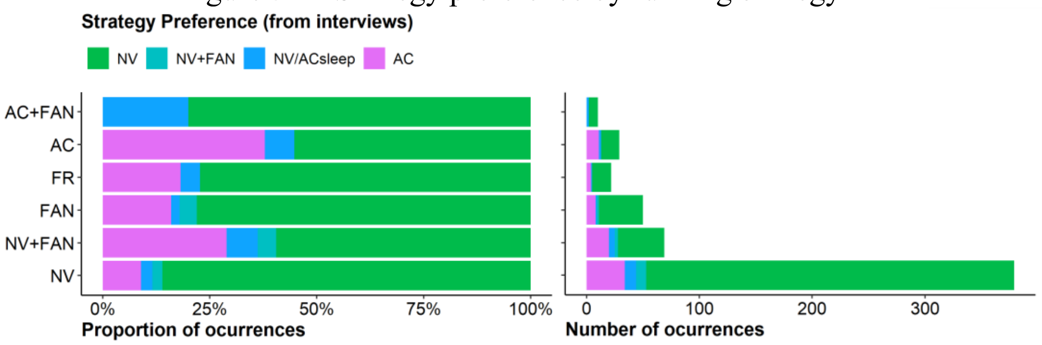
Five reasons not to adopt NV as a conditioning strategy were cited the most in the long-term monitoring and are highlighted in Figure 31. The interference from the outdoor environment was the most cited, followed by the household habit or routine of keeping windows closed. The outdoor interference impedes the opening of windows and doors for natural ventilation: entrance of unwanted solar radiation, use of blinds, strong wind, rain, insects, noise, odours, privacy, and security. The absence of a breeze from NV was the third most cited reason. For all the abovementioned reasons, households resorted to fans instead of air-conditioning in most occurrences.

Figure 31 – Reasons to not adopt NV and the running strategies



Source: elaborated by the author

Figure 32 – Strategy preference by running strategy



Source: elaborated by the author

In contrast, households who preferred to use AC used solely with or without fans. When windows were closed due to unpleasant temperatures or humidity, AC was turned on in half of the occurrences. As depicted in Figure 32, households who prefer to use AC at home are prone to use it more frequently. In contrast, more frequent NV usage was verified among households preferring to use NV at home. Nevertheless, the non-adoption of NV was minor in the long-term monitoring, confirming the status of a primary conditioning strategy for natural ventilation.

4.2.4 Discussion

The outcomes of long-term residential monitoring confirmed the primary use of natural ventilation in a Brazilian hot and humid climate due to thermal and non–thermal–related motivations. The outcomes are aligned with the households' preferences and routines reported in interviews. Most households (80%) prefer to use NV at home for several reasons and adopt it on most occasions (~80% corresponding to NV and NV+FAN in Table 5) of their occupancy routine except for sleep time, despite the large availability of AC in this sample (Table 6). Moreover, the frequency of usage and preference were also aligned for both NV and AC strategies. Ramos (2020) reported a similar preference pattern across the Brazilian territory, and so have the outcomes of the national survey presented in section 4.1. On the one hand, the preference for NV at home was not explained by income or AC availability in the long-term monitoring, per the national survey. On the other hand, the preference for NV+FAN was reported only by two households (in contrast to the national survey) who did not own AC.

Additionally, 5% of households reported a specific preference for NV during the day and AC during sleep. As learned from interviews and QL forms, NV and AC usage is related to households' routines for most occurrences, which their preferences can drive. When asked about adaptive measures at home during interviews, some households did not mention "turn on AC", and most did not cite "open or close windows". The absence of mentions indicates how inherent to households' routines those adaptive actions are – except for turning on AC in the low-income (<4) sample, which has the lowest AC availability (30%). Also, the declared preference for NV during the day and AC during sleep was minor (5%) compared to this sample's AC availability (63%). Therefore, this specific preference might be underestimated among the surveyed households.

The routine of AC adoption during sleep was hard to capture through long-term monitoring, except for the households who turned AC on early at night (before going to sleep) or did not turn it off early in the morning. Therefore, the proportion of QL occurrences under AC modes (AC-turned-on in Table 5) does not reflect the actual frequency of AC usage in those residences. Instead, the AC availability is a more reliable reference of how many participants are prone to use it following the sleep pattern reported in interviews. Nevertheless, AC was not usual during non-sleep hours, and NV prevailed regardless of income.

The use of AC to sleep – i.e., turned on overnight – possibly explains the higher relative humidity and the lower air temperature values before AC activation corresponding to the AC sample in Figure 25 and Figure 26. Therefore, switching from NV to AC was less related to outdoor and indoor air temperature and relative humidity. The lower outdoor wind speeds experienced by households before turning the AC on (Figure 27) could influence their decision, as night-time wind speeds are typically lower in São Luis. However, routine AC use characterises a continuous disconnection between indoor and outdoor environments.

A similar trend regarding the night-time AC usage pattern was reported by Mori et al. (2020) in Malaysia and Indonesia and Daniel (2018) in Australia. Mori et al. (2020) reported a window-opening schedule that varied among AC owners and non-owners. The authors indicated “insects” as the main hindrance to keeping windows open from a specific time of the day. Accordingly, outdoor interference posed impediments to opening windows and consequently to adopting NV in some occasions of long-term monitoring, as verified in previous studies (INDRAGANTI, 2010b; MALIK et al., 2020; RAMOS, 2020). Apart from habitual AC usage, AC was turned on mainly due to personal preference and an unfavourable thermal environment.

Despite the differences in indoor conditions between NV and AC operating modes (Figure 18), the corresponding thermal comfort evaluations are similar in some aspects – particularly the thermal pleasantness responses. Air movement evaluation from households under NV indicated an overall satisfactory scenario: 65% judged air movement as enough or too much and acceptable, and approximately 60% preferred not to change the current air movement. In addition to the usual metabolic rate and clothing adaptations in the residential sector, air movement from NV seems to have compensated for the higher indoor air temperatures compared to the AC rooms.

Previous studies indicated the role of increased air movement on thermal pleasure (PARKINSON; DE DEAR; CANDIDO, 2016), leading to occupants’ thermal environmental acceptability under similar controlled environmental conditions (DE DEAR, 2011). Moreover, dynamic airflows from mechanical devices have improved subjects’ thermal sensation and comfort votes in climate chambers and real-office settings (CUI et al., 2013a; HUA et al., 2012; ZHOU et al., 2006). Experiencing such air movement conditions from natural ventilation in residences – in which occupants adapt more flexibly – might contribute to the overall positive evaluation of the thermal environment.

In contrast to AC usage, fan usage is mainly associated with thermal environmental and economic constraints. The few occurrences of combined AC and fan usage are more likely related to inefficiency from the building envelope insulation or the equipment adopted. The thermal and air movement evaluation under FAN operating modes suggests an unfavourable scenario in which fans are adopted to mitigate thermal discomfort from higher indoor air temperatures and lower outdoor wind speeds. Thus, the fan adoption was related to indoor air temperature and outdoor wind speed but not outdoor air temperature. Conversely, Daniel (2018) reported a strong relationship between outdoor air temperature (in addition to indoor air temperature) and ceiling fan usage in Darwin, Australia.

The non-influence of outdoor air temperature on adopting NV (with and without fans) and AC in the present study contradicts the previous investigations in which this variable was one of the most determinants of window-opening and fan/AC usage behaviours (KIM et al., 2017; LAI et al., 2018; YAO; ZHAO, 2017). Alternatively, the outcomes agree with studies in which indoor temperature parameters were more relevant than outdoors (DANIEL, 2018; INDRAGANTI, 2010b; RIJAL, 2014). The outdoor wind speed was also relevant to this study's reality since the highest wind speeds were related to adopting natural ventilation due to a breezy day.

Households living in warm and hot climates rely on fans for a suitable thermal environment, particularly in low-income dwellings (MALIK et al., 2020; SOEBARTO; BENNETTS, 2014). Households with limitations to AC usage were adopting fans to support NV the most through long-term monitoring. Moreover, AC is the households' preferred conditioning strategy in 30% of the responses given in NV+FAN operation mode – the second largest. Based on the interviews, 63 of 106 residents reported energy-saving concerns in some order of importance, regardless of monthly income or perception of cooling energy cost. However, the daily concern reported on the QL forms ("energy saving concern" in Figure 30) was mainly linked to low-income households, indicating this influence on setting a conditioning strategy at home.

4.3 THERMAL DELIGHT AND THE DYNAMIC ASPECTS OF AIR MOVEMENT FROM NATURAL VENTILATION: FINDINGS FROM A RESIDENTIAL POINT-IN-TIME SURVEY IN BRAZIL'S HOT AND HUMID CLIMATE

The thermal and air movement evaluation of households during the point-in-time survey (researcher's visits to their homes) is addressed in this subsection. One hundred and six participants from 56 residences were interviewed and filled in the IQ forms, providing 523 responses to P1-P5 questions (air movement acceptability and preference, thermal pleasantness, thermal sensation and preference) and 106 responses to P6 and P7 questions (final air movement evaluation).

The dataset "IQ form responses" gathered 629 valid responses after excluding missing information – e.g. whether participants had to be absent from the interview room for a moment. Before starting the interview and the point-in-time survey, participants were asked to describe the activity they had been performing in the last 30 minutes and which clothes they wore. The information is summarised in Table 7. The sedentary activities and light clothing were predominant, although a significant portion of residents (~40%) performed non-sedentary activities such as cleaning the house or preparing a meal.

Table 7 – Participants' estimated metabolic rate and clothing insulation in the last 30 minutes before starting the point-in-time survey

Metabolic Rate (met)*			**Clothing Insulation (clo)***		
Category	*n*	*% total*	*Category*	*n*	*% total*
<1 met	93	14.8	0.25 clo	297	47.2
~1.1 met	286	45.5	0.36 clo	225	35.8
>1.6 met	250	39.7	0.57 clo	95	15.1
* From IQ form responses (n = 629)			0.74 clo	12	1.9

Source: elaborated by the author

The researcher took notes on the conditioning strategy during the point-in-time survey. All rooms were naturally ventilated, and most were naturally ventilated only (NV). Pedestal or table fans were turned on occasionally to increase indoor air movement (NV+FAN). As the researcher's presence could influence the chosen strategy for the point-in-time survey, the conditioning strategy in the room and at the time corresponding to the interviews was investigated. Thus, the researcher could conclude whether the current strategy corresponded to household routines (routine) or not (not routine). A summary is described in Table 8.

Table 8 – Quantitative of NV and NV+FAN running strategies in the point-in-time survey

Running Conditioning Strategy						
Category	*Residences*		*Interviewees*		*IQ form responses*	
	n	*% total*	*n*	*% total*	*n*	*% total*
NV (routine)	35	62	72	68	480	76
NV (not routine)	5	9	8	8		
NV+FAN (routine)	10	18	16	15	149	24
NV+FAN (not routine)	6	11	10	9		
Total	56	100	106	100	629	100

Source: elaborated by the author

According to Table 8, most current conditioning strategies observed during point-in-time surveys corresponded to households' routines (80%). The non-use of fans when those were the routine operation (NV – not routine) was related to an atypical day regarding temperature or air movement (more ventilated than usual) on half of the occasions. However, the opposite situation – unusually resorting to fans because of unfavourable air temperature or air movement conditions – was not verified. The use of fans may have reflected a concern with the researcher's presence in this case (NV+FAN – not routine).

Eleven of the 56 rooms where point-in-time surveys took place (primarily living rooms) had air conditioning equipment. However, none was turned on during the interviews, following households' routines with air conditioning – mainly turned on during sleep time in bedrooms and during social meetings in living rooms. Accordingly, nobody declared to routinely use air conditioning at home at occupancy times similar to the interviews (during the mornings, afternoons and early evenings).

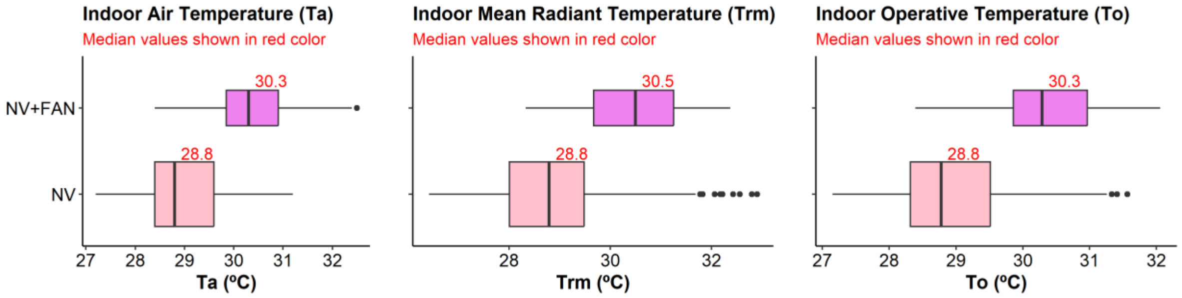
4.3.1 Indoor environmental conditions

The measured air temperature (T_a) and relative humidity (RH), as well as the derived mean radiant temperature (T_{rm}), operative temperature (T_o) and air velocity (V_a) during the point-in-time survey, are illustrated in Figure 33 to Figure 35. The temperature readings were between 27-32 °C, except for some outliers in T_{rm} > 32 ºC (Figure 33). Similarly to the long-term monitoring, the highest air temperatures were recorded under NV+FAN compared to NV. Therefore, fans were more frequent when T_a, T_{rm} and T_o ≥ 30 °C. Moreover, each running strategy's T_a, T_{rm} and T_o parameters distributions were similar.

According to Figure 34, relative humidity was slightly skewed towards lower values under NV+FAN operation. Lower relative humidities were related to higher air temperatures, as expected. Thus, the difference in median values was equal to 10%. Nevertheless, maximum

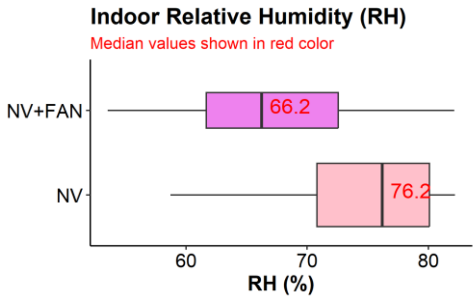
RH measurements > 80% were similar in both NV and NV+FAN operation modes. The relative humidity was within the comfortable range of 50-80% – not too high or too low.

Figure 33 – Indoor temperatures by running strategy during the point-in-time survey



Source: elaborated by the author

Figure 34 – Indoor relative humidity by running strategy during the point-in-time survey



Source: elaborated by the author

The time-based air velocity calculations are summarised in Frame 2. An average time of 1 minute – as recommended in ASHRAE 55 Standard – was adopted before (Va-1) and after (Va-1min-avg) participants started responding to questions P1-P5 repeatedly. Thus, the parameter Va-1min-avg corresponded to the most recent mean air velocity experienced by the participants when evaluating the point-in-time thermal and air movement conditions. The other parameters (Va-5, Va-10 and Va-all) were adopted as a reference to understand air velocity variations in time and the respective impact on subjective perception.

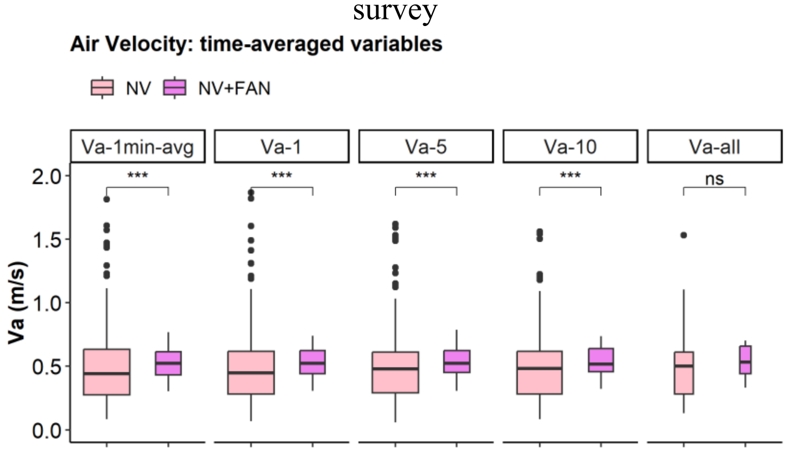
Frame 2 – Definition of time-averaged air velocity calculations in the point-in-time survey

Time-averaged air velocity calculations	
Parameter	*Definition*
Va-1min-avg	Averaged during 1 minute, from the moment participants started responding R1-R5
Va-1	Averaged 1 minute before participants started responding R1-R5
Va-5	Averaged 5 minutes before participants started responding R1-R5
Va-10	Averaged 10 minutes before participants started responding R1-R5
Va-all	Averaged from the beginning of the point-in-time survey to the final evaluation (F)

Source: elaborated by the author

The air velocity characterisation in the point-in-time survey is depicted in Figure 35. Air velocity distributions under NV were skewed towards the lower V_a values (lower values ~ 0.1 m/s and median values close to 0.5 m/s) with outliers above 1 m/s. In contrast, a small V_a range was observed under NV+FAN, with slightly higher median values. The instantaneous aspect of V_a under NV is perceptible in the highest V_a values in Va-1min-avg and Va-1 parameters in contrast to the mean air velocity in the complete point-in-time survey (Va-all). However, their frequency was insignificant in this sample since they were characterised as outliers. Accordingly, there were no significant differences in distribution between the five time-averaged V_a variables under NV (Kruskal test, $p = 0.98$).

Figure 35 – Indoor time-averaged air velocities by running strategy during the point-in-time survey



Source: elaborated by the author

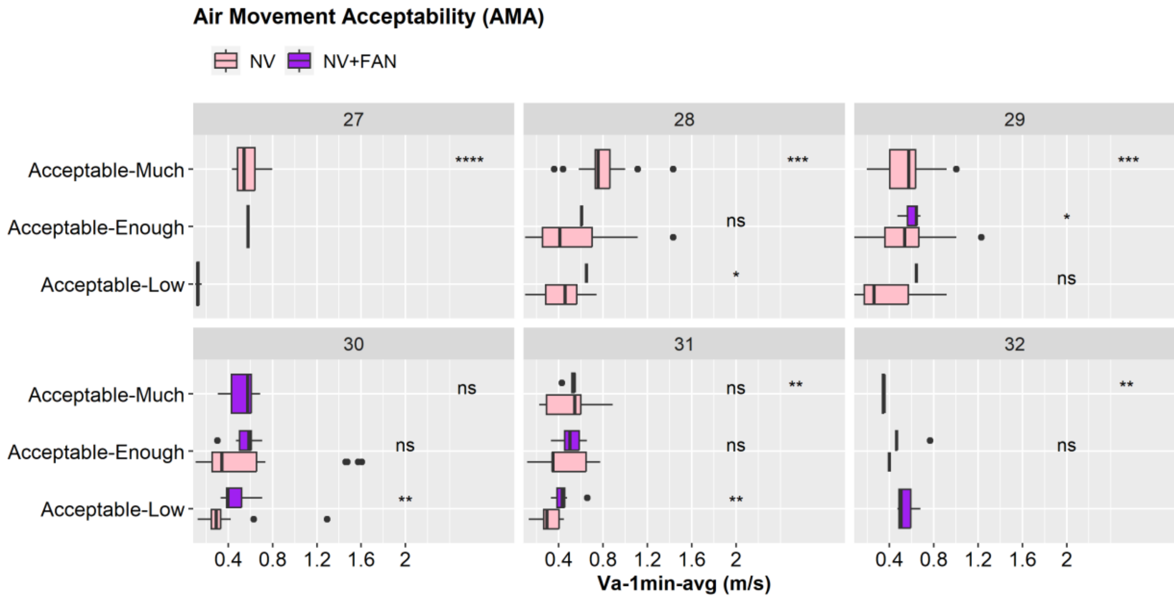
The comparison between air velocities in NV and NV+FAN showed significant differences in all time-averaged V_a variables, except for Va-all. The V_a range was prominent in the shorter average times and decreased until the average time corresponding to the complete point-in-time survey. It is concluded that NV and NV+FAN samples were similar regarding the overall mean air velocity but diverse regarding the variations within-survey. Therefore, NV+FAN was adopted as a comparison sample to NV throughout the thermal and air movement assessment in the following subsections.

4.3.2 Overall thermal and air movement evaluation

The point-in-time subjective evaluation corresponded to questions P1-P5 repeatedly asked (R1-R5) throughout the interviews. The discrimination of air velocities related to the points in the voting scales for each running strategy is presented in Figure 36 to Figure 40.

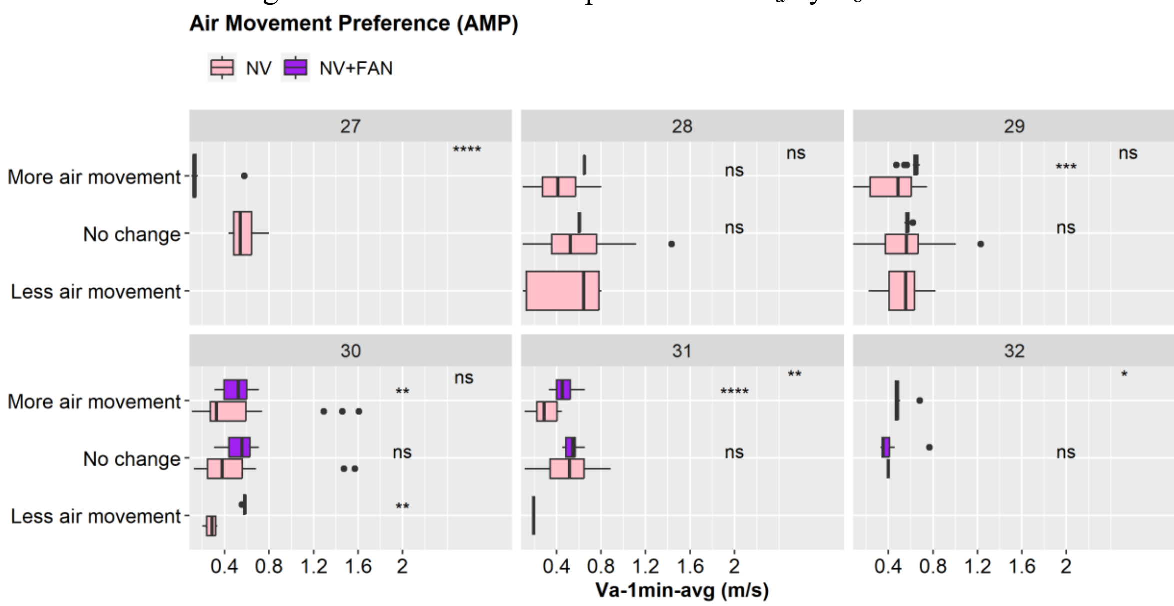
Operative temperature bins were adopted in the analyses since indoor temperature conditions differed between NV and NV+FAN strategies. Significance levels aligned to the horizontal coordinate = 2 m/s refer to the comparisons between NV and NV+FAN samples. Meanwhile, the significance level indicated on the upper left of each T_o frame refers to the comparison across the voting scales (e.g. the seven-point sensation scale). The n < 10 observations samples were excluded from the analyses to facilitate graphical interpretation.

Figure 36 – Air movement acceptability x V_a by T_o bins



Source: elaborated by the author

Figure 37 – Air movement preference x V_a by T_o bins

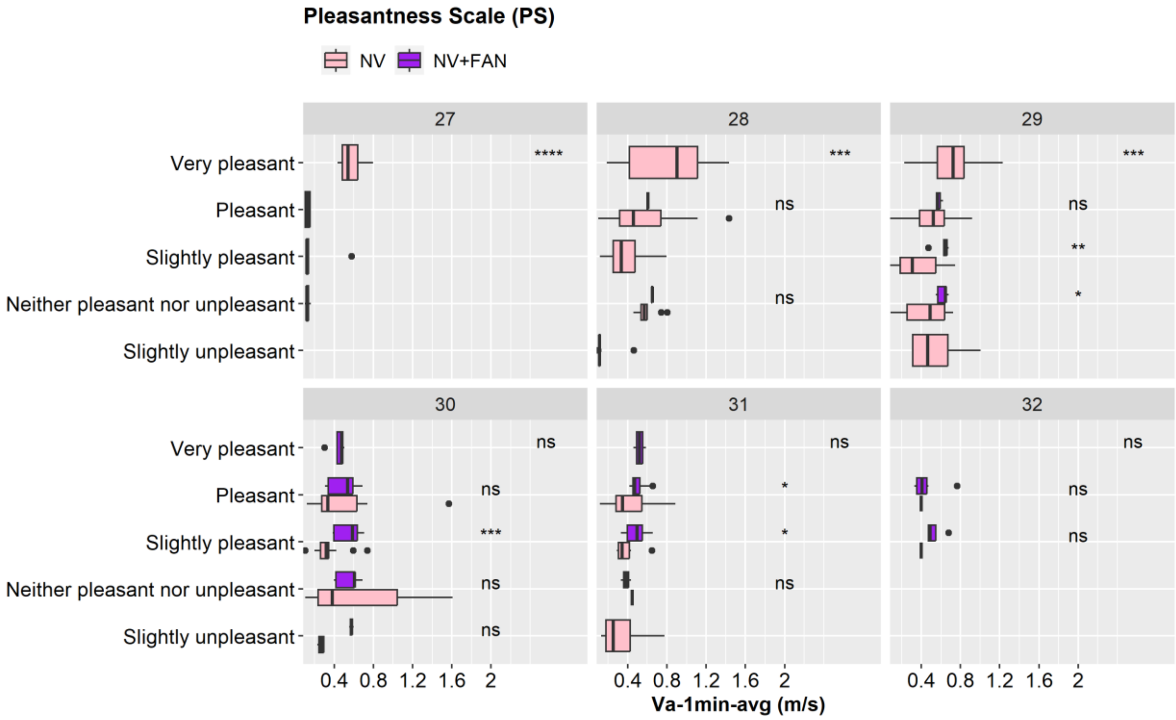


Source: elaborated by the author

The air movement evaluation (acceptability and preference criteria) is illustrated in Figure 36 and Figure 37. The air velocities judged as acceptable ranged between 0.2-1 m/s in 28-29 T_o bins. The upper limit of acceptable air velocity is reduced to approximately 0.8 m/s for $T_o \geq 30$ °C (outliers not considered). It is observed that V_a values corresponding to "enough" and "much air movement" responses are similar, in contrast to the values related to "low air movement" votes which lead to significant differences in distribution (Figure 36). Accordingly, the air velocities related to "more air movement" and "no change" responses are also similar (Figure 37). The preference for less air movement was minor (n = 36) and showed no clear relationship with the 1-minute averaged air velocities.

Regarding the comparison between NV and NV+FAN samples, it is noted that the median V_a values and interquartile ranges were slightly lower in NV – following the distributions shown in Figure 35 – in almost all available comparisons. However, it was not statistically significant (ns) on most occasions. Consistent trends to be drawn in this data are the differences in V_a distribution across "acceptable-low air movement" and "more air movement" responses, which complement each other. Thus, air velocities corresponding to the judgement of low air movement and the desire for more air movement were significantly lower in NV and higher in NV+FAN.

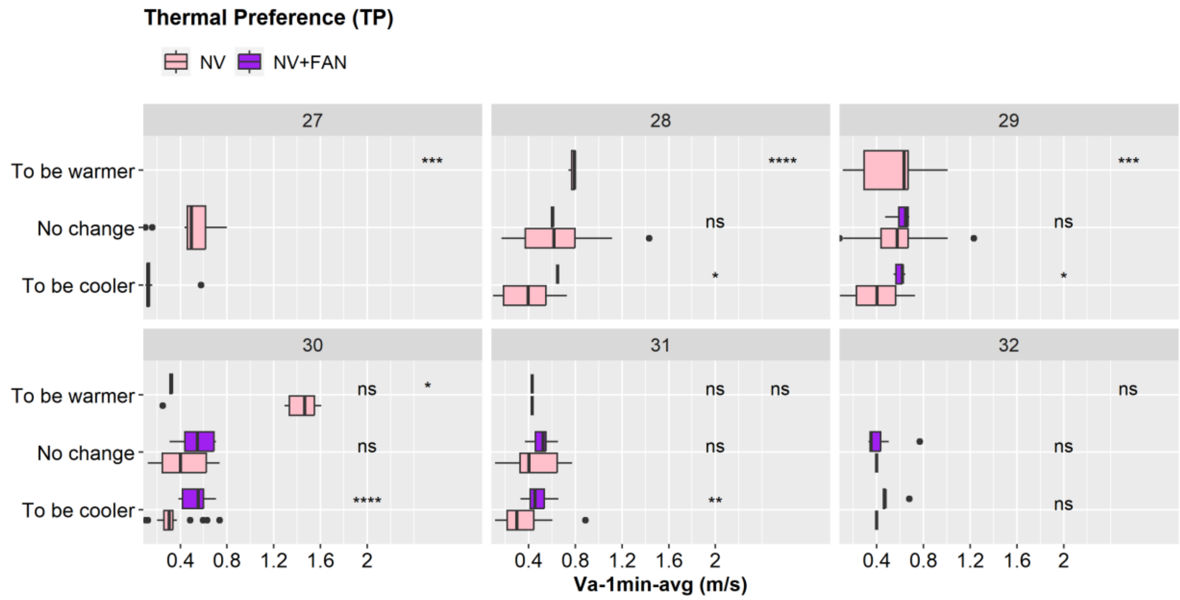
Figure 38 – Thermal pleasantness x V_a by T_o bins



Source: elaborated by the author

The thermal pleasantness evaluation concerning air velocity was impacted by operative temperature (Figure 38). Air velocity distributions across the seven-point pleasantness scale significantly differed when $T_o < 30$ °C. The V_a increase corresponded to the positive responses (+1, +2 and +3) in this circumstance. However, households' responses seem unrelated to air velocity under high operative temperatures ($T_o \geq 30$ °C). Delightful responses ("very pleasant") were observed mainly under V_a in a range of 0.4-1.4 m/s and $T_o < 30$ °C. On the one hand, all the "very pleasant" votes in those operative temperature conditions were registered under NV. On the other hand, the few "very pleasant" votes given under $T_o \geq 30$ °C corresponded to an NV+FAN environment. Following the air movement evaluation, lower V_a values were observed under NV compared to NV+FAN but without statistical significance (ns) in most pair comparisons.

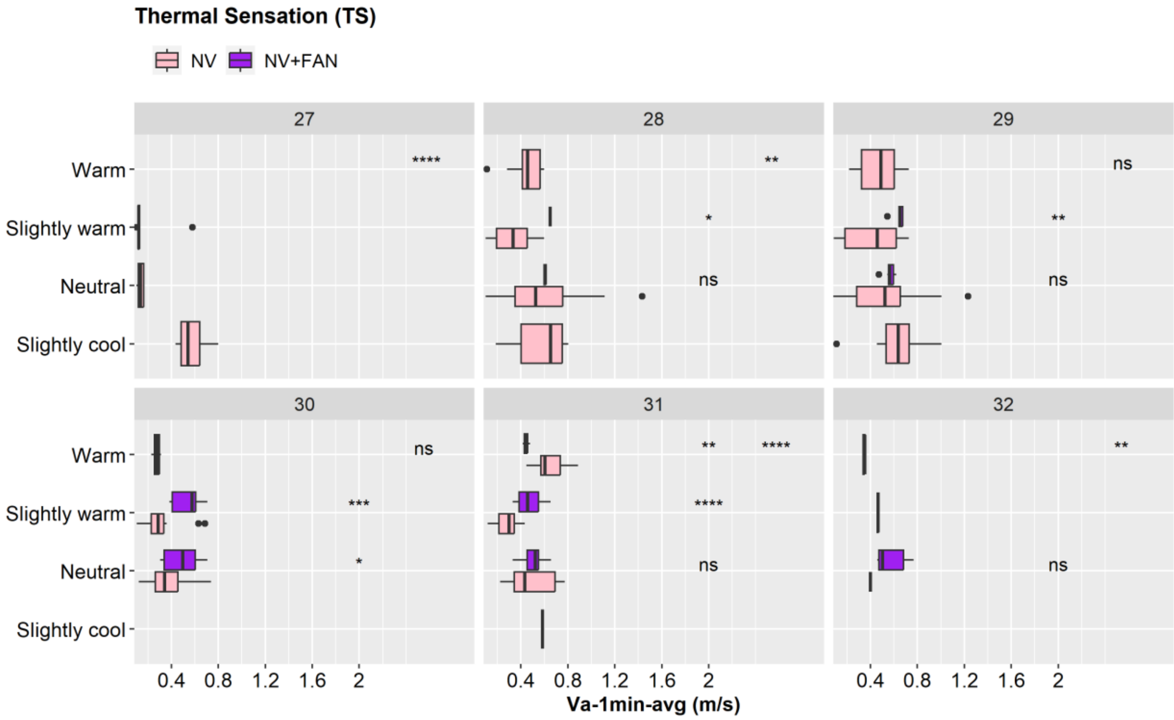
Figure 39 – Thermal preference x V_a by T_o bins



Source: elaborated by the author

Households' thermal preferences and sensations during the point-in-time survey are illustrated in Figure 39 and Figure 40, respectively. Air velocity influenced thermal preference mainly under operative temperatures below 30 °C. V_a values increased from "to be cooler" to "to be warmer" responses, except under $T_o \geq 31$ °C. Concerning thermal sensation, higher air velocities towards the "slightly cool" responses were observed in 27-29 T_o bins, although not statistically significant at 29 °C (Figure 40). Most air velocities related to the neutral and slightly cool thermal sensations were between 0.4-0.8 m/s at 28-29 °C and slightly cool at 27 °C — those conditions also met the preference for not changing the thermal environment in Figure 39.

Figure 40 – Thermal sensation x V_a by T_o bins

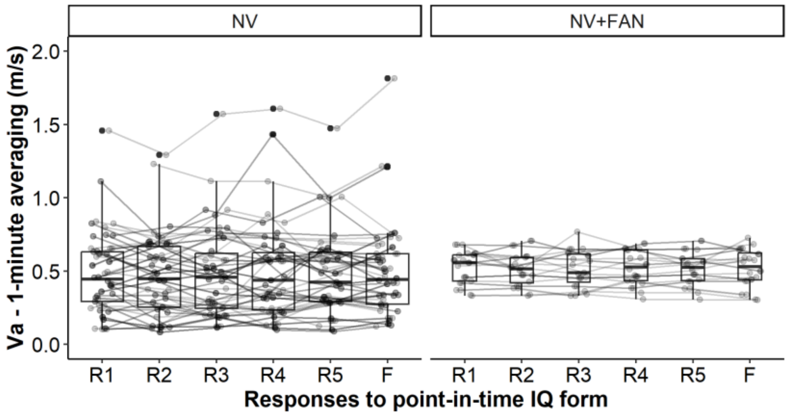


Source: elaborated by the author

4.3.3 Temporal analysis of air velocity and the impact on subjective perception

The distribution of 1-minute time-averaged air velocities according to the moments represented by R1 to R5 (questions P1-P5) and the following final air movement evaluation (P6-P7) is shown in Figure 41. A Friedman test with Dunn-Bonferroni adjustment was conducted for each running strategy to verify any casual influence of voting moments (order) on measured V_a. The results indicated no difference between all groups tested, confirming the random occurrence of V_a in both running modes (Friedman chi-squared = 5.3609, df = 5, p-value = 0.3734 for NV; Friedman chi-squared = 3.9221, df = 5, p-value = 0.5607 for NV+FAN).

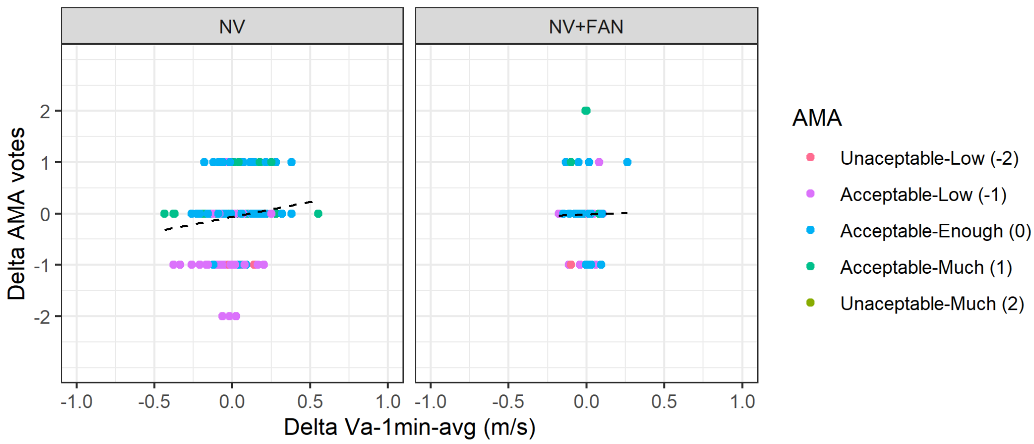
Figure 41 – Paired air velocities across the point-in-time survey by running strategy



Source: elaborated by the author

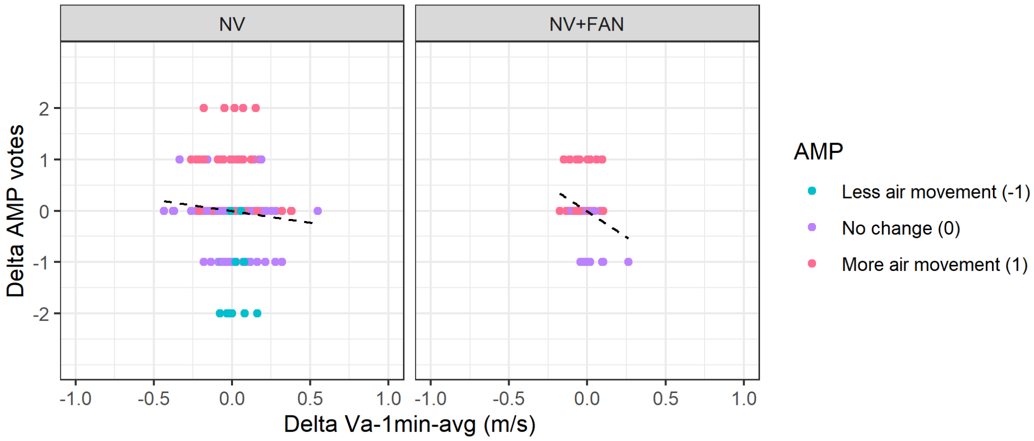
Disregarding any influence of voting moments on air velocity, the temporal dimension of subjective (ordinal) scales and V_a was based on the difference between a voting moment and its precedent – Delta (Δ). Therefore, a single value of ΔV_a corresponded to $V_{a\ R2}$ - $V_{a\ R1,}$ and the same goes for the R3-R2, R4-R3 and R5-R4. Similarly, a delta in the air movement acceptability scale corresponds to ΔAMA = AMA vote $_{R2}$ - AMA vote $_{R1}$. The procedure is to verify the association between increasing or decreasing V_a and changes in subjective scales in a timespan. Air movement acceptability (AMA, Figure 42), air movement preference (AMP, Figure 43), thermal pleasantness (PS, Figure 44 and Figure 45) and air movement satisfaction at the end of the point-in-time survey (AMS, Figure 46) were evaluated under that approach.

Figure 42 – ΔAMA versus ΔVa-1min-avg by running strategy



Source: elaborated by the author

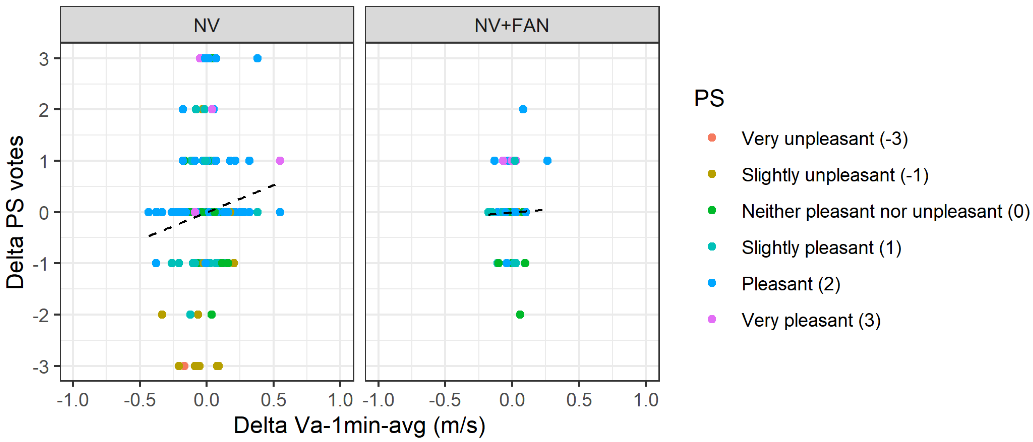
Figure 43 – ΔAMP versus ΔVa-1min-avg by running strategy



Source: elaborated by the author

The increase or decrease in air velocity through consecutive moments of voting (ΔV_a) reached 0.5 and 0.25 m/s under NV and NV+FAN, respectively. The air movement assessment indicated a concentration of unaltered responses (ΔAMA and ΔAMP = 0). Most corresponded to the vote of acceptable and enough air movement in the AMA scale despite the variations in air velocity. There was a tendency to increase AMA votes from -2 (low air movement) to 2 (much air movement) following the increase in V_a under NV, as indicated by the black dashed line in Figure 42. The opposite interpretation – decreasing AMA votes following the decrease in V_a – is also valid. The tendency to maintain the AMA responses throughout the point-in-time survey under NV+FAN was observed.

Figure 44 – ΔPS versus ΔVa-1min-avg by running strategy



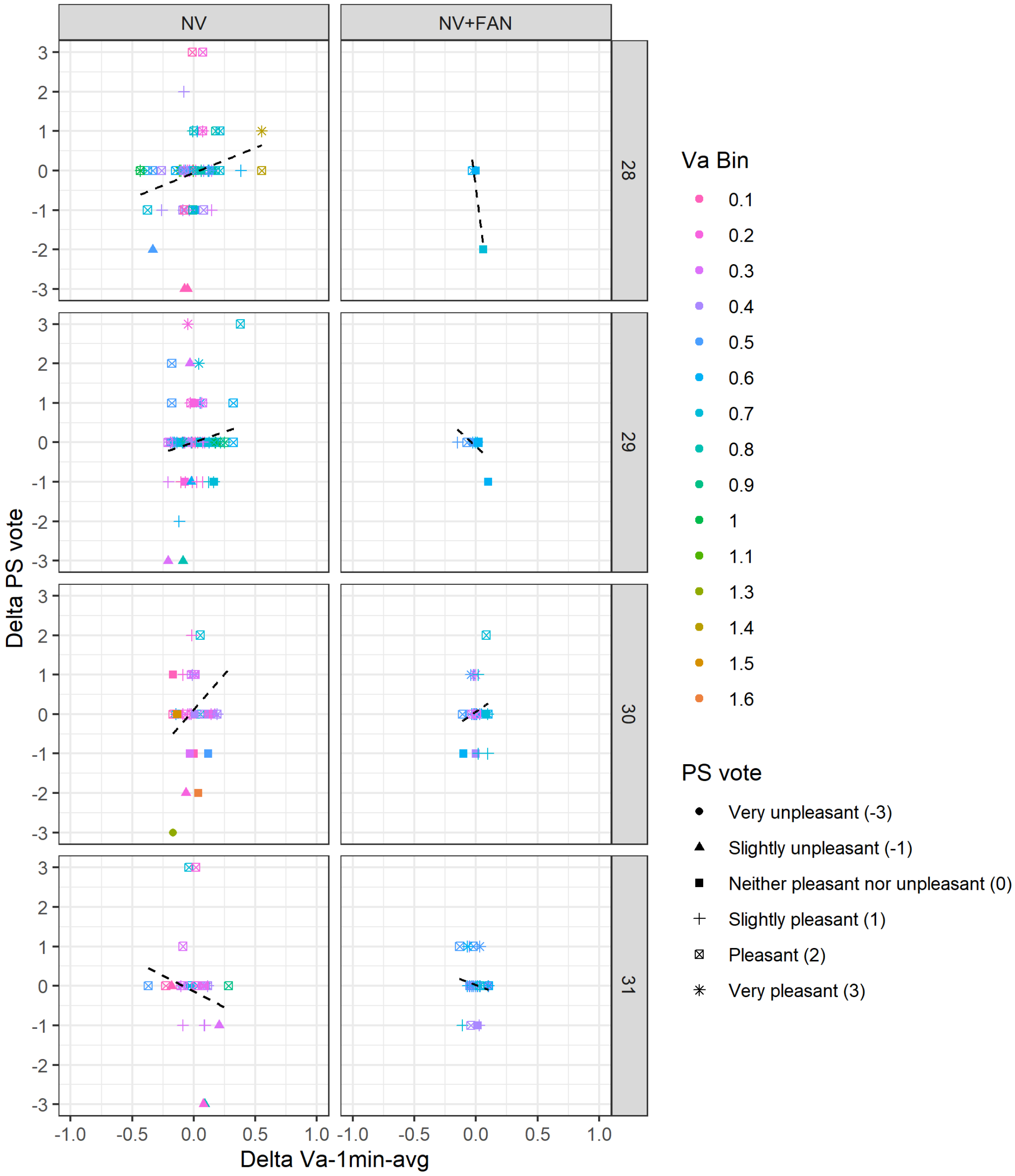
Source: elaborated by the author

A negative ΔV_a led to a positive ΔAMP (towards the "more air movement" vote) in both running strategies (Figure 43). The few changes from "more air movement" to "less air movement" responses (and vice-versa, |ΔAMP| = 2) were observed only in NV but did not correspond to the more significant ΔV_a. Nevertheless, ΔV_a was related to one-point changes ($|\Delta AMP| = 1$) in AMA and AMP scales.

The temporal evaluation of thermal pleasantness responses showed the tendency of increased PS votes following increased 1-minute averaged air velocities, particularly at ΔPS range from -1 to 1 under NV (Figure 44). Overall, the temporal variations in air velocity corresponded to PS responses on the positive side of the scale, maintaining the current vote from the precedent. Similarly to AMP, The more significant ΔPS ($|\Delta PS| = 3$) occurred only under NV and on a few occasions. For instance, the moving towards the negative side of the PS scale ($\Delta PS = -3$, from "pleasant" to "slightly unpleasant") was related to a decrease in air velocity (negative ΔV_a).

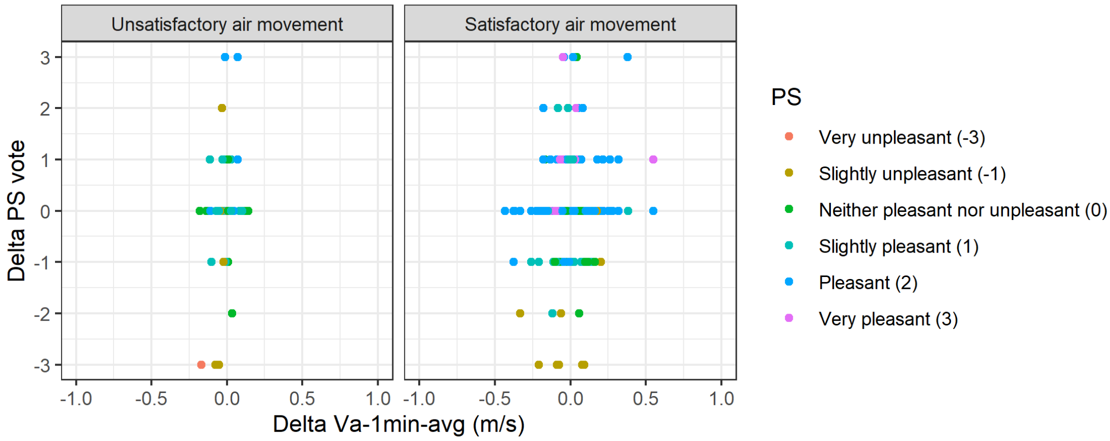
The effect of operative temperature and air velocity bins is considered in thermal pleasantness analysis, as illustrated in Figure 45. Overall air velocity (identified by the colour range) decreased as the operative temperature increased, resulting in an unclear trend based on the temporal dimension of air velocity for $T_o \geq 30$ °C. The positive ΔPS votes were not frequent at 30 and 31 T_o bins regardless of the corresponding V_a and ΔV_a conditions. The outcome suggests that the current air velocities – mostly under 0.4 m/s – solely maintained the pleasantness responses ($\Delta PS = 0$) instead of contributing to increasing ΔPS in this T_o range. It is observed that the highest $|\Delta V_a|$ values corresponded to positive PS evaluations (void shapes in Figure 45) and air velocities above 0.5 m/s (blue and green colours in Figure 45). The lower precedent air velocity (negative ΔV_a) did not change the pleasantness evaluation in this case due to its overall high intensity throughout the temporal assessment.

Figure 45 – ΔPS versus ΔVa-1min-avg by running strategy, T_o and V_a bins



Source: elaborated by the author

Figure 46 – ΔPS versus ΔVa-1min-avg by air movement satisfaction response



Source: elaborated by the author

Finally, households' satisfaction with the air movement experienced during the point-in-time survey was depicted by PS and ΔPS, as shown in Figure 46. The main difference between satisfactory and unsatisfactory air movement evaluations is the more significant presence of "pleasant" and "very pleasant" (delightful) responses, indicating an essential condition to achieve a satisfactory air movement evaluation. Decreasing air velocities (negative ΔV_a) from one voting moment to another did not necessarily impair air movement satisfaction at the end of the survey. However, the more significant positive ΔV_a values were observed in the satisfied group. Moreover, most households satisfied with the air movement maintained their positive pleasantness evaluation (ΔPS = 0) throughout the point-in-time survey.

4.3.4 Discussion

The point-in-time residential thermal comfort survey has presented a more detailed air velocity characterisation according to the current room operating strategy (natural ventilation only and supported by fans). The comparison between time-averaged air velocities distribution depicted the difference between NV and NV+FAN samples regarding constancy and variability (Figure 35 and Figure 41). Therefore, air velocity from NV had an overall greater amplitude with higher maximum values (1.5-2 m/s) and lower minimum values (approximately 0.1 m/s) corresponding to the moments of voting. In contrast, air velocity from NV+FAN was characterised by slightly higher median values of 0.5 m/s and lower amplitude (0.3 to 0.75 m/s).

The airspeeds measured under natural ventilation (NV) in the point-in-time survey (mean and median values equal to 0.47 and 0.44 m/s, respectively) were considerably higher than in other countries of similar climates such as Vietnam (DANG; PITTS, 2021), Singapore (DE DEAR; LEOW; FOO, 1991) and Indonesia (FERIADI; WONG, 2004) in naturally ventilated residences. Most V_a values were below 0.2 m/s in those studies. In contrast, the airspeeds measured during the use of fans were lower compared to some previous literature from the Indian residential sector, which reported a mean air velocity close to 1 m/s in the hottest months of the year (SANSANIWAL et al., 2020).

During the point-in-time survey, indoor temperature parameters influenced households' use of fans. Therefore, fans were not turned on for operative temperatures below 28 °C, and fans always supported natural ventilation for operative temperatures around 32 °C. The ranges of air velocity corresponding to each evaluation criterion were frequently broader (lower and higher air velocities) under NV than under NV+FAN, depicting the variability inherent to the natural wind. The assessment criteria driven by V_a were more evident under NV than under NV+FAN since V_a distributions across the same criterion (e.g., thermal pleasantness responses) were notably diverse for the former but similar for the latter. Thus, air movement from NV seemed to affect subjective perception more significantly than NV+FAN, which aligns with the literature's findings on dynamic airflows compared to constant airflows. The exception is made for operative temperatures above 30 °C, under which the influence of air velocity on subjective assessment was unclear for both operating modes. Analogously, the experimental conditions of indoor temperatures were not above 30 °C in previous studies.

The assessment criteria in the point-in-time survey pointed to an optimal operative temperature of up to 29 °C in NV. Most households considered the air velocity fluctuations between 0.4-1.4 m/s delightful at 29 °C. Moreover, air velocities ranging between 0.4-0.8 m/s were related to the neutral and slightly cool thermal sensations and the preference for not changing the thermal environment. Considering the overall preference of inhabitants from hot climates to be cooler than neutral in indoor environments (BUONOCORE et al., 2020a; FERIADI; WONG, 2004; MALIK; BARDHAN, 2021; XU et al., 2018), those combinations of T_o and V_a were sufficient to ensure pleasant thermal conditions to households performing sedentary activities and wearing light clothes in the Brazilian hot and humid climate.

The outcomes highlighted the occurrence of thermal pleasure induced by air movement out of the neutrality zone and moving towards the cold side of the thermal sensation scale. Moreover, the broader range of air velocities corresponding to positive responses to the pleasantness scale compared to "neutral" and "slightly cool" thermal sensations agree with the experimental findings from Schweiker et al. (2020b) regarding optimum thermal conditions based on both criteria.

It should be emphasised that the conclusions drawn in the present study refer to indoor operative temperature conditions ranging between 27-32 °C and air velocities of up to 1.8 m/s (1-minute average). Thus, the implications of dynamic air movement from natural ventilation on thermal perception under lower temperatures could lead to unpleasant feelings, as previously reported and related to draught discomfort in controlled settings (TIAN et al., 2019; ZHOU et al., 2006). The occurrence of unpleasant air velocities within the same V_a range at 29 °C associated with the non-occurrence at 27 °C were then attributed to non-thermal aspects of the point-in-time survey. Analogously, no conclusions from dynamic airflows can be drawn for hotter thermal environments (T_o > 32 °C). However, the effect of air velocity on thermal perception was limited under operative temperatures beyond 30 °C in this study and previous recent investigations (ZHOU et al., 2023a, 2023b).

The literature concerning the impact of dynamic airflows (simulated natural wind, sinusoidal and intermittent patterns) on human thermal perception under temperatures of 27-30 °C in controlled environments has reported an overall better comfort evaluation than constant mechanical airflows at the same mean air velocity (0.5-1 m/s). It is observed that the minimum airspeeds in most of those studies were close to 0.4 m/s (CUI et al., 2013a; HUANG; OUYANG; ZHU, 2012; PARKINSON; DE DEAR, 2015a; ZHOU et al., 2006), which was the reference for the lowest air velocities corresponding to the optimal evaluation at $T_o \leq 29$ °C under NV. Cui et al. (2013a) observed a better performance of constant mechanical wind at 28 °C and simulated natural wind at 30 °C. This trend contradicts the present study, in which NV's more fluctuating air velocities were more effective at the lower T_o range. The air velocities of at least 0.4 m/s under NV were crucial to households' positive evaluation of thermal delight in the point-in-time survey, moving beyond air movement acceptability.

As indoor temperature measures appear as a determinant factor concerning overall thermal comfort, most outcomes from field studies suggest a vast range of acceptable or comfortable conditions following adaptation in the residential sector. The upper limit for indoor temperature would be 30 °C in Japan (RIJAL, 2014), 31.1 °C in Vietnam (DANG; PITTS, 2021) and 32.2 °C in Indian affordable housing (MALIK; BARDHAN, 2021). However, such conditions are likely far from desired by occupants for several reasons, including socioeconomic background. The air velocities observed in the point-in-time survey did not influence households' thermal delight when T_o was above 30 °C. According to

Indraganti (2010b), occupants prefer to have much more air movement when they are far from thermal neutrality. Nevertheless, even the highest air velocities (up to 1.6 m/s) registered under NV could not stimulate thermal perception at such high operative temperatures.

The more constant airflow from fans was crucial to maintain a satisfactory thermal and air movement evaluation under operative temperatures above 30 °C. The air velocities corresponding to the optimal evaluation ("no change" votes in thermal preference and air movement criteria) were at least 0.4 m/s and ideally close to 0.6 m/s. A similar outcome was reported by Kumar et al. (2016b) in residential and office buildings during the summer of the Indian composite climate. The comfort temperature, preferred air velocity and preferred clothing insulation were reported to be 30.6 °C, 0.62 m/s and 0.3 clo, respectively. Dang and Pitts (2021) reported a minimum air velocity of 0.5 m/s for households' acceptability and 0.8 m/s for comfort under temperatures between 29.3-31.1 °C and similar clothing conditions in Vietnam.

According to Zhang, Arens and Zhai (2015b), air movement has a corrective power in non-neutral, warm-to-hot thermal environments. Their review of chamber studies indicated a required air velocity of 0.8-1 m/s or more at an ambient temperature of 30 °C. More recent chamber studies reported preferred airspeeds beyond 1 m/s under such conditions and the ineffectiveness of chosen airspeeds (up to 2 m/s) at 32 °C of air temperature to increase thermal satisfaction (ZHOU et al., 2023a, 2023b). Therefore, the corrective power of air movement in hot environments is limited based on indoor air temperature. The limitation suggests the need to concomitantly cool the air and increase its speed as an alternative to solely cooling it (TANG et al., 2021). Furthermore, the projections of increased air temperatures from extreme climate events such as heat waves will likely impair the effectiveness of natural ventilation (air movement-related) as a passive cooling strategy (BIENVENIDO-HUERTAS et al., 2022; SÁNCHEZ-GARCÍA et al., 2018). Thus, other passive and low-energy solutions will be required to lower indoor temperatures and favour the adoption of air movement concomitantly.

The corrective power analysis is related to restoring the neutral thermal conditions because it considers equivalent thermal sensations at different temperatures. Bearing in mind the distinction between sensation and pleasure stated by Schweiker et al. (2020b), positive feelings regarding the thermal environment arise from specific situations. An example is the alliesthesia model, which is related to the psychophysiological needs of the body (ZHANG; ARENS; ZHAI, 2015b) and dynamic environmental conditions (SCHWEIKER et al., 2020b). There is evidence of subjective pleasant sensations under transient conditions – mainly induced by temperature overshooting – during experimental exposure periods despite the limited effect of the stimuli through time (ARENS; ZHANG; HUIZENGA, 2006; TAMURA et al., 2021; TSUTSUMI et al., 2007). According to those studies, the stronger the overshoot, the greater the magnitude of "pleasant" and "comfortable" responses.

However, the more pleasant responses in the present study ("pleasant" and "very pleasant") were not necessarily related to the most significant increases in air velocity between two consecutive voting moments. Moreover, most positive pleasantness evaluations in this study were maintained for longer than two consecutive voting moments, in contrast to the short-duration overshoot from previous studies. Therefore, if thermal alliesthesia relies on a previous discomfort, the effect of dynamic air movement from natural ventilation in maintaining subjects' thermal delight over time might fall out of the alliesthesia framework. In other words, participants were not necessarily uncomfortable when reporting thermal delight, which agrees with the outcome reported by Parkinson, De Dear and Candido (2016): the occurrence of thermal pleasure was not dependent on a thermal stress precondition.

It is worth noting that households did not experience temperature or humidity ramps and maintained their metabolic rate and clothing insulation level throughout a point-in-time survey in the present study. Therefore, they were susceptible only to a range of air velocities from natural ventilation in warm-to-hot environments as a potential source of thermal pleasure or unpleasure, depending on their perception of air velocity when responding to the IQ form. Thermal pleasure votes (from "slightly pleasant" to "very pleasant") were reported and maintained across the surveys, resulting in air movement satisfaction at the end of each survey, mainly at operative temperatures of 27-30 °C and air velocities ranging between 0.4-1.8 m/s. The outcome confirms the research hypothesis of an association between pleasant thermal votes during the point-in-time survey and satisfactory air movement evaluation at the end of the survey.

Under such indoor conditions, the increase or decrease in air velocity (fluctuating characteristic of natural ventilation) did not impair households' votes on the positive side of the pleasantness scale until the end of the survey (Figure 45). The research hypothesis of an association between pleasant thermal votes and increasing air velocities in short timespans (positive ΔV_a) is confirmed. However, thermal delight was not dependent only on increasing air velocities since it was also related to decreasing air velocities in this study. Therefore, considering this survey's context and similar occupants' parameters, the occurrence and maintenance of positive pleasantness responses in naturally ventilated environments rely on a lower limit of air velocity near 0.4 m/s and an upper limit of operative temperature = 30 °C.

The findings of the present survey agree with the experimental outcomes reported by Parkinson, De Dear and Candido (2016) in two main trends. First, thermal pleasure is not dependent on a thermal stress precondition. Second, the air movement overshooting effect is limited under the highest indoor temperatures (32 °C). Maintaining a relatively high air velocity through the occupancy time under a dynamic airflow pattern is crucial to ensuring an appropriate cooling effect in warm environments, as highlighted by Parkinson and de Dear (2017) and verified in the present investigation. In previous chamber investigations, minimum and maximum airspeeds from dynamic airflow patterns resulting in perceptible cooling effects ranged from 0.2-0.5 m/s and 1.2-1.5 m/s, respectively (CUI et al., 2013b; HUANG; OUYANG; ZHU, 2012; ZHOU et al., 2006). In the present study, the minimum air velocity = 0.4 m/s is associated with the exact moment of voting (instantaneous perception). Therefore, it does not imply a non-occurrence of lower air velocities outside of the moments of voting. Nevertheless, the maximum air velocities observed in this study are similar to the airspeeds previously reported in controlled settings.

5 CONCLUSION

The research addressed natural ventilation as a conditioning strategy and its implications on human thermal comfort in Brazilian residences via a national survey and a local field campaign in the hot and humid city of São Luis. The national questionnaire obtained 1,348 responses from all Brazilian regions on adopting natural ventilation at home (routines and motivations). One hundred eleven participants joined the local field study, providing 597 and 629 valid responses to two subjective thermal environmental evaluation forms filled in during and after a researcher visited their residences. The former assessment corresponded to the point-in-time survey with instant airspeed measurements in living rooms and bedrooms. The latter referred to the long-term monitoring of residential rooms with air temperature and relative humidity measurements for approximately a month.

5.1 RESORTING TO NATURAL VENTILATION AND COMPLEMENTARY CONDITIONING STRATEGIES

Based on all participants' data collection instruments, natural ventilation is a default conditioning strategy in Brazilian homes, as it is the most frequently adopted. Fans and air conditioners are considered complementary strategies because of their lower frequency of use. Based on the local long-term monitoring, the choice for a strategy was more related to the habitual and socioeconomic backgrounds than the thermal environmental background. Regarding income, participants from the national survey acknowledged more frequent use of natural ventilation supported by fans among the lowest income range (<4 minimum wages). The declared preference for a conditioning strategy was also impacted by income since participants from the lowest income range preferred using fans.

In contrast, the more significant preference for air conditioning came from the sample of participants from the highest income range (> 10 minimum wages) in the national survey. Preference and usage patterns were also aligned in the local survey: the more significant proportion of participants who preferred air conditioning is within the sample using it. The energy-saving as a reason to resort to natural ventilation was a financial aspect that affected the households' declared preference in the national survey. Although it was a general concern in both surveys, it has significantly influenced the daily option for a strategy in the lower income range only. Participants arguing this motivation were experiencing relatively higher indoor air temperatures (median value ~30 °C) and resorting more to fans than participants who based their current option on other motivations during the local survey.

Apart from income, the influence of indoor temperature, outdoor temperature and outdoor wind speed on choosing a conditioning strategy was evaluated in the long-term monitoring in São Luis. The association between motivations, running strategies and physical variables showed that when households attributed the choice for natural ventilation to a mild temperature, the indoor air temperatures were slightly lower (median value ~29 °C) than those related to other motivations. The proportion of fans in use on this occasion was the lowest. The same was observed for those attributing their choice to a breezy day: the outdoor wind speeds were slightly higher (median value ~3 m/s) than those related to other motivations. No association with the outdoor air temperature was found for adopting natural ventilation. However, natural ventilation was mainly chosen based on a daily routine, which best explains the broadest range of indoor and outdoor variables among all running strategies.

No association with indoor and outdoor temperatures was verified among households that switched from natural ventilation to an air conditioning strategy. The indoor temperatures before the activation of air conditioning were similar to those registered under natural ventilation (29 °C). Alternatively, the outdoor temperatures were lower, indicating an activation pattern at nighttime to sleep that was mentioned by many households in the interviews. Outdoor wind speeds were relatively lower before the activation of air conditioning and among the households who attributed their choice to a not-breezy day. However, the main reason for abandoning natural ventilation in national and local surveys is the impediments to opening windows to the outdoors, which was unrelated to the physical parameters addressed. Nevertheless, air conditioning users mainly followed a routine for their use, as well as natural ventilation users.

5.2 THERMAL AND AIR MOVEMENT EVALUATION UNDER DIVERSE CONDITIONING STRATEGIES

The thermal pleasantness, preference and sensation assessment during the long-term monitoring reflected the warmer and more humid conditions registered in naturally ventilated rooms compared to air-conditioned rooms. Therefore, households experiencing air-conditioned environments showed the highest pleasantness (88%) and preference for no change (85%) rates. The second-best assessment rates were under natural ventilation, despite the significantly different indoor environmental conditions experienced (median air temperature = 29 °C and relative humidity = 69% under natural ventilation and 27.1 °C / 57% under air-conditioning). The neutral thermal sensation rate was equal (61%) in both conditioning strategies, although 33% of households preferred to feel colder in naturally ventilated rooms against 15% in air-conditioned rooms. Controlling the thermal environment is also relevant, influencing households' preference to maintain the indoor conditions currently assessed.

The use of fans to increase mean air velocity in both naturally ventilated and air-conditioned environments is associated with higher indoor air temperatures (+0.5-0.7 °C in median values) compared to natural ventilation only and air-conditioning only, respectively. Consequently, the subjective assessment of households adopting fan strategies was significantly worse, with higher unpleasantness, warm-to-hot thermal sensation and colder preference rates. The air movement evaluation also reflected the indoor air temperature in the long-term monitoring since significant rates of low air movement judgement (60%) and preference for more air movement (70%) were observed under fan operation.

The use of fans in naturally-ventilated rooms associated with higher indoor temperatures compared to natural ventilation solely was also observed during the interviews (point-in-time survey). When disregarding the influence of operative temperature on thermal and air movement evaluation, no significant differences were observed in indoor air velocity distributions under natural ventilation (with and without fans), which corresponded to the same voting criteria. Nevertheless, adopting fans was crucial to ensure positive votes on the thermal pleasantness scale at operative temperatures above 30 °C.

5.3 DYNAMIC ASPECTS OF AIR MOVEMENT FROM NATURAL VENTILATION

The subjective assessment criteria adopted on the point-in-time survey allowed the discussion of households' thermal delight and satisfaction beyond acceptability concerning indoor temperature and velocity parameters. The time-averaged characterisation of air velocity indicated no significant differences when averaged for 1, 5 and 10 minutes, except for a few values beyond 1.2 m/s representing higher-than-average air velocities within specific surveys. The occurrence of undesired excessive air velocities was rare, so the study focused on undesired low and desired air velocities considering the effect of operative temperature.

The combined analysis of households' responses by absolute and increasing or decreasing air velocities throughout the point-in-time survey exposed a thermal delight condition from natural ventilation corresponding to at least 0.4 m/s under an operative temperature up to 30 °C. If the minimum air velocity threshold was maintained throughout the survey, the fluctuations in air movement intensity did not impair the maintenance of thermal delight, resulting in the households' satisfaction with air movement at the end. The research hypotheses proposed were then confirmed, highlighting that positive thermal pleasant responses could be maintained even if air velocity decreased between two consecutive moments of voting. The research findings corroborate the importance of the thermal comfort aspect of natural ventilation, considering all the factors already favouring its adoption in the Brazilian residential sector.

5.4 LIMITATIONS TO THE STUDY

The main limitations of the research are listed as follows.

- The national survey sample was biased towards the highest income ranges and education levels due to the primary disclosure strategy. The option for disseminating among academic networks aimed at obtaining the targeted sample size in a short time (2 months). Although the survey findings on preferences, routines and motivations are valid and valuable, they likely represent a minor piece of the Brazilian population;
- The sample size in the field campaign conducted in São Luis (point-in-time and long-term monitoring) was limited due to schedule constraints arising from the COVID-19 pandemic. Therefore, the field campaign duration was restricted to one semester (the second of 2022), and each residence's long-term monitoring was shortened to a month.
- A final (additional) air velocity measurement initially planned in each residence could not be conducted due to constraints in the researcher's schedule. Nevertheless, the airflow pattern assumed throughout the long-time monitoring (assumed air velocities) was highly prone to imprecision. Therefore, when responding to the QL form, households might not have experienced an airflow pattern similar to the one measured during the visits. Moreover, the rate of assumed air velocities was only 56% of the dataset. Thus, the air velocity conditions were unknown in almost half of the long-term monitoring sample.

- Adopting omnidirectional airspeed sensors in the point-in-time survey was crucial considering the researcher's impossibility of controlling the local air movement sources. However, it was unfavourable to the temporal precision when measuring airspeeds. In other words, measured airspeeds were not instantaneous. Thus, the time-averaged air velocity assigned to the moments of voting may not have corresponded to the exact moment of filling in the IQ form. Moreover, omnidirectional airspeed sensors did not favour the adoption of turbulence intensity as a descriptor of temporal variability of air velocity in the naturally ventilated rooms assessed. The comparisons between readings from the omnidirectional airspeed sensors presented in Appendix H offered an overview of the temporal delay from SENSU sensors compared to TESTO, more time-responsive sensors.

5.5 SUGGESTIONS FOR FUTURE STUDIES

Considering the default adoption of natural ventilation in Brazilian residences in light of extreme events arising from global climate change, it is essential to study households' routines and adaptations to hot thermal conditions in the future, particularly among the lower income levels. More extended monitoring periods could capture households' actions and evaluations under extreme events such as heatwaves and thus should be considered in future studies.

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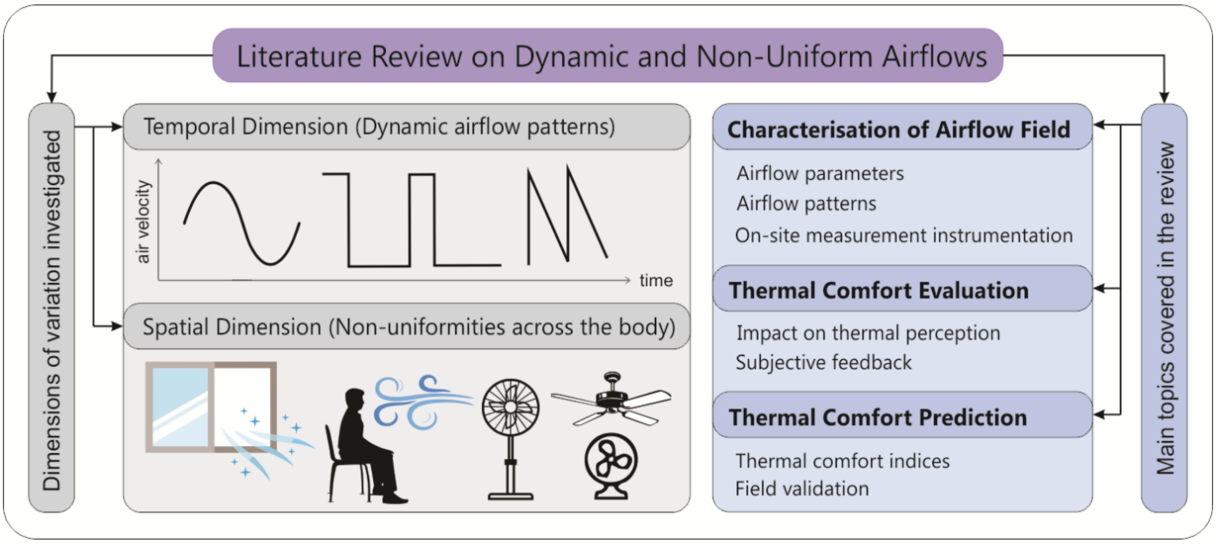
APPENDIX A – Literature Review Article Transcript

ABSTRACT

The transitioning from overall steady-state thermal conditions indoors to non-steady and non-uniform conditions encompasses the airflow field generated by means of air conditioning and ventilation systems, devices for increased air movement and even cross-ventilation in naturally ventilated buildings. The indoor airflow field is susceptible to large variations with respect to time and space, which makes its characterisation and evaluation in real occupancy buildings a complex task. A literature review focusing on dynamic and non-uniform airflows applied for human thermal comfort in buildings was conducted with the aim of documenting recent findings on three main topics: airflow characterisation, thermal comfort evaluation and thermal comfort prediction. Over 150 articles from the past two decades of research carried out in climate chambers, experimental rooms, laboratories and real occupancy buildings were reviewed. The main findings indicate that the more dynamic and unpredictable airflows tested in studies with subjects had better preference, sensation and comfort ratings when compared to constant and sinusoidal patterns. Field validation is required to (1) verify the applicability of simulated natural airflows in real occupancy buildings and (2) optimize delivered mean air speeds – up to 0.9 m/s – and their respective time spans – from 10 seconds to 3 minutes – in intermittent airflow patterns, to avoid the risk of draughts and lack of air motion. Temporal variations in air velocity, whose standard deviation was up to 0.5 m/s in studies with sources of increased airflow, should be addressed in detail with respect to the corresponding subjective feedback. Furthermore, there is a gap to be filled regarding the incorporation of temporal variations into the prediction models to be proposed and validated.

Keywords: Dynamic airflows; non-uniform airflows; thermal comfort; airflow characterisation; airflow evaluation.

GRAPHICAL ABSTRACT



SYMBOLS AND ABBREVIATIONS

HVAC – Heating, ventilation and air conditioning

IQR – Inter quartile range

OTS – Overall thermal sensation

PD – Predicted percentage of people dissatisfied due to draught

PMV – Predicted mean vote

RH – Relative humidity, in %

SET – Standard effective temperature

SS – Systematic search

SSF – Systematic search flow

StDev – Standard deviation of a sample

TCV – Thermal comfort vote

TSV – Thermal sensation vote

Tu – Turbulence intensity, in % (ISO 7730 Standard (ISO, 2005) definition)

T_a – Indoor air temperature, in °C

V_a – Indoor average air speed surrounding a representative occupant, with respect to location and time, in m/s (ASHRAE 55 Standard (ASHRAE, 2020) definition)

β value – negative slope of the double logarithmic power spectrum analysis curve

1 INTRODUCTION

The air movement in buildings has been addressed from the perspectives of human thermal comfort, energy consumption and air quality, which are interconnected. The last one has been drawing attention recently, particularly due to the disclosure of COVID-19 pandemic. Apart from air quality aspects, the impact of air movement on human thermal comfort indoors has been extensively addressed in recent decades. The nuances of airflow perception and thermal comfort, however, have been driven by both negative and positive aspects of air movement over the years. The early research findings of Indraganti et al. (INDRAGANTI, 2010), Cândido et al. (CÂNDIDO et al., 2010), Huang et al. (HUANG et al., 2013) and Zhang et al. (ZHANG; LIU; MENG, 2015) have shed light on upper air speed thresholds desired by populations accustomed to increased air movement as a mechanism of thermal adaption in warm and hot environments. In this regard, review articles (DE DEAR, 2011; DEAR et al., 2013; TOFTUM, 2004) and research articles (CÂNDIDO et al., 2010; TANABE; KIMURA, 1994; XIA et al., 2000) have highlighted the overall thermal conditions associated with both unpleasant and pleasant airflows in buildings. Hence, the approach of indoor air movement within the scope of thermal comfort has evolved from a negative impact, represented mainly by the draught risk model in early ASHRAE, EN and ISO standards, to a positive effect of offsetting high air temperature and humidity indoors. This shift is clearly perceived in the Addenda to ANSI/ASHRAE Standard 55-2010, where the acceptable operative temperature limits are increased as a result of increased air speed in naturally ventilated spaces. Accordingly, the Standard Effective Temperature (SET) evaluation model was extended in the adaptive comfort zone to include the cooling effect of air movement under warmer thermal conditions in the 2013 version of the standard. The EN 16798-1 (CEN, 2019) and ISO 7730 (ISO, 2005) standards also address the air speeds required to offset the increased indoor temperatures, although direct occupant control over air speed must be provided. Thus, high indoor air speeds (> 0.8 m/s) are not only deemed as acceptable, but also needed and preferred, particularly in tropical climates (BUONOCORE et al., 2018; DAMIATI et al., 2016).

Whilst increased air movement was largely addressed in thermal comfort studies through the definition of allowable, suitable, required and/or preferred air speeds, dynamic and non-uniform airflows have also been investigated during the past two decades. Research on the dynamic characteristics of air motion and their respective impact on subjective perception included the assessment of turbulence intensity (GRIEFAHN; KÜNEMUND;

GEHRING, 2000; HUANG et al., 2014; XIA et al., 2000), fluctuation frequency of air speed (HUANG; OUYANG; ZHU, 2012; XIE et al., 2018) and the duration of intermittent high/low air speeds (KABANSHI et al., 2016; TIAN et al., 2019), in addition to the intensity of airflow (i.e., air speed) only. By exploring these dynamic features, airflow cooling is likely achieved without necessarily setting impracticable air speeds in some spaces (above 1 m/s) that could favour the occurrence of perceived draught, thermal boredom and fatigue indoors (LUO et al., 2018; ZHOU et al., 2006). The different possibilities for enhancing the cooling effect from airflows, besides applying high and constant air speeds, have been addressed in several studies, mainly focusing on targeted body segments (CHLUDZIŃSKA; BOGDAN, 2015; UĞURSAL; CULP, 2013; ZHANG et al., 2010a) and aroused skin thermoreceptors due to sequential speed fluctuations (LAMPRET et al., 2018; PARKINSON; DE DEAR, 2017; TAWACKOLIAN; LICHTNER; KRIEGEL, 2020). These aspects are identified as the spatial and temporal dimensions of comfort airflows, respectively.

Despite the considerable interest in adopting airflows for cooling people in warm and hot environments, the issues with unwanted local air movement have not been overlooked. In this context, the air movement approach in more recent versions of ASHRAE 55 standard (2013, 2017 and the current 2020 version) included two main modifications. Firstly, localised airflow across the body is now addressed by an ankle draught risk model (LIU et al., 2017; SCHIAVON et al., 2016a) in the 2020 version (ASHRAE, 2020) and secondly, occupant control of air speed was gradually incorporated and is now considered as crucial for thermal and air movement acceptability. Hence, determining upper and lower air speed thresholds for optimal thermal conditions tends to assume a minor role in building regulations, since occupants would be responsible for controlling their (personal) immediate thermal environment and thus choosing the preferred airflow settings. This is particularly important for thermal comfort prediction models under non-steady conditions, since previous studies suggested that widespread whole-body heat balance models, such as the Predicted Mean Vote (PMV) and SET models, are not suitable under these circumstances (SCHELLEN et al., 2013; ZHAI et al., 2013; ZHANG; ARENS; ZHAI, 2015).

The motivations behind addressing dynamic and non-uniform airflows are mainly the rising demand for space cooling and its environmental and energy implications (IEA, 2018), which have unveiled the need to develop and implement resilient cooling solutions that ensure occupants' thermal comfort (IEA, 2020). Dynamic and unsteady indoor conditions were highlighted as promising with respect to new comfort expectations and energy savings. De Dear et al. (DE DEAR, 2011) proposed a shift in the notion of thermal comfort from the perspective of people experiencing such conditions. The authors argued that occupants' adaptive mechanisms would be reactivated under non-steady-state thermal conditions. Following the same line of reasoning, Zhu et al. (ZHU et al., 2016) and Mishra et al. (MISHRA; LOOMANS; HENSEN, 2016) compiled their main comfort findings under dynamic environmental conditions, in which airflows were included. Moreover, the shift from general space cooling needs to personal cooling needs favours the occurrence of spatial and temporal variations, such as those in the airflow field, which must be properly characterised in real buildings by following diverse patterns of occupancy and user control. For instance, the adaptive use of air movement in neutral, warm or hot conditions has been extensively explored, mainly focusing on personal control systems (SCHIAVON et al., 2016b; ZHAI et al., 2013; ZHANG; LIU; MENG, 2015), low-power conditioning systems (LIU et al., 2018; ZHANG et al., 2010a) and heterogeneous or transient thermal environments (DU et al., 2018; ZHAI et al., 2019).

Unsteady and heterogeneous thermal environments in comfort studies have been reviewed as a whole (DE DEAR, 2011; MISHRA; LOOMANS; HENSEN, 2016; ZHU et al., 2016), but few papers have been focused on summarising the findings regarding the non-uniformities of airflows in particular. Zhu et al. (ZHU et al., 2015) addressed the dynamic characteristics and comfort assessment of indoor airflows in a review article. The authors described the main airflow parameters to be assessed in thermal comfort studies, which include the air velocity (V_a), turbulence intensity (Tu) and fluctuation frequency. Their research focus, however, was the comfort evaluation of airflows characterised by constant and high air speeds. The comfort evaluation of dynamic patterns was not performed, but new studies on this subject have been conducted since their publication (CHEN; ZHANG; TANG, 2017; KABANSHI et al., 2016; OBAYASHI et al., 2019; VAN CRAENENDONCK et al., 2019). De Dear et al. (DE DEAR, 2011; DEAR et al., 2013) dedicated part of their review articles to emphasising the sensitivity of skin thermo receptors to the dynamic and transient characteristics of airflows. Furthermore, alliesthesia was suggested as a background for enhanced air movement perception, with two opposing scenarios: positive alliesthesia (pleasant and desirable airflow) and negative alliesthesia (unwanted cooling from airflow) (CANDIDO; DE DEAR, 2012; PARKINSON; DE DEAR; CANDIDO, 2016). This phenomenon is associated with air movement perception under non-steady and heterogeneous thermal conditions and comprises both spatial and temporal dimensions due to localised and dynamic stimuli directed onto the body.

Considering the above, this review article presents and evaluates the state-of-art of dynamic and non-uniform airflows in thermal comfort studies. The novelty of this work is mainly related to two aspects: the thermal comfort evaluation of recently addressed dynamic airflow patterns, which has not been found in the previous search conducted in this work; and the contribution to on-site air speed measurements in occupied buildings, based on the temporal and spatial dimensions of airflow perception. Thus, the approach in this paper encompasses spatial and temporal variations in the airflow field that are potentially relevant to characterisation, comfort evaluation and comfort prediction. Regarding the characterisation, airflow patterns and parameters addressed in several studies are reported. A summary of comfort evaluations from diverse airflows is presented as well as the impacts of fluctuant and localised stimuli on subjective thermal and air movement evaluations. Finally, the suitability of current thermal comfort indices to predict the occupants' thermal perception associated with dynamic and non-uniform airflows is discussed. The overall objective of this paper is to review and document recent findings in relation to airflow characterisation and comfort evaluation in human thermal comfort studies, particularly under dynamic and/or non-uniform indoor airflow conditions.

2 LITERATURE SEARCH STRATEGY AND METHODS

The literature review presented herein was driven by specific research questions as follows:

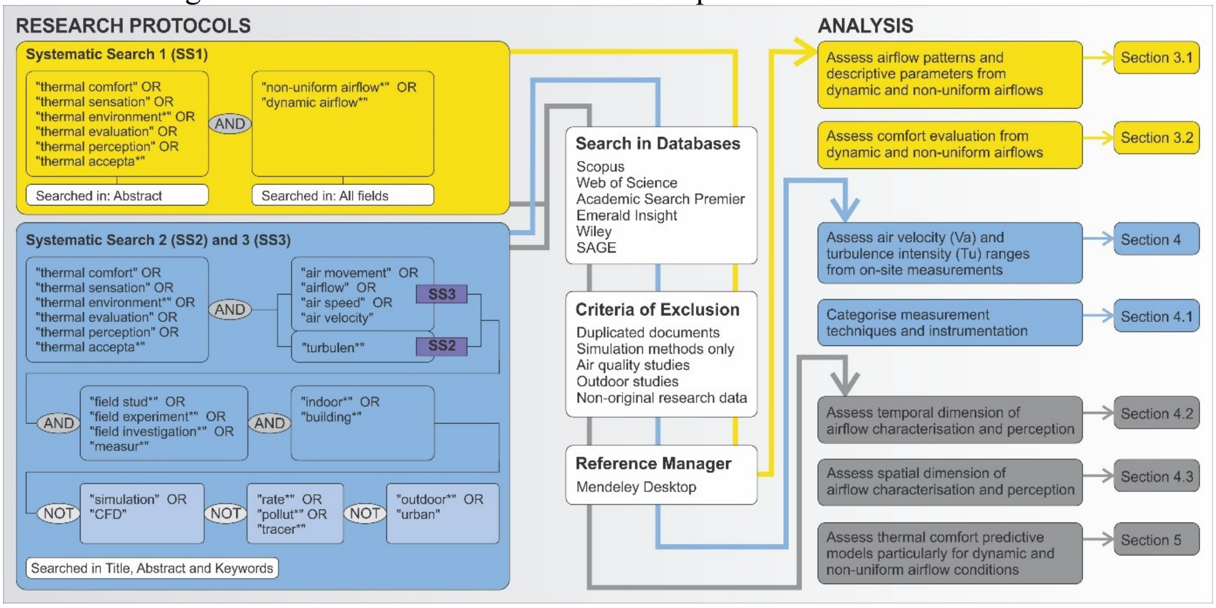
- What are the main findings concerning the influence of dynamic and non-uniform airflows on thermal comfort and perception?
- What are the main airflow patterns and parameters assessed in thermal comfort studies and which have the greatest impact and are the most promising in terms of triggering subjective perception?
- How should the most commonly assessed airflow parameters (air velocity/speed and turbulence intensity) be measured or determined in thermal comfort studies conducted in indoor spaces, considering the spatial and temporal variations to which indoor airflows are susceptible?
- Are the current methods for on-site characterisation and comfort prediction suitable under dynamic and/or non-uniform airflow conditions?

These research questions were used as a reference for the definition of three systematic search (SS) strings, which are detailed in Figure 47. SS1 is focused on the overall picture of dynamic and/or non-uniform airflows in thermal comfort studies, whilst SS2/SS3 are expected to expand the scope of airflow assessment in comfort studies to on-site (*in loco*) measurements in real occupancy buildings (field studies), test rooms, laboratories or climatic chambers. Turbulence intensity and air velocity/speed measurements were addressed in SS2 and SS3, respectively.

The review is restricted to indoor thermal comfort studies in which the environmental characterisation was carried out by means of on-site measurements. In other words, these studies were conducted in real indoor spaces susceptible to diverse airflows, including both experimental and real life conditions. The reason this criterion was established is its relevance in characterising and evaluating the current airflow patterns and the interactions with users in occupied indoor spaces (mainly in field studies). Hence, airflow characterisations by means of computational simulation methods were beyond the scope of this review, as were thermal comfort studies conducted outdoors and studies focusing on air motion which is not related to the issue of thermal comfort (such as airflow rate and CO_2 concentration). Additional details regarding the research protocols – including search strings and databases – and the steps to be followed in the analysis throughout the review paper can be found in Figure 47.

The search was restricted to publications in English and the time period was defined as the past two decades (2000-2020). The systematic searches were performed in November and December 2020. The literature review was entirely conducted by only one researcher and based on the systematic search flow (SSF) method proposed by Ferenhof and Fernandes (FERENHOF; FERNANDES, 2018). In total, over 150 articles were included in the literature review.

Figure 47 – Flowchart of the methods adopted in the literature review.



3 DYNAMIC AND NON-UNIFORM AIRFLOWS IN THERMAL COMFORT STUDIES

3.1 DESCRIPTION OF AIRFLOW PATTERNS AND PARAMETERS

Indoor airflows of different patterns and diverse characteristics have been assessed thoroughly in human thermal comfort studies during the past two decades. In these studies, the airflows were mainly generated by air supply devices in a controlled or semi-controlled environment (climate chamber (CUI et al., 2013; LUO et al., 2018; ZHOU et al., 2006), test room (CHEN; ZHANG; TANG, 2017; TIAN et al., 2019) and laboratory (LAMPRET et al., 2018; UĞURSAL; CULP, 2013)), and the prevalent neutral-to-warm indoor thermal conditions were designed to evaluate the cooling effect from dynamic airflows. A summary of the main airflow patterns addressed is shown in Table 9. Four airflow patterns were of main interest: constant mechanical, intermittent (also referred to as periodic (KABANSHI; WIGÖ; SANDBERG, 2016; TAWACKOLIAN; LICHTNER; KRIEGEL, 2020) or pulsating (TIAN et al., 2019)), simulated natural and sinusoidal.

Constant mechanical airflows are characterized by negligible fluctuation in the magnitude of air velocity (i.e., air speed, in m/s), low turbulence intensities (<40%) and low β values (≈0.3) in the energy distribution of the airflow (power spectrum analysis) during its operation. The effect of diverse air speed thresholds from constant airflows on the subject's thermal comfort has been well documented in the research field. Thus, the suitable air speeds for different populations under a range of indoor conditions (mainly air temperature and humidity) have been determined (HUANG et al., 2013; PARKINSON; DE DEAR, 2017; ZHU et al., 2015). As the research community gradually dedicated more effort to the dynamic characteristics of the thermal environment, other airflow patterns and parameters, deemed as dynamic, were evaluated, with an emphasis on the temporal variations of air speed. Hence, the inclusion of constant mechanical patterns in thermal comfort studies addressing dynamic airflows is useful to compare the subjective perceptions in the two cases (constant versus dynamic).

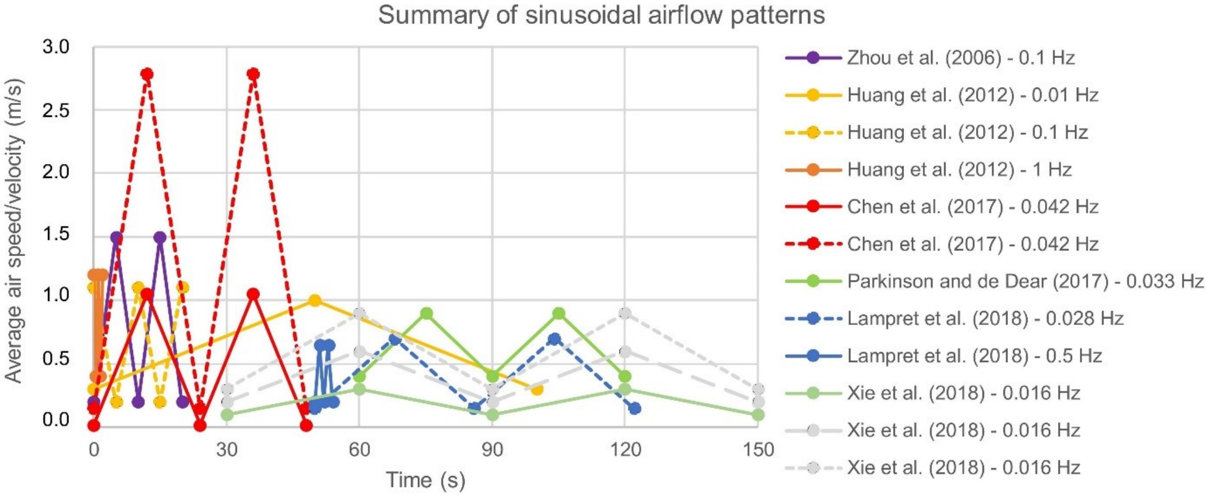
Table 9 - Summary of the airflow patterns studied.

Airflow Patterns (sample size)	Average Air Speed/Velocity (m/s)			Turbulence Intensity (%)			β value
	Median	Mean	IQR (1st - 3rd)	Median	Mean	IQR (1st - 3rd)	Median
Constant mechanical (54)	0.68	0.80	0.60 (0.40 – 1.00)	26.0	26.7	10.0 (22.0 – 32.0)	0.35
Intermittent (26)	0.47	0.49	0.21 (0.40 – 0.61)	23.2	24.3	6.9 (21.1 – 28.0)	-
Simulated natural (6)	0.80	0.70	0.27 (0.58 – 0.85)	43.5	42.0	9.0 (36.8 – 45.8)	1.25
Sinusoidal (23)	0.53	0.57	0.22 (0.41 – 0.63)	48.9	46.5	8.1 (42.5 – 50.6)	1.2

Source: Adapted from the references presented in supplementary file 1.

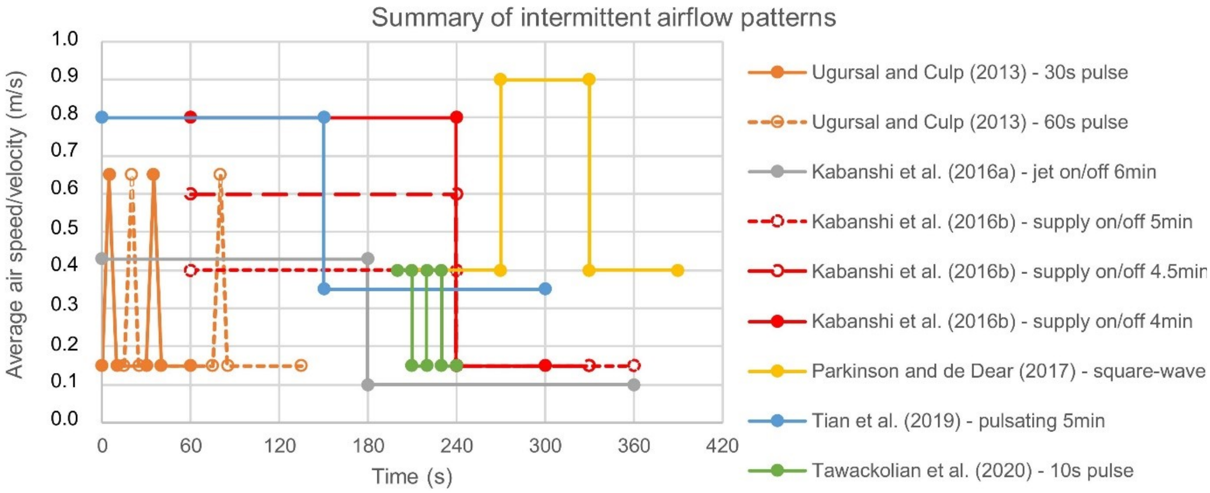
The sinusoidal pattern is characterised by high turbulence intensities (>40%) and periodic fluctuations in the air speed/velocity. It is represented by the fluctuation frequency parameter, as shown in Figure 48. The summarised fluctuation frequencies were in a range of 0.01-1 Hz, although other frequencies have also been tested. Huang et al. (HUANG; OUYANG; ZHU, 2012) explored fluctuation frequencies between 0.005 and 2.5 Hz under warm conditions (28/30 °C) with a mean air velocity of 0.6 m/s. This is probably the widest range of air speed fluctuation frequencies investigated so far. However, not all sinusoidal airflows are perceived as fluctuating, probably due to a shorter or longer oscillation of air speed with a small amplitude (range of minimum and maximum speeds). Huang et al. (HUANG; OUYANG; ZHU, 2012) stated that perceptible frequencies in their study were between 0.2-1.5 Hz, whilst the mean air speed values ranged from 0.2 to 1.2 m/s. The amplitude of mean air speed values is usually given for the sinusoidal airflow patterns, as shown on the y-axis of Figure 48.

Figure 48 – Average air speed versus time of exposure for sinusoidal airflow patterns.



The intermittent airflow pattern has been assessed more recently in thermal comfort studies focusing on dynamic airflows, when compared to sinusoidal patterns. The behaviour of the average air speed as a function of time in intermittent airflows lies between those of the constant and sinusoidal patterns, as seen in Figure 49. The presence of time intervals with constant air speed might have contributed to the lower Tu values (<40%) registered under intermittent airflows. However, the mean, median and IQR values for the average air speed/velocity were similar for the documented sinusoidal and intermittent patterns (Table 9), as well as the prevalent amplitude of delivered air speeds (0.0-1.0 m/s in Figures Figure 48 and Figure 49).

Figure 49 – Averaged air speed versus time of exposure for intermittent airflow patterns.



Lastly, a simulated natural airflow is artificially generated to reproduce the main aspects of natural wind. Some authors have addressed this issue by investigating the dynamic characteristics of outdoor wind (DJAMILA; MING; KUMARESAN, 2016; KANG; SONG; SCHIAVON, 2013) and its reproducibility indoors (LUO et al., 2018; ZHOU et al., 2006). Since natural wind is characterised by high Tu (>40%) and high β (≈1.5) values (HUA et al., 2012; OUYANG et al., 2006), the simulated natural airflows described in Table 9 performed reasonably well. However, some improvements in the mechanical features, design and control of air supply devices (as presented by Hua et al. (HUA et al., 2012) and Luo et al. (LUO et al., 2018)) were required to better reproduce the dynamic characteristics of natural wind in indoor spaces. In contrast to constant, sinusoidal and intermittent patterns, natural wind has no periodic or regular distribution of high and low air speeds. However, simulated natural airflows delivered by specific devices do present some regularity in their flow pattern. For instance, the dynamic air supply device presented by Hua et al. (HUA et al., 2012) and adopted in other studies (CUI et al., 2013; YANG et al., 2013) continuously repeated the same simulated natural wind pattern within short time intervals during the experimental tests. Luo et al. (LUO et al., 2018) argued that their default configuration for repeating the current airflow automatically would be 20 min if no switching command was provided. Whether this repetition would positively or negatively affect the thermal and air movement perception of simulated natural wind compared to an actual natural breeze has yet to be addressed.

3.2 THERMAL COMFORT EVALUATION

Human thermal response to the environmental conditions created by dynamic/non-uniform airflows indoors has been assessed in several studies. The thermal sensation vote (TSV) and draught dissatisfaction rate are common subjective measures for thermal comfort evaluation and reported results are compiled in Table 11. The thermal comfort vote (TCV) was also obtained from subjects in several studies but, unlike the TSV, it was assessed on various numeric scales. Subjects wore typical summer office clothes (0.5-0.7 clo) and were performing nearly sedentary activities (1.2 met) during most of the experimental conditions tested. As observed in Table 11, the targeted body segments to receive airflow stimuli were mainly unclothed due to the expected convective effect from air movement over the bare skin. Thus, covering those body segments with clothing ensembles was not allowed in some studies (LAMPRET et al., 2018; SCHIAVON et al., 2016a).

There is consistent evidence of a stronger cooling effect induced by sinusoidal, intermittent or simulated natural airflow patterns compared with constant airflows with the same mean air speed in a warm environment (27-30 °C) (CUI et al., 2013; LUO et al., 2018; TIAN et al., 2019; ZHOU et al., 2006). This is true considering not only TSV and TCV, but also other subjective measures. Zhou et al. (ZHOU et al., 2006) reported significantly better thermal comfort, significant reductions in TSV and high preference for dynamic airflows (sinusoidal and simulated natural). A simulated natural airflow was also the preferred option under all conditions tested by Luo et al. (LUO et al., 2018), who reported better thermal comfort and a reduction in TSV on adopting this airflow. Similarly, thermal comfort was significantly improved under intermittent (pulsating) air supply compared with constant airflow in a study by Tian (TIAN et al., 2019). Cui et al. (CUI et al., 2013) found that a constant airflow performed better at 28 °C, while a simulated natural airflow performed better at 30 °C in terms of TCV, although TSV was consistently reduced by the effect of simulated natural airflow under both temperature conditions.

With regard to the influence of diverse dynamic airflow patterns on thermal perception, different trends were observed. Huang et al. (HUANG; OUYANG; ZHU, 2012) reported a stronger cooling effect delivered to subjects when the fluctuation frequency of sinusoidal airflows was between 0.5-1 Hz. A lower TSV and a higher comfort rate were achieved at 30 °C with a fluctuation frequency of 0.5 Hz. These findings are in accordance with the results obtained by Zhou et al. (ZHOU et al., 2006) for a frequency below 0.1 Hz under neutral and warm temperatures (26/30 °C). However, no significant differences in terms of TSV were found in more recent studies addressing fluctuation frequencies below 0.1 Hz. This was verified in the studies conducted by Xie et al. (XIE et al., 2018) and Lampret et al. (LAMPRET et al., 2018), both carried out with an indoor air temperature of 23 °C. Parkinson and de Dear (PARKINSON; DE DEAR, 2017) reported no significant changes in the TSV and thermal pleasure votes on comparing a constant, a sinusoidal (0.033 Hz) and two intermittent patterns at 27.5 °C (Table 11).

These findings indicate that sinusoidal airflows with low fluctuation frequency (<0.1 Hz) are perceived as constant, due to the time taken for the air speed to oscillate in a cycle. This was postulated by Chen et al. (CHEN; ZHANG; TANG, 2017) for a test frequency of 0.042 Hz, despite peak air speeds above 2 m/s being tested in their study (see Figure 48). Moreover, the airflow fluctuation frequencies with a strong cooling effect compiled by Huang et al. (HUANG; OUYANG; ZHU, 2012) are in the range of 0.2-1 Hz. Thus, the cooling effect from airflow patterns deemed as constant or almost constant (<0.1 Hz or >1 Hz) would be diminished due to the adaptation of skin thermoreceptors to static air speeds (CHEN; ZHANG; TANG, 2017), at least for velocity amplitudes in the range of 0 to 1 m/s. Besides the fluctuation frequency, other factors, such as the amplitude of a fluctuating airflow, could be adopted to distinguish perceptions associated with constant and dynamic patterns. Parkinson and de Dear (PARKINSON; DE DEAR, 2017) argued that a velocity amplitude greater than 0.5 m/s would enhance the airflow cooling effect perceived by subjects. Xie et al. (XIE et al., 2018) addressed both fluctuation frequencies (0.016-0.1 Hz) and amplitudes (0.2, 0.4 and 0.6 m/s between minimum and maximum speeds). They characterized airflows with larger and smaller amplitudes and reported that the former resembled a sinusoidal pattern (β value > 1.1) and the latter was similar to a constant pattern (β value < 1.1). Although different fluctuation frequencies did not influence the TSV specifically, a combination of high fluctuation frequency and low mean air velocity enhanced the thermal comfort of the subjects in their study. A brief comparison between strengths and weaknesses of applying dynamic and/or non-uniform airflows for thermal comfort indoors is summarised in Table 10.

Table 10 - Summary of the strengths and weaknesses based on the reviewed studies.

Strengths / Potentials	Weaknesses / Limitations
Reduced TSV (towards neutral or slightly cool), better thermal comfort evaluation and better preference ratings in comparison to constant mechanical airflow under the same air temperature (26-30 °C) and mean air speed (0.5-1 m/s).	Limited effectiveness for cooling based only in moving air under high indoor temperatures (30 °C). Not tested yet under higher temperatures (> 30 °C) and/or high relative humidity (> 50%).
Possibility to vary airflow parameters other than air speed, when maximum air speed is limited. For instance, the fluctuation frequency and the interval of occurrence may be varied in dynamic airflow patterns.	Risk of draught from exposure to high air speeds through long time spans, especially at mild air temperatures (26 °C). On the other hand, short time spans (fluctuation frequency <0.1 Hz) may lead to imperceptible airflow.
Possible reduction in cooling energy consumption from steady-state thermal environments with strict and low set points (below 23 ºC).	Mechanical devices to produce dynamic airflows should be improved. For example, to produce simulated natural airflows randomly throughout the occupancy time.

There is evidence of reduced heat stress at high indoor temperatures due to the increased cooling effect from dynamic intermittent airflows. Kabanshi et al. (KABANSHI et al., 2016) reported an improvement in both the thermal acceptance and satisfaction even under test conditions with a relatively high indoor temperature (28 °C) and relatively low velocity (0.4 m/s) when the air supply was on. Ugursal and Culp (UǦURSAL; CULP, 2013) hypothesised that pulsed airflows would enhance the stimulation of cold receptors in a warm environment by repeating the pulse at shorter intervals. They reported a greater cooling effect from an airflow with a 30-s pulse in comparison to both a 60-s pulse and constant airflows. Alternatively, in some thermal comfort studies on intermittent airflow patterns the draught dissatisfaction rate under neutral-to-cool thermal conditions was investigated. Kabanshi et al.

(KABANSHI et al., 2016) tested and confirmed the hypothesis of reduced discomfort due to air movements by setting the combinations of longer air supply off time at a lower indoor temperature (22.5 °C) and shorter air supply off time at a higher temperature (28.5 °C).

Tian et al. (TIAN et al., 2019) assessed two intermittent patterns with cycle durations of 2 and 5 min under similar indoor temperature conditions (27 °C), but the impact of the pulsing time on the TSV was unclear. However, the authors reported a higher draught dissatisfaction rate for the longest period of air supply at a mean air velocity of 0.8 m/s. A similar trend was observed in a study by Tawackolian et al. (TAWACKOLIAN; LICHTNER; KRIEGEL, 2020) for a thermal environment considered to be neutral by the authors, where increased draught dissatisfaction rates were related to increased air speeds and pulse durations. As seen from the studies conducted by Zhou et al. (ZHOU et al., 2006) and Tian et al. (TIAN et al., 2019), draught dissatisfaction in the presence of dynamic airflows was noted for indoor temperatures around 26/27 °C, which can be described as mild or warm under certain circumstances. There are two possible explanations for these findings. Firstly, the cooling effect is enhanced under such conditions, driving subjects' perceptions towards the colder side of the thermal sensation scale and thus generating complaints of a draught and, secondly, the dissatisfaction is due to issues other than thermally related factors and is mistaken for a draught (i.e. unwanted local cooling).

3.3 REMARKS REGARDING DYNAMIC/NON-UNIFORM AIRFLOWS

Dynamic airflows were proven to affect human responses to air movement and thermal comfort conditions under diverse combinations of environmental variables. These responses were positive in most studies, given the main purpose of diversifying the alternatives available to cool down the body and prevent subjects feeling discomfort related to draught. Two main dimensions of the airflow effect can be highlighted as determinant for enhanced subjective perception: spatial and temporal variations. The spatial dimension refers to non-uniform (asymmetric) exposure to airflows across the human body. There is evidence of the impact of localised airflow stimuli on overall thermal perception indoors, supported by the theory of alliesthesia (positive and pleasant impact of airflow (PARKINSON; DE DEAR, 2017; UĞURSAL; CULP, 2013) and by the ASHRAE draught model (unwanted local convective cooling (LAMPRET et al., 2018; SCHIAVON et al., 2016a)). The body segments to be reached by targeted airflows were chosen considering those commonly recognised in the literature as the most sensitive to air movements (unclothed head, face and back of the neck).

The airflow direction and the distance between airflow source and airflow target have been addressed in a few studies and they affect some aspects of the predicted (YANG et al., 2015) and actual (UĞURSAL; CULP, 2013; XIE et al., 2018) thermal perception.

With regard to the temporal dimension of airflows, dynamic patterns were evaluated in terms of thermal perception and their characteristics were summarised. The airflow patterns documented in this review may be treated as tending toward constant mechanical airflows or natural wind, based on their inherent characteristics of power spectrum, turbulence intensity and periodicity of air speed values. Of the airflow parameters addressed, air speed/velocity is considered in all studies, although the time of exposure to each distinct air speed range may also need to be taken into account. A single average value for the air speed/velocity may not adequately represent its cooling effect in some circumstances. For simulated natural airflows, for instance, the corresponding perception can differ from that of the constant mechanical airflows under the same mean air speed considered under the experimental conditions. Moreover, varying the magnitude of the airflow (i.e., air speed) within a time span can allow the desired cooling effect to be obtained in each experimental study.

Turbulence intensity was also assessed in most studies with dynamic airflow patterns, since there is evidence of increased body heat transfer when Tu > 40% (HUANG et al., 2014). This was the case for sinusoidal airflows, simulated natural airflows and natural wind according in previous studies (KANG; SONG; SCHIAVON, 2013; OUYANG et al., 2006). Despite the trend of predominantly low Tu values being registered under constant mechanical and intermittent patterns, spatial variations in this parameter were recorded across experimental rooms with fans blowing air at a constant mean speed (HUANG et al., 2014; MIHARA et al., 2019). Moreover, Huang et al. (HUANG et al., 2014) and Xie et al. (XIE et al., 2018) reported increased Tu values as the distance between an airflow source and the targeted subjects/thermal manikins increased. In contrast to air speed/velocity and Tu, the β-value is a parameter adopted to distinguish the airflow energy distribution at different frequencies. Notable differences between mechanical and natural wind regarding this aspect have been documented. The β-values obtained from sinusoidal and simulated natural airflows were clearly higher than those recorded for constant airflows, but they did not reach values typical of natural wind (≈1.5) (HUA et al., 2012; OUYANG et al., 2006). Lastly, airflow fluctuation frequency was found to be an important parameter in a couple of studies addressing thermal comfort and air movement perception. However, these investigations were limited to airflows with a periodic behaviour generated by mechanic devices (e.g., sinusoidal pattern).

Of the parameters adopted to describe the behaviour of dynamic airflows, the most promising results in terms of enhanced cooling effect were obtained with a certain combination of air speed/velocity ranges (amplitudes) and interval of occurrence. This issue has been addressed through the adoption of sinusoidal patterns and, more recently, intermittent patterns at test sites. The amplitudes tested were quite low, probably due to practical limitations in providing air speeds higher than 1 m/s in some circumstances that must be considered in the design of the test conditions. Nevertheless, it is possible to assess subjective responses to dynamic airflows with large amplitudes and optimal combinations of air speeds delivered and time of exposure, particularly in warm environments. Moreover, the dynamic airflow patterns delivered by compact and practical devices should also be tested in real occupancy buildings (large scale studies) to check for their applicability in terms of user satisfaction with the device and the air motion, since the results reported so far have come from studies with few participants in controlled environments. The unpredictable behaviour of delivered airflows could also be improved, given the increasing interest in generating air movement that resembles the characteristics of natural wind revealed in the studies reviewed (CUI et al., 2013; HUA et al., 2012; LUO et al., 2018; ZHOU et al., 2006) (see Table 11).

Table 11 - Thermal sensation and draught dissatisfaction with exposure to dynamic airflows.

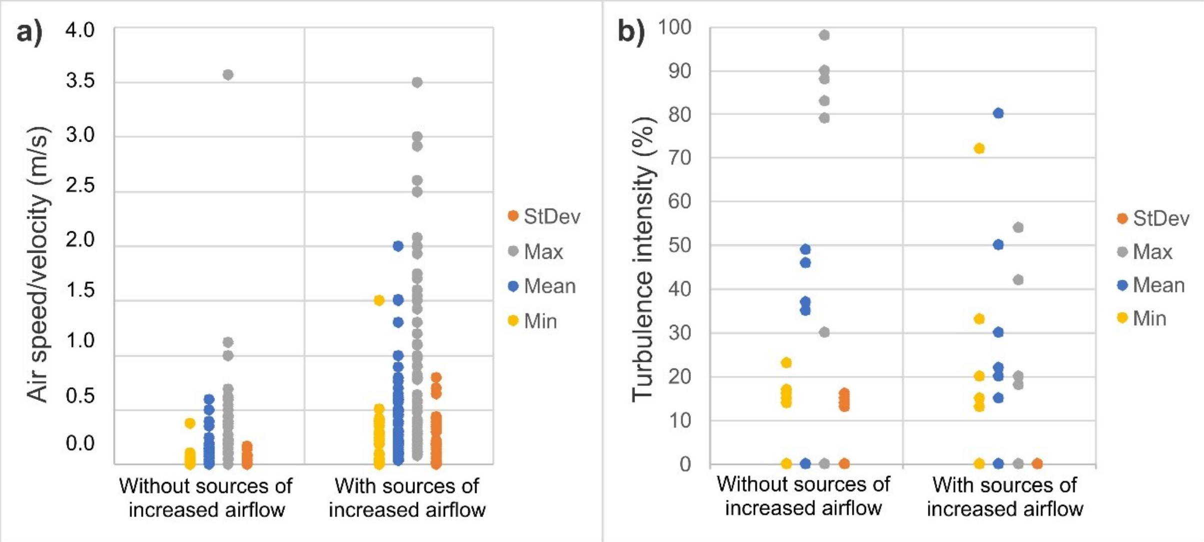
Reference	Targeted body segment	T_a (°C)	RH (%)	V_a (m/s)	Airflow pattern	Description	TSV	TSV under constant mechanical airflow	p-value	Draught dissatisfaction (%)
(ZHOU et al., 2006)	unspecific	26	50	0.8	sinusoidal	0.1 Hz	-0.88	-0.64	p < 0.01	36.5
		26	50	0.8	simulated natural	-	-0.92	-0.64	p < 0.01	33.9
		30	50	0.8	sinusoidal	0.1 Hz	0.22	0.61	p < 0.01	24.5
		30	50	0.8	simulated natural	-	0.24	0.61	p < 0.01	4.2
(HUA et al., 2012)	face	28	50	0.8	simulated natural	-	-0.05	0	p > 0.05	-
		30	50	0.8	simulated natural	-	0.45	0.58	p > 0.05	-
		28	40	0.8-1	simulated natural	-	-0.04	-0.04	p > 0.05	-
(HUANG; OUYANG; ZHU, 2012)	face	28	35	0.6	sinusoidal	0.5 Hz	-0.2	-	p < 0.05	-
		28	35	0.6	sinusoidal	1 Hz	-0.3	-		-
		30	35	0.6	sinusoidal	0.5 Hz	0.3	-	p < 0.05	-
		30	35	0.6	sinusoidal	1 Hz	0.5	-		-
(CUI et al., 2013)	unspecific	28	-	1	simulated natural	-	0.14	0.28	p < 0.05	-
		30	-	1	simulated natural	-	0.56	0.86	p < 0.05	-
(PARKINSON; DE DEAR, 2017)	back of the neck	27.5	50	0.65	sinusoidal	0.033 Hz	0.07	0.08	p > 0.05	-
		27.5	50	0.65	intermittent	square-wave pattern	-0.17	0.08	p > 0.05	-
		27.5	50	0.65	intermittent	saw pattern	-0.33	0.08	p > 0.05	-
(LUO et al., 2018)	unspecific	28	50	0.5	simulated natural	-	0	0.25	p < 0.05	-
		30	50	0.9	simulated natural	-	0.31	0.45	p > 0.05	-
(LAMPRET et al., 2018)	back of the neck	23.5	50	0.42	sinusoidal	0.028 Hz	-0.83	-	-	73.3
		23.5	50	0.42	sinusoidal	0.5 Hz	-0.77	-	-	70
(XIE et al., 2018)	head	23	50-70	0.2-0.6	sinusoidal	0.016 Hz	-0.21	-	p > 0.05	-
		23	50-70	0.2-0.6	sinusoidal	0.033 Hz	-0.28	-		-
		23	50-70	0.2-0.6	sinusoidal	0.1 Hz	-0.43	-		-
		25	50-70	0.2-0.6	sinusoidal	0.016 Hz	-0.16	-	p > 0.05	-
		25	50-70	0.2-0.6	sinusoidal	0.033 Hz	0.04	-		-
		25	50-70	0.2-0.6	sinusoidal	0.1 Hz	0	-		-
(TIAN et al., 2019)	head	27	45-50	0.53	intermittent	pulsating 5 min	-0.2	-0.73	-	21.7
		27	45-50	N.A.	intermittent	pulsating 2 min	-0.2	-0.73	-	9.2
(TAWACKOLIAN; LICHTNER; KRIEGEL, 2020)	head and neck	22	-	0.2	intermittent	10s pulse	-	-	-	≈20
		22	-	0.2	intermittent	20s pulse	-	-	-	≈30
		22	-	0.2	intermittent	30s pulse	-	-	-	≈30
		22	-	0.4	intermittent	10s pulse	-	-	-	≈35
		22	-	0.4	intermittent	20s pulse	-	-	-	≈45
		22	-	0.4	intermittent	30s pulse	-	-	-	≈50
		22	-	0.6	intermittent	10s pulse	-	-	-	≈70
		22	-	0.6	intermittent	20s pulse	-	-	-	≈70
		22	-	0.6	intermittent	30s pulse	-	-	-	≈60

4 ON-SITE AIRFLOW CHARACTERISATIONS

The average air speed (V_a) is generally characterised in indoor thermal comfort studies by on-site measurements. In this regard, on the one hand, special attention has been directed to V_a in cases where sources of increased airflow, such as natural cross-ventilation from openings and/or supplementary ventilation devices, are available to the occupants (BUONOCORE et al., 2018; CÂNDIDO et al., 2010; ISMAIL; ABDUL RAHMAN, 2010; KUMAR et al., 2016). The main issues to be addressed in these studies are the human thermal adaptation to warm/hot environmental conditions (DJAMILA; MING; KUMARESAN, 2014; KUMAR; SINGH, 2019; SANSANIWAL et al., 2020) and the adoption of non-uniform airflows for thermal comfort (CHLUDZIŃSKA; BOGDAN, 2015; KABANSHI et al., 2016; OBAYASHI et al., 2019). On the other hand, the airflow characterisation was more comprehensive (including both V_a and Tu characterisations in room spaces) when draught risk was the main concern (AZAD et al., 2018; GE; FAZIO, 2004). This was verified in thermal comfort studies conducted in spaces mainly operated with HVAC systems such as mixing (KABANSHI et al., 2016; WU; LUO; LIU, 2019), displacement (CAUSONE et al., 2010; MAGNIER; ZMEUREANU; DEROME, 2012; MELIKOV et al., 2005), underfloor (SCHIAVON et al., 2016a; SEKHAR; CHING, 2002) and stratum ventilation (TIAN; LIN; WANG, 2011). Thus, the criterion of existing and operating sources of increased airflow was adopted in this broad characterisation of data measured on site. An overview of the maximum and minimum values, mean values and standard deviation values for V_a and Tu samples is provided in Figure 50.

It can be observed that, overall, the V_a values were noticeably higher in the sample with any source of increased airflow, which is expected. However, this trend was not verified for Tu, for which the mean values were concentrated below 50% regardless of whether sources of increased airflow available or not (Figure 50b). In fact, Tu was assessed in only a few studies and these were mostly conducted under predictable airflow patterns, such as the airflows from mixing ventilation systems (KABANSHI et al., 2016; WU; LUO; LIU, 2019), displacement ventilation systems (CAUSONE et al., 2010; MAGNIER; ZMEUREANU; DEROME, 2012; MELIKOV et al., 2005), air jet diffusers (KABANSHI et al., 2016; YAO et al., 2015) and ventilation devices (CSAKY; KALMAR; KALMAR, 2019; GRIEFAHN; KÜNEMUND; GEHRING, 2000; HUANG et al., 2014) (e.g., fans and ventilators). Very few Tu measurements came from field studies in buildings that were occupied and none originated from naturally ventilated spaces. This is not surprising since Tu is supposed to be adopted in the objective assessment of draught risk in neutral-to-cool thermal conditions. As pointed out in section 3.3, Tu is not only time-dependent, but also dependent on the proximity to the dominant airflow sources. The accuracy of the Tu measurement is primarily dependent on the use of appropriate measurement devices to capture fast velocity fluctuations (ISO, 2005) and this issue will be further discussed in section 4.1.

Figure 50 – Summary of V_a and Tu values obtained from on-site measurements.



Source: Adapted from the references given in supplementary file 2.

It can be noted that considerably higher standard deviation values for V_a (StDev ≈ 0.5 m/s) were obtained in the studies with a source of increased airflow (Figure 50a). This implies the possibility of a large spread in a sample of measured values, especially in buildings that rely on cross-ventilation as the main strategy for achieving thermal comfort under neutral, warm or hot conditions. There are several reports of the prevalence of low V_a values (below 0.2 m/s) in indoor spaces with recurrent operation of natural ventilation (WANG et al., 2010; YAN et al., 2020; YANG; ZHANG, 2008), although the occupants' expectations indicate a clear preference for more air movement (MISHRA; RAMGOPAL, 2014; ZHANG; LIU; MENG, 2015). The frequency of high V_a values (> 0.8 m/s) is usually very low in these situations and their inclusion in an analysis based on mean V_a values only may underestimate the implications of alternated low and high V_a on snapshot subjective perception (more details can be found in section 4.2). Thus, this variability provides a good opportunity to also assess the dynamic behaviour of V_a over time in real occupancy spaces.

4.1 REMARKS ON MEASUREMENT TECHNIQUES AND INSTRUMENTATION

The characterisation of indoor airflow for thermal comfort purposes is mainly conducted through simulation and on-site (full-scale) measurements. As far as room airflow field is concerned, prediction methods, such as computational fluid dynamics (CFD), are very useful to capture and visualise the non-uniformities across time and space, regardless of the occupants' positioning inside the room (BRAGANÇA et al., 2016; MEYER; TAN, 2014). Conversely, full-scale measurements rely on a few specific points in the space to represent a typical occupancy pattern, i.e., the positions of the occupants. The two approaches should complement each other, since computational prediction models need constant validation from on-site measurements (CEHLIN; MOSHFEGH, 2010; CHEN; MOSHFEGH; CEHLIN, 2013). Similarly, airflow distribution patterns from specific HVAC systems may have been previously outlined and this information could serve as guide for thermal comfort studies with an on-site measurement approach. Within the scope of this review, the goal is to discuss the main aspects of characterisation by means of on-site measurements under dynamic and/or non-uniform airflow conditions.

According to Yang et al. (YANG et al., 2019a), the measurement methods can be described as intrusive or non-intrusive. In non-intrusive measurements, sensors are not in contact with the flow field to be measured, i.e., they do not disturb the flow field. In the articles reviewed, very few authors adopted sonic anemometry for point-wise measurements (MARTINEZ et al., 2014; RYU; KIM; LEE, 2009) and particle image/streak velocimetry (PIV/PSV/PST) for global-wise measurements (LI et al., 2017; WANG; WANG; LI, 2020; YOU et al., 2019). The latter approach provides a detailed picture of the room airflow, by providing the true components of the air velocity vector with high accuracy. It has been adopted for assessing the airflow patterns from several airflow sources, including aircraft cabins (LI et al., 2017; WANG et al., 2018a; YOU et al., 2019) and ceiling fans in enclosed spaces (WANG et al., 2020; WANG; WANG; LI, 2020). However, such techniques may be unsuitable for measurements taken in real occupancy spaces subjected to unsteady environmental conditions. Wu et al. (WU; LUO; LIU, 2019) argued that the application of PIV in full-scale measurements is rather limited due to the complexity and fragility of the measurement system components. Yang et al. (YANG et al., 2019a) noted that the flow field must be stabilised during the measurement process, which may be very time-consuming and suitable only for stationary conditions in a laboratory environment. Moreover, most of the non-intrusive methods are based on optical principles and thus seeding particles are needed to visualise and track the airflow field (WANG et al., 2020). This would be a hindrance and impracticable for measuring under certain circumstances in thermal comfort studies, such as in the presence of human subjects and the monitoring of naturally ventilated rooms.

With regard to intrusive methods, which are characterised by sensors in contact with the flow field to be measured, thermal anemometry (including hot-wire, hot sphere and thermistors) has been widely applied to measure V_a and Tu in most of the studies assessed. This technique is extensively applied in both chamber and field studies, due to its practicality and cost-effectiveness (hand-held and portable instruments). According to ISO 7726 (ISO, 1998), the calibration and response time of anemometers must be considered to obtain accurate measurements of V_a and Tu, respectively. Short response times will give a better picture of the fluctuations characteristic of a typical turbulent airflow. In the literature, hot-wire anemometers are recognised as providing the fastest response time and better temporal resolution (VOELKER; MAEMPEL; KORNADT, 2014; YAO et al., 2015), although hot-sphere anemometers may also have good performance. Both et al. (BOTH; SZÁNTHÓ; GODA, 2017) compared the Tu values measured using hot-wire (response time of less than 0.2 s) and hot-sphere (response time of about 2/3 s) sensors in a controlled environment and found no significant differences between the Tu readings. Hot-sphere anemometers are easier to calibrate (BOTH; SZÁNTHÓ; GODA, 2017) and the heated element reaches a lower temperature compared to hot-wire anemometers. Another characteristic of thermal anemometers is that, in general, the uncertainty of the velocity reading is below 0.1 m/s (CEHLIN; MOSHFEGH, 2010; CHEN; MOSHFEGH; CEHLIN, 2013), although this may be a minor issue when the targeted or expected air velocities are higher.

The directionality issue is also of great importance in the assessment of indoor airflow. Omnidirectional sensors are not sensitive to a specific flow direction, while unidirectional sensors are sensitive to one direction (the plane normal to the probe). Hot-wire sensors are typically unidirectional and thus their applicability is limited based on the recommendations of the ASHRAE 55 Standard (ASHRAE, 2020) for average air speed (V_a) and Class I of the field research protocols (DE DEAR; BRAGER; COOPER, 1997) for thermal comfort studies. However, this should not be the case when the predominant airflow direction is well known. Smoke sticks were adopted to visualise the main airflow pattern in some studies, so that the unidirectional probe could be oriented accordingly (BUONOCORE et al., 2018; CÂNDIDO et al., 2010; WANG et al., 2016b). Directionality is also an issue when high air velocities are to be measured. Ryu et al. (RYU; KIM; LEE, 2009) and Wang et al. (WANG et al., 2010) considered the dominant wind flow and the strongest wind when assessing the air velocity in naturally ventilated residences. In contrast, omnidirectional sensors would be recommended in situations where the air velocities are typically low and the direction of the airflow is not well defined (CHEN; MOSHFEGH; CEHLIN, 2013). However, the omnidirectionality of some sensors is relative, since the airflow is affected close to the sensor support (ISO, 1998). For instance, in a practical application, Magnier et al. (MAGNIER; ZMEUREANU; DEROME, 2012) noted that omnidirectional anemometers were surprisingly sensitive to the airflow direction, especially at a distance of 0.6 m or more from the airflow source.

Based on the literature, thermal anemometry has been applied significantly more frequently than any other technique. The suitable measuring ranges (0.05-1 m/s according to the requirements of the ISO Standard 7726 for Class C - Comfort), the possibility of recalibration and the fast responsiveness of these sensors are important features to be considered when dynamic airflows are evaluated in thermal comfort studies. Substantial improvements in the measuring techniques are required to overcome the main limitations of current methods, such as the inaccuracy at low air velocities. In this regard, in the next few years, a new trend could emerge, where indoors airflows are measured by means of ultrasonic anemometry, which is commonly adopted in outdoor studies because of the greater accuracy and wide measurement range (DJAMILA; MING; KUMARESAN, 2016; WOOD et al., 2013; YANG et al., 2017). Recently, a new prototype for an ultrasonic anemometer for indoor applications was presented by Arens et al. (ARENS et al., 2020), which was described as inexpensive, low-power and three-dimensional. Advances along this research line could allow some of the current limitations in thermal anemometry to be overcome, such as the sensitivity at low air speeds and the power consumption of the heated element, which is particularly important for long-term monitoring and evaluations.

4.2 TEMPORAL DIMENSION OF AIRFLOW CHARACTERISATION AND PERCEPTION

In addition to considering the factors inherent to measurement instruments, such as response time and sampling frequency (rate), the integration of instantaneous air velocity measurements over an interval (time-averaged V_a) should be carried out in thermal comfort studies. In the literature, this interval is referred to as the sampling interval or sampling period. With regard to the thermal comfort evaluation and prediction, the ASHRAE Standard 55 states that sampling intervals for V_a measurements should be not less than 1 min or more than 3 min. Although most of the publications reviewed refer to the ASHRAE 55 Standard for measuring procedures, there is a recommendation in ASHRAE RP-884 (DE DEAR; BRAGER; COOPER, 1997) to calculate time-averaged V_a considering an interval of not less than 3 min in field studies. This may be due to a greater range (variability) of indoor environmental conditions, which should be considered in subjective evaluations. The recommendations in the ISO Standard 7726 do not include a sampling interval but it is noted that airflows with high Tu and low frequency of velocity fluctuations would require longer measuring periods. Hence, a previous characterisation of room airflow to identify the expected ranges of V_a and Tu would be of great use before conducting right-here-right-now surveys (with simultaneous monitoring of physical variables and subjective feedback from occupants). This characterisation is available in the literature for most HVAC systems, but very few studies have addressed this issue in naturally ventilated spaces, where the airflow fields are difficult to predict.

With regard to natural ventilation, Ryu et al. (RYU; KIM; LEE, 2009) and Djamila et al. (DJAMILA; MING; KUMARESAN, 2016) measured instantaneous air velocities from natural wind and showed the sensitivity of V_a to the sampling interval. Omrani et al. (OMRANI et al., 2017) conducted full-scale measurements in a naturally ventilated apartment and also highlighted the time scale for averaging speeds as an important issue for V_a characterisation, since some sampling intervals would not reflect transient aspects of the thermal environment, such as fluctuating air speeds. Djamila et al. (DJAMILA; MING; KUMARESAN, 2016) reported a stronger correlation between V_a and Tu when the sampling interval was lower (3 s versus 1 min). However, the authors argued that Tu may not be a good measure to describe and address the rapid variations in wind speed. Thus, they proposed a ratio of increasing wind variation (RIW) to represent the difference between maximum and minimum wind speeds over the time interval. Considering the typical variations in air velocity, the ratio of the increase or decrease in the speed might be useful for airflow characterisation in addition to considering average air speeds only.

Table 12 - Examples of subjective assessments for air movement in thermal comfort studies.

Criteria for air movement evaluation	**First extreme of scale**	**Second extreme of scale**	**Reference**
intensity	no movement	strong	(CUI et al., 2013; LAMPRET et al., 2018; ZHANG; LIU; MENG, 2015)
sensation	too still/very low	too windy/very high	(BUONOCORE et al., 2018; CÂNDIDO et al., 2010; DU et al., 2018; MIHARA et al., 2019; TAWACKOLIAN; LICHTNER; KRIEGEL, 2020; WANG et al., 2010; YANG; ZHANG, 2008)
draught (direct assessment)	no draught	strong draught	(KALMÁR; KALMÁR, 2018; KOSTIAINEN et al., 2008; WIGÖ, 2013)

acceptability	clearly unacceptable	clearly acceptable	(BUONOCORE et al., 2018; CÂNDIDO et al., 2010; CHEN; ZHANG; TANG, 2017; KABANSHI et al., 2019; SCHIAVON et al., 2016a)
preference	less/decrease/weaker	more/increase/stronger	(BUONOCORE et al., 2018; CÂNDIDO et al., 2010; CUI et al., 2013; LUO et al., 2018; SCHIAVON et al., 2016a; WIGÖ, 2013; ZHAI et al., 2019)
fluctuation	monotone	fluctuating	(HUANG; OUYANG; ZHU, 2012; ZHOU et al., 2006)

Despite the recommendations in the standards, sampling intervals of V_a measurements varied considerably among the papers reviewed. In fact, the time-averaged V_a is expected to reflect thermal and/or air movement perception at the time feedback is requested from subjects in a thermal comfort survey (see Table 12). Therefore, sampling intervals were associated with the frequency of subjective evaluation in Table 13. It can be noted that the sampling intervals ranged from less than 1 min to 15 min regardless of the expected airflow behaviour as a function of the main airflow source. In fact, sampling intervals for airflows of predictable behaviour were mainly determined based on the time required to complete one or more cycles of the designed airflow patterns (CHEN; ZHANG; TANG, 2017; TIAN et al., 2019). As shown in Figure 49, this time reached up to 6 min for intermittent airflows. However, the assessment of these dynamic patterns could take up to 30 min of exposure to the same airflow condition (KABANSHI et al., 2016). The time of exposure to high and constant fan speeds (0.8-1.87 m/s) reached 40-45 min with a single subjective evaluation (LIU et al., 2018; MIHARA et al., 2019). Such long-term exposures could diminish the perceived cooling effect of airflows, even in the case of repeated dynamic patterns, and result in some type of dissatisfaction with the air movement, as noted by Mihara et al. (MIHARA et al., 2019) and Du et al. (DU et al., 2018). Alternatively, the shortest exposure intervals were reported by Xie et al. (XIE et al., 2018) and Parkinson and de Dear (PARKINSON; DE DEAR, 2017), who argued that reliable feedback from subjects would be achieved within 20 min of exposure to a particular environmental configuration.

Table 13 - Summary of sampling intervals.

Reference	**Main airflow source**	**Exposure interval***	**Subjective evaluation**	**Sampling interval**
(KABANSHI et al., 2016)	intermittent air jet diffusers	30 min	every 30 min	1 min for 10 min
(CHEN; ZHANG; TANG, 2017)	pedestal fans	10 min	every 10 min	1 cycle of fans (24 s)
(PARKINSON; DE DEAR, 2017)	low-power personal fans with diffusers	5 min	three times in 5 min	3 s
(XIE et al., 2018)	air nozzles	3 min	every 3 min	10 min
(TIAN et al., 2019)	pulsating air supply	20-30 min	five times in 90 min	3 cycles of pulse (6 /15 min)

(TIAN et al., 2019)	constant air supply	20-30 min	five times in 90 min	10 min
(MIHARA et al., 2019)	ceiling fans	45 min	once in 45 min	3 min
(DAGHIGH et al., 2009)	natural ventilation from openings and AC	unspecified	once in the survey	1 min
(KUCHEN; FISCH, 2009)	natural ventilation from openings and AC	unspecified	once in the survey	1 min
(YAO; LIU; LI, 2010)	natural ventilation from openings and ceiling fans	unspecified	unspecified	> 5 min
(CÂNDIDO et al., 2010)	natural ventilation from openings and ceiling fans	120 min	every 20 min	5 min
(CHOI; AZIZ; LOFTNESS, 2010)	HVAC systems	unspecified	once in the survey	4 min
(DEB; RAMACHANDRAIAH, 2010)	natural ventilation and ceiling/wall-mounted fans	unspecified	once in the survey	5-10 min
(ARENS et al., 2015)	air diffusers	unspecified	unspecified	3 min
(SHAN et al., 2016)	mixing ventilation / passive displacement ventilation	120 min	after 60 min	2 min
(KHALID et al., 2018)	AC	10-15 min	once in 10-15 min	10 min
(LIU et al., 2018)	pedestal fans	40 min	once in 40 min	3 min

* Exposure interval to a specific airflow condition

Some studies in the literature have shown that the temporal dimension of subjective perception needs to be considered in airflow characterisations. In other words, changes in the speed and direction of airflows should be accounted for even within the shortest exposure intervals. Thus, thermal and air movement perception on exposure to airflows was investigated with respect to the temporal dimension and a summary of the findings is presented in Table 14. The time span represents the interval during which subjects were constantly exposed to the same airflow pattern, and this time was sufficient to elicit a change in subject's perception (repetitions of airflow patterns were included in the time span). Fast fluctuations in V_a (in the order of 10 s) were perceived in experiments, as reported by Xie et al. (XIE et al., 2018) and Tawackolian et al. (TAWACKOLIAN; LICHTNER; KRIEGEL, 2020). Kabanshi et al. (KABANSHI et al., 2019) observed a demand for increased and constant V_a during an interval of more than 3 min while testing an intermittent system. These nuances were perceptible for subjects exposed to dynamic airflows for short durations (10 min), regardless of the experimental conditions.

Steady-state thermal sensation was reached quickly by the action of air movements in the studies of Schiavon et al. (SCHIAVON et al., 2016a), Parkinson and de Dear (PARKINSON; DE DEAR, 2017) and Zhai et al. (ZHAI et al., 2019). This may be due to the cooling effect of increased and/or dynamic airflow on disturbing or restoring the subjects' thermal sensation after experiencing still air conditions previously. Hence, a contrast between asymmetrical thermal stimuli, changing from dissatisfaction to thermal pleasure and vice-versa, is likely to favour a faster airflow perception from subjects. This is aligned to the findings of Parkinson et al. (PARKINSON; DE DEAR; CANDIDO, 2016) regarding air movement alliesthesia in a warm-to-hot environment. In their study, the higher the levels of displeasure with the thermal environment before transitioning to a favourable condition (e.g., experiencing an upward ramping of ambient temperatures), the stronger was the positive alliesthesia from the opposite and favourable condition (e.g., setting a fan to provide high air speeds). The relief provided by air speed lasted 2 min, according to the thermal pleasure votes (subjective measure) and around 3 min according to the drop in localised and overall skin temperatures (objective measure), when indoor temperatures were increased from 28 to 32 ºC meanwhile fans were operating (PARKINSON; DE DEAR; CANDIDO, 2016). On following the conceptual framework of alliesthesia, it is not clear for how long such airflow stimuli would be perceived as pleasant and thus would be suitable to elicit occupants' thermal comfort or thermal pleasure for longer periods of building occupancy under neutral, warm or hot environmental conditions. As alliesthesia from air movement is essentially a dynamic mechanism, it is assumed that thermal pleasure is also related to the unpredictable characteristic of airflows such as natural ventilation, but a long-term evaluation would be needed to address this issue.

Table 14 - Summary of findings on the temporal perception of airflows.

Reference	**Airflow characteristic**	**Time span**	**Main effect on thermal and air movement perception**
(SCHIAVON et al., 2016a)	Draughty at ankle level	5 min	reducing overall thermal sensation and reaching steady state
(PARKINSON; DE DEAR, 2017)	Fluctuating (spatial alliesthesia)	5 min	reducing overall thermal sensation and reaching steady state
(XIE et al., 2018)	Sinusoidal	3 min	10-s fluctuating period enhanced air movement perception
(LAMPRET et al., 2018)	Temperature and velocity fluctuations	3 min	highest percentages of dissatisfaction due to temperature fluctuation in cool conditions
(TAWACKOLIAN; LICHTNER; KRIEGEL, 2020)	Intermittent airflow	5 min	30-s pulse duration increased draught rate
(KALMÁR, 2018)	Variable airflow direction	10 min	preferred decrease in air velocity after 30 min of exposure
(KALMÁR; KALMÁR, 2018)	Variable airflow direction and velocity	10 min	perceived draught rate was stable after 30 min of exposure
(KABANSHI et al., 2019)	Intermittent airflow	4-5 min	demand for a longer exposure to high air movement at 28.5 °C
(ZHAI et al., 2019)	Personal control of fans	7-8 min	reducing overall thermal sensation and reaching steady state

Other aspects related to the temporal dimension of airflow characterisation and evaluation should also be highlighted. The most common approach in studies conducted by means of on-site measurements is the use of right-here-right-now surveys, in which subjective responses from the occupants are collected at the same time as the indoor variables are monitored in a room. Although this was the case for most studies with subject participation, the absence of people during the measurement process was observed in some investigations (CHOI; AZIZ; LOFTNESS, 2010; KALMÁR; KALMÁR, 2018; MELIKOV et al., 2005). This enabled measurements to be taken at the exact position subjects were expected to occupy in the room, but before actual occupancy. It was noted that the measurement procedure without subjects in the same space and/or at the same time was applied in rooms with negligible or minimal variations in the overall airflow field. Hence, possible fluctuations in the airflow field would be previously recorded. Similarly, associations between previously measured V_a values and power levels from airflow devices (e.g., fan, air nozzle, air jet) were adopted in some investigations to characterise the main airflow field around the occupants (BOERSTRA et al., 2015; GUENTHER; SAWODNY, 2019; LIU et al., 2018; ZHAI et al., 2019). Thus, power levels were previously monitored and correlated to an average air velocity in the subsequent thermal comfort analysis. This is particularly useful in studies addressing occupant control over personal cooling devices or systems.

4.3 SPATIAL DIMENSION OF AIRFLOW CHARACTERISATION AND PERCEPTION

Spatial airflow characterisation has been thoroughly researched in controlled rooms without subject participation, mainly focusing on HVAC system design, ventilation effectiveness and predicted thermal comfort (CAUSONE et al., 2010; MAGNIER; ZMEUREANU; DEROME, 2012; SHAN et al., 2016; TIAN; LIN; WANG, 2011; WANG et al., 2018b). The airflow field produced by ceiling and pedestal fans is also well documented in the literature (CONCEIÇÃO et al., 2006; MIHARA et al., 2019; RAFTERY et al., 2019; WANG et al., 2020), since these appliances are widely used indoors to provide a dominant and directed airflow to occupants. Recently, Luo et al. (LUO et al., 2021) collected a dataset of air speeds in commercial buildings with ceiling fans. The authors showed the interactions between typical office furniture and the resulting airflows, as well as the effect of ceiling fan layout on air speed uniformity across the rooms. Their findings provide an important insight into airflow characterisation in real occupancy buildings, as previous studies on this subject were restricted to experimental rooms. Such efforts are valuable from the perspective of characterisation, as one can easily estimate the airflow distribution that is likely to occur by operating these systems and devices. However, considering the trend of non-uniform thermal conditions and assuming the influence of occupants on the thermal environment in real occupancy buildings, the task of characterising airflows that have the greatest impact on a subject’s perception becomes more challenging.

The difficulty in accessing the airflow field on-site is related to unpredictable events, such as the adaptive actions of occupants, who may operate doors, windows and/or additional airflow sources. Therefore, the spatial airflow distribution may occur without a prevalent pattern during the occupancy time. Additionally, intrusion from measuring instruments and blockage effects from the furniture in the room can hinder on-site measurements. Zhang et al. (ZHANG et al., 2010a) argued that measuring next to the subjects while they took part in the survey would be an intrusive procedure. Melikov et al. (MELIKOV et al., 2005) positioned the sensors in their investigation considering the local airflow direction and possible blockage effects, to ensure the accuracy of the measurements. Sekhar and Ching (SEKHAR; CHING, 2002) and Wan and Chao (WAN; CHAO, 2002) reported significant obstructions to the room airflow from underfloor air-conditioning and ventilation systems in real occupancy buildings. These findings highlight the importance of considering the circumstantial factors regarding occupancy in on-site characterisations, especially when significant changes in the thermal environment are likely to occur due to adaptive actions by the users. Melikov et al. (MELIKOV et al., 2005) reported some modifications in surveyed offices to block the passage of the supplied cold air toward the occupants in a displacement ventilation system. Indraganti et al. (INDRAGANTI; OOKA; RIJAL, 2013a, 2013b) and Damiati et al. (DAMIATI et al., 2016) reported several means of thermal adaptation to warm and hot indoor conditions by users through the adoption of increased air movement, including simultaneous running of natural cross-ventilation and fans. Such occurrences are likely to be perceived by the occupants across on-site measurements and should be considered in local airflow characterisation.

The representative positioning of occupants in a space must be considered for the characterisation and subsequent thermal comfort prediction and evaluation, as recommended in ASHRAE Standard 55 (ASHRAE, 2020). Thermal environmental variables were usually measured as close as possible to the subjects in right-here-right-now surveys addressed in this review. There is no consensus regarding a standard meter of proximity to the occupants as a reference. Some authors quantified the distance adopted, while others referred to it generically – with terms such as “next”, “close to”, “around”, etc. In the studies for which the distance to the subjects is given, the most commonly cited were 0.2 m (LÓPEZ-PÉREZ; FLORES-PRIETO; RÍOS-ROJAS, 2019; PARKINSON; DE DEAR, 2017; YANG et al., 2013), 0.3 m (WU et al., 2017; ZHANG; LIU; MENG, 2015), 0.5 m (GRIEFAHN; KÜNEMUND; GEHRING, 2000; KHALID et al., 2018) and 1.0 m (CÂNDIDO; DE DEAR; LAMBERTS, 2011; DAMIATI et al., 2016; GOU et al., 2018).

Regarding the spatial dimension of airflow characterisation and evaluation, the non-uniformities across the human body should also be considered. If occupants are exposed to airflows from specific sources towards the body, the body segments targeted and under the influence of the airflow are generally noted. This is due to the expected significance of V_a values measured locally for thermal comfort evaluation purposes. By revisiting the concept of V_a from ASHRAE Standard 55 (ASHRAE, 2020), the spatial average is obtained considering three measurement heights, which correspond to the ankle, waist and head levels, equally weighted. However, most researchers have assessed air speed under non-uniform airflows by tracking the body segments susceptible to increased air movement or by adopting the highest air speed values among the measured heights, regardless of the recommendations provided in this standard. Further discussions concerning the evaluation domain are presented in section 5.

Furthermore, some factors would contribute to the increased or decreased perception of air movement across the human body in real occupancy spaces. The arrangement of local airflow sources and furniture could interfere, as well as clothed skin surfaces (according to the building dress codes). Liu et al. (LIU et al., 2018) noted that increased air movement might not be sensed in the area of covered body parts in tropical countries. Thus, the head region was adopted as a measurement spot in their investigation conducted in classrooms, considering the predominance of bare skin.

It is therefore clear that the air movement reaching on the human body can result in diverse subjective perceptions depending on the targeted body segments. Also, there is evidence in the literature that hot and cold stimuli are perceived differently in each of the body segments (ARENS; ZHANG; HUIZENGA, 2006; HUIZENGA et al., 2004; SCHIAVON et al., 2016a; WANG et al., 2019; YANG et al., 2019b; ZHANG et al., 2010b). De Dear et al. (DE DEAR et al., 1997) has quantified the convective heat transfer coefficients for each of the 16 bare body segments and it was found that the peripheral members such as feet and hands have the highest coefficients under forced convection. On the other hand, Arens et al. (ARENS; ZHANG; HUIZENGA, 2006) studied the impact of local thermal sensation (local body segments) on whole-body thermal sensation during localised cooling stimuli and reported a minor influence of the feet and hands' local sensation on overall thermal perception.

Thus, sensitivity to air movement stimuli would also vary across the human body and could be determinant in an association between measured air velocities and predicted thermal comfort. To address this issue, details on the perception of localised airflow at different body segments are given in Table 15. As observed in studies focused on dynamic and non-uniform airflows (see Table 11), the targeted body segments are mainly the extremities of the body, with an emphasis on the head/face, which corresponds to one of the measuring levels in the ASHRAE Standard 55. The major pleasant cooling or draught effect is identified in the upper body parts, with emphasis on the head and neck. Part of this effect may be attributed to the bare skin surface, as these segments are usually unclothed on people living in tropical countries and the effect of airflow on the human body is diminished by covering with clothing layers (clothing insulation). For instance, de Dear et al. (DE DEAR et al., 1997) reported a diminished heat transfer coefficient for the head of their manikin because it was partially covered by hair. They also found high coefficients for body segments that are typically covered in offices, like the lower legs, forearms and upper arms.

Table 15 - Summary of localised airflow perception in thermal comfort studies.

Reference	**Environmental conditions**	**Targeted body segments**	**Major cooling effect / draught perception**
(UĞURSAL; CULP, 2013)	neutral (23.9 °C) and warm (28.3 °C). RH=45%	head only/head, hands, feet simultaneously	head, hands, feet simultaneously
(VAN CRAENENDONCK et al., 2019)	cool-to-neutral (21.2/22.9 °C). RH=40%	legs / chest / head	lower arm / hand
(GRIEFAHN; KÜNEMUND; GEHRING, 2000)	23 °C. RH = 40-60%	left dorsolateral body	forearm / neck
(ZHANG et al., 2010a)	neutral (25 °C), warm (28 °C) and hot (30 °C)	head and hands	head and hands (no distinction)
(CHLUDZIŃSKA; BOGDAN, 2015)	summer (24/26/28 °C) and winter (18/20/22°C). RH = 50%	face and ankles	head and chest level in summer conditions
(SHAN et al., 2016)	neutral (23/24 °C). RH = 55-75%	unspecific	feet
(KABANSHI et al., 2016)	transient (22.5/25.5/28.5 °C). RH = 18-30%	unspecific	head, neck, arms and hands
(LIN et al., 2016)	warm (25 °C), moderate (22.5 °C) and cool (20 °C). RH < 30%	unspecific	head, shoulder, hands, arms and feet
(DU et al., 2020)	cold (12/14/16/18 °C). RH = 60%	feet, lower body, upper body, hands, head	feet, lower body
(SANSANIWAL et al., 2020)	predominantly warm/hot (29/31 °C). RH = 8-95%	unspecific	neck / head

The head is one of the most sensitive body segments according to the literature, especially under warm or hot environmental conditions (CHLUDZIŃSKA; BOGDAN, 2015; SANSANIWAL et al., 2020; ZHANG et al., 2010b). Also, subjects demonstrated a preference for airflow towards their face for cooling purposes (CHLUDZIŃSKA; BOGDAN, 2015; HUANG et al., 2014). Local thermal perception in the head region seems to play a major role in overall perception under warm environmental conditions. This is mainly attributed to the skin thermoreceptors, which are more sensitive to cooling stimuli and more densely distributed despite the reduced skin surface area (YANG et al., 2019b; ZHANG et al., 2004).

In addition, there is evidence of thermal sensitivity at the neck level of subjects exposed to cool environmental conditions (LAMPRET et al., 2018; TAWACKOLIAN; LICHTNER; KRIEGEL, 2020). Of the papers reviewed, V_a was measured at the head level in most of the investigations in which one measurement height was adopted. The air velocity assessment in the region of the upper body parts and mainly at the head level was emphasised in some studies. Yang et al. (YANG et al., 2013) cited a high alliesthesial thermal sensitivity and Wigö (WIGÖ, 2013) mentioned an efficient cooling effect at the head level. Liu et al. (LIU et al., 2018) argued that the head is a relevant body segment to consider in the assessment of overall thermal comfort because the airflow is easily sensed by the head skin surface in tropical regions. Sansaniwal et al. (SANSANIWAL et al., 2020) reported a significant localised thermal discomfort in the head and neck region because of sweating in Indian offices. Indeed, this issue should draw attention in the case of indoor environments where the occupants are susceptible to heat discomfort due to high temperature and humidity, thus relying on air movement to be cooled by evaporation.

Regarding the other extremity of the human body, the feet have been cited as sensitive body segments under neutral, cool and cold thermal conditions (DU et al., 2020; SHAN et al., 2016). As far as non-uniform environmental conditions are concerned, cooling the feet in a warm environment is not as representative of the overall thermal perception as heating the feet in a cool environment (ARENS; ZHANG; HUIZENGA, 2006; ZHANG et al., 2010b). Considering increased air movement in warm or hot environments for heat dissipation, it is expected that measurement at the ankle level will assume a minor role in the study planning and set up. Instead, its assessment would be required in investigations conducted in neutral to cold environments, in which subjects are susceptible to local discomfort by unwanted local cooling. In fact, special consideration is given to airflow at the ankle level and other lower body parts in studies on draught risk in rooms with underfloor air distribution or displacement ventilation (SCHIAVON et al., 2016a; SEKHAR; CHING, 2002; WAN; CHAO, 2002). Lastly, there is limited evidence regarding the significance of local thermal perception specifically at the abdomen level, particularly regarding the possible impact of localised airflow. This is probably due to the interference of clothing and/or furniture in a practical occupancy situation, which would cause a diminished perception of air movement.

5 THERMAL COMFORT PREDICTION UNDER DYNAMIC AND NON-UNIFORM AIRFLOW CONDITIONS

The predictive models and indices that are extensively adopted in thermal comfort studies rely mainly on physical and personal variables, which must be assessed and/or estimated with great accuracy to properly assess the thermal comfort of building occupants. Evaluation criteria from whole-body (CONCEIÇÃO et al., 2008; KABANSHI; WIGÖ; SANDBERG, 2016; WANG et al., 2016a) and multi-segment (SCHELLEN et al., 2013; ZHANG et al., 2010c) thermal comfort models have been developed and improved in recent decades for application to a wide range of environmental conditions and circumstances found in real occupancy buildings. In this regard, comfort evaluation under transitional and non-uniform environmental conditions rather than the steady-state approach has recently drawn attention. Similarly, personal and multi-segment models have been developed to account for thermal asymmetry across the human body and its impact on sensation and comfort (ZHANG et al., 2010b, 2010c, 2010d).

With regard to airflow in subjective evaluations, V_a is the physical parameter inputted for the calculation of well-known thermal comfort indices like predicted mean vote (PMV) and standard effective temperature (SET). In this case, the cooling effect corresponding to the action of air movement is assumed to be from constant V_a and Tu. However, as discussed in section 3, thermal perception is affected by the dynamic characteristics of airflows, such as the frequency of fluctuation and the intermittency of the V_a pulse, since the cooling mechanisms of periodic and constant airflows are different (KABANSHI et al., 2019). In other words, variations in V_a from dynamic airflows induced a different subjective evaluation compared to constant airflows with the same average air speed (as seen in Table 11) and this is also likely to influence thermal comfort predictions. Similarly, the V_a values used in the calculation of thermal comfort indices, such as PMV, and the operative temperature corresponded to the head level only instead of the waist level – as recommended in ASHRAE 55 Standard. This procedure was clearly based on the perceived airflow stimuli at the head level in the studies by Luo et al. (LUO et al., 2018), Liu et al. (LIU et al., 2018) and Zhai et al. (ZHAI et al., 2013, 2017).

Considering the above, the thermal comfort prediction and evaluation was addressed in the reviewed papers regarding the spatial and/or temporal non-uniformities of the air movement. Comparisons between the predictive indices and the corresponding actual subjective evaluations were performed in most studies. A summary is presented in Table 16. As expected, the PMV index has been extensively adopted in thermal comfort studies, although there is evidence suggesting it is not suitable for comfort prediction under increased air movement, due to underestimation of the cooling effect from increased or dynamic airflows. Gao et al. (GAO; WANG; WARGOCKI, 2015) reported a greater deviation between TSV and PMV when V_a was greater than 0.2 m/s in a naturally ventilated environment, which is expected since PMV is recommended for V_a values below this threshold (ASHRAE, 2020). Regarding the spatial dimension of non-uniform airflows, Kalmár (KALMÁR, 2018) and Huang et al. (HUANG et al., 2014) reported relevant deviations between TSV and PMV in a situation of airflow directed towards the head of subjects. Moreover, Huang et al. (HUANG et al., 2014) noted an overestimation of the TSV based on the calculated PMV within a threshold of increased skin wetness, which is a practical situation for occupants subjected to heat discomfort indoors. Alternatively, Tian et al. (TIAN et al., 2019) reported a reasonable agreement between the time-averaged PMV and the actual thermal sensation under a pulsating airflow pattern with minor air velocity (0.17-0.53 m/s) and air temperature fluctuations in the occupied zone.

Overall, the PMV was found to overestimate the actual mean TSV when occupants were provided with opportunities for environmental adaption under warm or hot environmental conditions (T_a above 28 °C). However, it is often not possible to discern how much of this overestimation would be due to the expected variations in air movement, because diverse adaptive mechanisms, including adjustments such as regulating airflow sources and sweating, could be taking place simultaneously (HOSSAIN et al., 2019). In addition, large individual differences regarding personal variables, thermal background and expectations contribute significantly to the overall inaccuracy of the PMV as thermal comfort index in real buildings (INDRAGANTI; OOKA; RIJAL, 2013b; WANG et al., 2017; YAU; CHEW; SAIFULLAH, 2013). The SET model overcomes the issue of underestimated the cooling effect from airflows and is suitable for evaluations in warm environments. Previous studies have addressed the applicability of the SET index, including limited responsiveness to non-steady and dynamic conditions, such as those provided by personal comfort systems (PCS) (ZHAI et al., 2013; ZHANG; ARENS; ZHAI, 2015). According to Zhu et al. (ZHU et al., 2015), concerns regarding the suitability of the SET index under non-uniform airflows include the averaged heat transfer coefficient and the non-inclusion of air movement parameters other than V_a. However, good agreement between SET and TSV was found in the studies reviewed. This was reported by Mihara et al. (MIHARA et al., 2019) and Gao et al. (GAO; WANG; WARGOCKI, 2015) regardless of the V_a values (up to 1.87 m/s) measured at the head level (MIHARA et al., 2019), for ceiling fans and natural ventilation assisted by fans, respectively.

Huang et al. (HUANG et al., 2014) investigated the suitability of whole-body models (PMV and SET) under non-uniform air movement for thermal evaluations. The experiment was conducted in a climate chamber with fans blowing air towards the face of subjects, who were seated. The authors adopted two inputs of V_a in the SET model: the air speed in front of the face and the averaged speed at three heights for seated occupants (0.1, 0.6 and 1.1 m). The air speeds targeted at the face varied between 0.6 and 1 m/s (details for the other measurements taken around the subjects were not given). The results indicated a good approximation between the predictive SET models under warm conditions (26-34 °C), despite a slight overestimation of the cooling effect in the case of air speed for the face region. Under these environmental conditions, tracking the airflow with the highest V_a appears to be appropriate for comfort prediction. Yang et al. (YANG et al., 2015) compared the proposed cooling fan efficiency (CFE) index for pedestal fans by adopting the maximum velocity (which was measured at the head level) and average velocity (for three levels) as input values. The authors reported a significant difference between the resulting temperature offsets (i.e., cooling effect, in °C), given by CFE in both situations. The study was conducted under experimental conditions ranging from 24 to 30 °C with thermal manikins and thus evaporative heat loss was not considered.

In addition to the prevalent perception of localised high V_a, the comfort and air movement evaluation of people subjected to non-uniform airflow conditions across the body was found to be dependent on the overall thermal sensation in some studies. Melikov et al. (MELIKOV et al., 2005) noted significant individual differences between occupant sensitivity to air movement, which compromised the prediction of the draught dissatisfaction rate using the ASHRAE Draught Rating Model when occupants felt cooler or warmer than neutral. Nevertheless, the authors obtained good accuracy in the prediction of subjects feeling neutral in rooms with displacement ventilation (with air velocity slightly higher at the ankle level). Schiavon et al. (SCHIAVON et al., 2016a) and Liu et al. (LIU et al., 2017) addressed the ankle draught issue in spaces equipped with displacement or underfloor air distribution systems. They proposed an ankle draught risk model which was recently incorporated into the ASHRAE Standard 55 (ASHRAE, 2020). Although ankle draught represents local thermal discomfort, the percentage of dissatisfaction depends on the whole-body thermal sensation, which is now calculated using the average air temperature and speed at the head and waist levels. Hence, two measuring levels represent overall the thermal sensation and the air speed at the ankle level is limited according to the proposed local discomfort criteria.

Kabanshi et al. (KABANSHI et al., 2019) evaluated occupants' perception of air movements from an intermittent air supply system. The experimental conditions of T_a and V_a corresponded to 22.5-28.5 °C and 0.15-0.8 m/s, respectively. Based on their findings, a model to predict the percentage of satisfaction with the air movement under intermittent airflow conditions was developed. Overall thermal sensation (OTS) ranging from +0.49 and -0.49 on ASHRAE seven-point scale was adopted as a criterion to predict air movement acceptability. According to the authors, air movement acceptability is related to the subjects' OTS, since air movement could increase or decrease the deviation from thermal neutrality (KABANSHI et al., 2019). In practice, comfort predictions are considerably more reliable within the range of thermal conditions considered as neutral or almost neutral. Hence, deviations towards the colder or warmer sides of the thermal sensation scale should be considered carefully.

Furthermore, individual prediction approaches may also be of increasing interest in thermal comfort studies, since individual differences might not be properly represented by the usual average predictions. Bearing this issue in mind, Guenther and Sawodny (GUENTHER; SAWODNY, 2019) proposed a personalized thermal comfort prediction based on the PMV and a couple of parameters which have a strong influence. Controllable ceiling fans were adopted as a means of increasing air movement and the V_a from the fan levels was previously accessed. The outcomes indicated higher individual prediction accuracy when compared to the standard PMV calculation only, and both the supply air temperature and the change in fan level were determinant as predictors in the personalised model. A recent publication by Itani et al. (ITANI et al., 2021) presented a similar approach to predict thermal comfort in naturally ventilated spaces with personalized ventilation based on multiple variables such as indoor temperature, relative humidity and facial temperature. In this regard, whether occupants have control over their immediate environment or not, which might include cooling or ventilation devices, should be considered as boundary conditions to propose and validate the prediction models. Therefore, this approach seems to be promising in situations where air movement that is potentially increased and user controlled is the prevalent airflow source indoors.

Table 16 - Comparison between predicted and actual subjective perception under dynamic and non-uniform airflows.

Reference	Type / main source of airflow	Prediction Index	Validation / Comparison	Conclusion
(HUANG et al., 2014)	spatially non-uniform airflow	SET	SETface (one level) / SETwhole-body (average from three levels) x TSV	good agreement (R^2 = 0.94 / 0.93)
(HUANG et al., 2014)	spatially non-uniform airflow	PMV	PMV x TSV	predicts well when skin wetness < 0.06; overestimates TSV when skin wetness > 0.06
(YANG et al., 2015)	spatially non-uniform airflow	Cooling Fan Efficiency (CFE)	CFE maximum velocity (head level) x CFE average velocity (three levels)	inputted V_a values have strong influence on cooling effect
(TIAN et al., 2019)	pulsating airflow	TAPMV / TAPPD (time averaged PMV/PPD)	PMV prediction at the head level x actual sensation vote	reasonable agreement
(MIHARA et al., 2019)	constant fan speed	SET	average SET at head level x mean thermal sensation	highly correlated (R^2 = 0.97)
(MELIKOV et al., 2005)	displacement ventilation	Predicted dissatisfied due to draught (PD)	PD x percentage bothered by draught at the ankle level	good accuracy when applied to occupants whose thermal sensation is neutral
(ZHANG; LIU; MENG, 2015)	natural ventilation from openings and fans	ET*	ET* x percentage acceptable	good second-order polynomial relationship (R^2 = 0.84)
(GAO; WANG; WARGOCKI, 2015)	natural ventilation from openings and fans	PMV	PMV x TSV	TSV is close to PMV when the air velocity is less than 0.2 m/s, but the TSV is less than PMV when the air velocity is larger than 0.2 m/s
(GAO; WANG; WARGOCKI, 2015)	natural ventilation from openings and fans	SET	SET x TSV	TSV is close to SET when the air velocity is less than or greater than 0.2 m/s
(KALMÁR, 2018)	personalized ventilation system	PMV	PMV x subjective thermal comfort sensation	significantly lower value for subjective thermal comfort sensation than the calculated PMV value
(GUENTHER; SAWODNY, 2019)	VAC system and ceiling fans	Personalized thermal comfort prediction based on PMV	74% higher individual prediction accuracy compared to the standard PMV calculation	the main comfort factors in the test model were supply air temperature and a change in the fan level
(KABANSHI et al., 2019)	intermittent air jet diffusers	Predicted percentage satisfied with air movements (PSAM)	PSAM as a function of OTS (overall thermal sensation)	87% of occupants with neutral overall thermal sensation (between -0.5 and +0.5) would be satisfied with intermittent air speeds ranging from 0.4 to 0.8 m/s, across room air temperatures of 23.7-29.1 °C

6 CONCLUSIONS

To address the applicability of dynamic and non-uniform airflows for human thermal comfort in buildings, the spatial and temporal dimensions of airflow characterisation and evaluation, including the subjective perception of thermal and air movement conditions, were discussed in this review. The main findings can be summarised as follows:

- Dynamic airflow patterns are effective in enhancing the cooling effect in warm and hot thermal environments (T_a = 27~30 °C). Optimal thermal sensation (close to 0 in the seven-point sensation scale) and comfort votes, as well as high airflow preference rates, are reported under the simulated natural pattern. A promising trend is to deliver to occupants the main aspects of natural wind, such as varying air velocity magnitude within the range of 0.1-1.0 m/s and alternating fluctuation frequencies in the range of 0.01-1 Hz. The unpredictability of simulated natural airflows needs to be improved and also tested in real occupancy buildings, since natural ventilation (natural wind) is ineffective in some indoor spaces. Additionally, there has been increasing interest in intermittent patterns in relation to draught dissatisfaction and air movement preference. The implications of this with regard to subjective perception under warmer indoor conditions (air temperature above 27 °C) are unclear and thus further investigation is required, aimed at optimising the maximum air speeds and time spans of occurrence. It is expected that such efforts could lead to improvements to the design and operation of mechanical airflow devices in buildings.
- Air velocity is by far the most commonly assessed descriptor of air movement behaviour in occupied spaces. With respect to large velocity amplitudes in dynamic airflows (maximum air velocities beyond 1.0 m/s), recording the magnitude of air velocity alone may not be sufficient to capture the typical oscillations and the associated cooling effect, because this variable is highly time dependent. As was noted in the literature review that sampling intervals for time-averaged air velocities may vary significantly (from less than 1 minute to 15 minutes), and this could lead to the underestimation or overestimation of the effect of air movement on thermal perception. Hence, other metrics that describe the temporal dimension of air speeds more properly should be considered and tested in addition to the average air speed within the scope of a thermal comfort evaluation. Furthermore, new efforts are needed to understand the airflow mechanisms required to ensure thermal pleasure and comfort over longer periods of occupancy in buildings, since previous studies regarding

dynamic airflows were concerned with point-in-time evaluations. In other words, long-term assessments should be conducted, focusing on the constant optimization of dynamic features (such as fluctuating air speeds) throughout the occupancy time.

- Thermal comfort evaluation under non-uniform airflow conditions is dependent on the prevalent sources of air movement and consequently on the highest air velocities provided. As seen in the literature review, airflows were mainly directed towards (and air speeds were measured with respect to) the upper body parts, since a stronger cooling effect is reported for the head and neck regions. Nevertheless, the non-uniformities in the airflow field under warm thermal conditions are not considered for characterisation and evaluation purposes in the scope of ASHRAE 55 Standard. The non-uniformities, the temporal variations in air speed and their implications to thermal comfort in occupied buildings are poorly addressed in the main standards, despite the evidence from chamber and field studies regarding localised and dynamic airflows. Therefore, the characterisation and evaluation of such airflows – particularly in field studies to be conducted in real life spaces – should be properly oriented in the related standards and guidelines.
- As far as comfort prediction is concerned, the SET index was reasonably suitable under localised and prevalent airflow fields directed towards the human body. However, these were characterised by constant velocities over time. Temporal variations in air speed are not assumed for air velocities in PMV and SET models, although they have been shown to influence people's subjective perception by enhancing the perceived cooling when compared to the effect of constant airflows. Therefore, there is a gap to be filled regarding the comfort prediction of subjects experiencing dynamic airflows with large variations in air speed over time. Moreover, user-centred control of air movement should be considered in future approaches for the development and validation of comfort models suitable under unsteady and dynamic airflow fields, since personally controlled sources of air movement directed toward the human body are prone to be adopted in real occupancy buildings for personal adaptation.

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APPENDIX B – National Survey Questionnaire Transcript

Welcome to this survey!

We invite you to take part in the survey entitled "Perceptions about natural ventilation in Brazilian dwellings", which is part of a PhD research in the Architecture and Urbanism Academic Doctoral Degree Program (PósARQ) at the Federal University of Santa Catarina (UFSC), under the responsibility of Carolina Buonocore, Msc, and supervision of Prof. Roberto Lamberts, PhD.

Your participation is essential for understanding the circumstances, motivations and barriers regarding adopting natural ventilation for thermal comfort in Brazilian homes. By clicking "Start survey" below, you will be directed to a questionnaire with 15 questions and an estimated completion time of 10 minutes. Participation is voluntary, anonymous and may be interrupted at any time. Your answers will be recorded only after the completion of the questionnaire.

Thank you for your valuable collaboration!

Note: This research was approved by the Ethics Committee on Research with Human Beings (CEPSH/UFSC) under CAAE identifier no. 51459421.0.0000.0121. This body ensures that research with human beings is developed and conducted within ethical standards. For more details, you can access the informed consent form by clicking on the link:

https://docs.google.com/document/d/1JD4_UkHmLUhTgQggr7bvDktSWPGkmPxRBzNMMYgSmvs/edit?usp=sharing.

Click on "Start survey" to begin
☐ Start survey

Part 1: General Information

Select the State where you live.
State: [Select]

In which city do you live?
City: ____________________

Sex
☐ Male
☐ Female
☐ I prefer not to answer

Age
☐ Under 25 years old
☐ Between 25 and 34 years old
☐ Between 35 and 54 years old
☐ Over 55 years old
☐ I prefer not to answer

Education

☐ Primary school
☐ Secondary education (incomplete)
☐ Secondary education (complete)
☐ Higher (incomplete)
☐ Higher (complete)
☐ Postgraduate
☐ I prefer not to answer

Family income
☐ Up to R$ 1,100 (up to 1 minimum wage[6])
☐ From R$ 1,100 to R$ 2,200 (between 1 and 2 minimum wages)
☐ From R$ 2,200 to R$ 4,400 (between 2 and 4 minimum wages)
☐ From R$ 4,400 to R$ 11,000 (between 4 and 10 minimum wages)
☐ From R$ 11,000 to R$ 17,600 (between 10 and 16 minimum wages)
☐ Over R$ 17,600 (over 16 minimum wages)
☐ I prefer not to answer

Part 2: Natural ventilation at home

Natural ventilation is one of the central conditioning strategies adopted in Brazilian homes to get thermal comfort in summer. A breeze from natural ventilation might come from opening windows and doors. This allows air circulation (air movement) through the rooms so the air can reach the body, cooling it.

Overall, I consider my residence to be:
☐ Well-ventilated throughout the year
☐ Well-ventilated most of the year
☐ Poorly ventilated most of the year
☐ Poorly ventilated throughout the year

Which of the alternatives below best describes your PREFERENCE at home during the year's HOT season?
☐ Keep windows and/or doors open (use natural ventilation)
☐ Keep windows and/or doors open, plus fans on to increase air movement (use natural ventilation and fans)
☐ Keep windows and/or doors closed for air conditioning (use air-conditioning)

Part 3: Routines of use

Please describe your approximate routine of staying at home currently:
☐ I stay every (or almost every) day
☐ I stay only on working days
☐ I stay only at weekends
☐ I stay on alternate days and/or times
☐ I hardly stay at home

Are you used to moving around inside the house because of natural ventilation (for example, going to a more ventilated room)?
☐ Always
☐ Often
☐ Sometimes
☐ Rarely
☐ Never

If you have fans (ceiling, pedestal and/or table fans) at home, how would you describe the condition of use during the year's HOT season? Consider the room(s) where you stay the longest.

[6] 1 minimum wage = R$ 1,100 in 2021

☐ I have no fans at home
☐ The fan(s) remain on according to my routine at home, regardless of the condition of air movement from natural ventilation
☐ I switch on the fan(s) only when I feel the need for more air movement

Which best describes how often you use natural ventilation at home during the year's HOT season? Consider the room(s) you spend the most time in.
☐ My house is always naturally ventilated (I do not own or use air conditioning)
☐ Natural ventilation is not part of my routine at home (I use air conditioning all the time)
☐ Rooms are naturally ventilated on specific days and/or at specific times (e.g. during the day, during the nights more ventilated etc.)

If you have ticked the last alternative in the previous question, which of the options below best describes the condition of using natural ventilation?
☐ The rooms are naturally ventilated mainly during the day (morning and/or afternoon)
☐ The rooms are naturally ventilated mainly at night (dusk and/or dawn)
☐ Rooms are naturally ventilated only when it is colder and/or ventilated
☐ Other: ________________________________

Part 4: Perceptions

Thinking about the typical characteristics of natural ventilation on a HOT day, tick the alternative that corresponds to your opinion for each of the following:

Characteristics	I like	Indifferent	I don't like it
Predominantly breezy	☐	☐	☐
Absence of breezes	☐	☐	☐
Constancy (constant or regular breeze)	☐	☐	☐
Oscillation (intervals with and without breeze)	☐	☐	☐
Unpredictability (dependence on external wind, season etc.)	☐	☐	☐
Controllability (possibility to regulate the breeze, increasing or decreasing the intensity)	☐	☐	☐

Are any other features you like or dislike? ______________________________

Thinking about the reality of your residence, point out the reason(s) for adopting and for not adopting natural ventilation:
Multiple answers are possible
NOTE: Please select up to 3 alternatives that you consider most important.

Reasons to ADOPT natural ventilation at home	Reasons NOT to ADOPT natural ventilation at home
☐ Personal preference (I like natural ventilation)	☐ Personal preference (I'm not too fond of natural ventilation)
☐ Thermal comfort (cooling the body by air movement)	☐ Thermal discomfort (absence / insufficient air movement)
☐ Favourable scenario (my house is well-ventilated)	☐ Unfavourable scenario (my house is poorly ventilated)
☐ Feasibility of keeping windows or doors open	☐ Impediments to opening windows or doors*
☐ Air renewal in the room(s)	
☐ Cooling energy saving	

☐ Other: ________________	☐ Other: ________________

* Examples of impediments to opening windows and/or doors for natural ventilation: entrance of unwanted solar radiation, use of blinds, strong wind, rain, insects, noise, odours, privacy, security, etc.

How do you evaluate the frequency of use of natural ventilation in the room(s) you spend the most time in after the advent of the COVID-19 pandemic in Brazil?
☐ remained the same (I did not change the frequency of use of natural ventilation)
☐ It was reduced (I reduced the frequency of use of natural ventilation)
☐ It was increased (I increased the frequency of use of natural ventilation)

Space for contributions and additional considerations
[Insert a free comment box].

E-mail address (in case you wish to have access to the search results): ______________________________

APPENDIX C – Pilot Field Study

A pilot field study was conducted to put into practice the proposed research methods in real-world settings before carrying out the field survey campaign in São Luis, the northeast region of Brazil. The pilot was conducted in Florianópolis, southern Brazil, through February and March 2022 (summer season). Nine residences were visited and monitored during this campaign. By conducting the pilot study, the researcher was able to

- test the instruments of personal data collection – interview scripts and questionnaires,
- get familiarised with the measuring equipment for physical variables, and
- confirm the practical protocols suitable for the field study in São Luis.

Furthermore, it was possible to glimpse the data collected and decide how to organise it for subsequent analyses. Each of the changes made to any of those instruments was depicted and justified in this appendix based on the field evidence from the pilot.

C.1. Practical research protocols

The pilot was implemented from the first contact with potential volunteers known to the researcher or her environment. This contact was via WhatsApp message or telephone call to present the study – goals and how it would be conducted – and schedule a visit if they were available and willing to participate. Some visits were difficult to schedule due to national carnival holidays, bad weather days (rainy or stormy), and conflicts on the participant's agenda. Thus, it was necessary to conciliate their agenda and the forecasted weather conditions, which was challenging and time-consuming.

The national meteorological service[7] was adopted as a reference for weather forecasts throughout the pilot study. The most favourable weather conditions considered were sunny or partially cloudy days with (at least) moderate wind – which did not happen very often during the pilot. It was also impossible to conduct all visits under those conditions because of the researcher's tight schedule in Florianópolis. Some monitoring campaigns had to be shortened (from the intended four weeks to two weeks) for the same reason.

During the visit to each home, the researcher presented the study in person with a consent form (APPENDIX D – Consent Form for Participation in the Field Study), which the

[7] INMET :: Previsão. Available at: https://previsao.inmet.gov.br/.

researcher and the participant signed. Then, the researcher briefly conversed with the participant to decide where the interview would be conducted in residence. The researcher explained that a place where the air motion from natural ventilation could be felt on the skin (in the context of this research, a place in the residence deemed as well-ventilated), if existent, would be preferred. However, householders were also free to choose the place according to their convenience. Participants were encouraged to adopt the climatisation strategy they wished, disregarding the researcher's presence.

The selected rooms were generally living or dining rooms because those are specific social areas in Brazilian homes. Regarding the climatisation strategy operating during the visit, 8 out of 9 residences were naturally ventilated (windows opened, and external doors in some cases); air conditioning was on in one house. Fans were on in one out of 8 naturally ventilated homes. The participants and the researcher were sitting during the interviews; the microclimatic station, adopted to measure physical variables, was positioned within 1m from the sitting post occupied by respondents (Figure C 1).

Figure C 1 – Positioning of the microclimatic station during the interview

Source: elaborated by the author

The approach tested in the pilot study encompassed the conduction of interviews and the filling in a point-in-time questionnaire by residents simultaneously, aiming to save time in the moment of visiting. The estimated duration of the interviews was 30 minutes. This estimation was to decide on which moments the point-in-time questionnaire – in which questions about air movement and thermal comfort were asked repeatedly – would be filled in. Initially, it was estimated that the group of questions (depicted in APPENDIX F – Point-in-Time (Instant) Survey Questionnaire (IQ)) would be asked five times with intervals of 5 minutes, totalling 30 minutes – the first answer was required after 5 minutes of conversation. This interval was enough for most respondents to perceive environmental changes, especially air movement conditions. However, 4 out of 9 interviews lasted 40 to 45 minutes, and one conversation with two interviewees (an unusual situation) lasted one hour. The duration of conversations also depended on the speaking rhythm and the amount of information participants would like to share. Thus, when interviews were extended, the intervals between responses to the point-in-time questionnaire (IQ) increased to 10 minutes. Thus, the adequate procedure for the field study is to keep the 5-minute intervals as default and the possibility of increasing intervals up to 10 minutes depending on the rhythm and flow of the conversation.

Figure C 2 – Additional measurements in places and operation modes of frequent use

Source: elaborated by the author

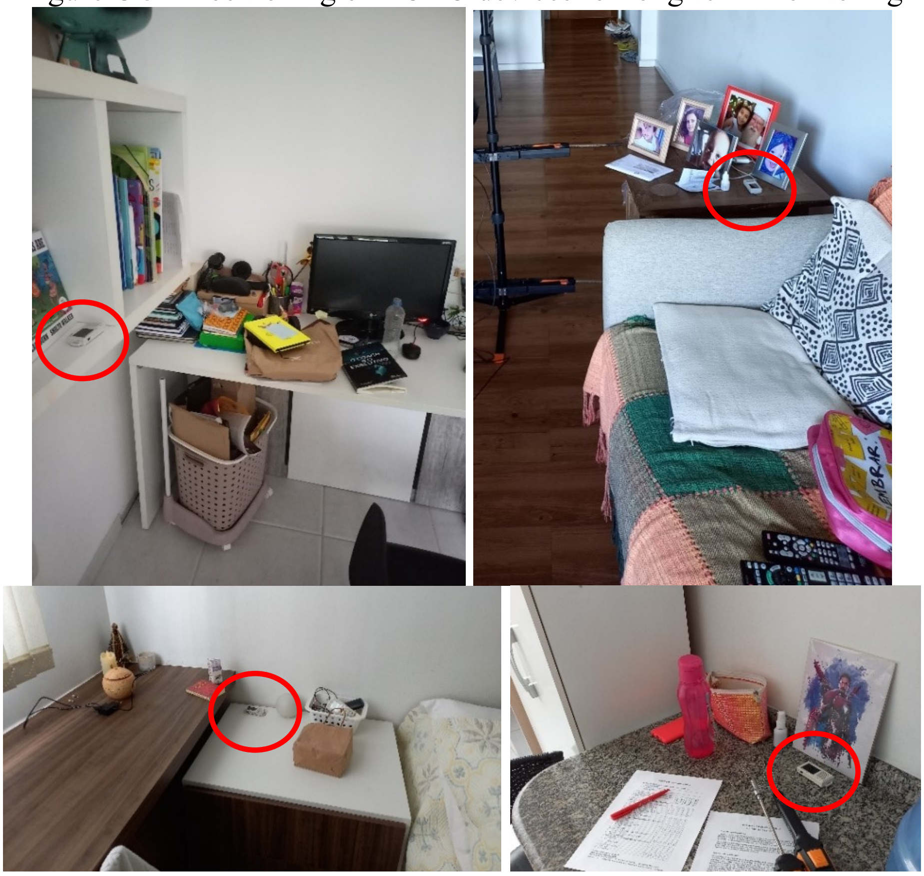
After the interviews, the researcher moved the microclimatic station to measure the physical variables for approximately 30 minutes in other places that the householders would often use for their activities, if any. Those were mainly home offices used during remote work, as illustrated in Figure C 2. Accordingly, HOBO measuring devices were positioned over desks and shelves in living rooms, dining rooms, home offices and bedrooms for the 4-week long-term monitoring (Figure C 3). The following were observed as criteria for positioning the devices

- proximity to the place which participants are expected to occupy,

- absence of solar radiation/sources of heat, and
- to be out of reach of children or pets.

During long-term monitoring, the researcher sought to interact with the participants through a quick online questionnaire sent via WhatsApp messages. The moments to send the questionnaire were mainly based on the indication of moderate wind from the national weather forecast (which resulted in the outdoor conditions depicted in Figure C 4) but also considered participants' routine at home, i.e. when they were at home according to the schedule reported on the interview. An interval of at least three days between requests was observed in this monitoring. In total, 14 participants agreed to interact in this phase – 10 were interviewed on the first visit – and 64 messages were sent. As a result, 52 answers were given, and 50 answers corresponded to moments when participants were at home; this represented a rate of response of 81% concerning the requests and 96% of responses which are valid in the scope of this study. Some participants spent most of their time out of home for work or leisure, thus having only a few participations (one or two answers to the online questionnaire).

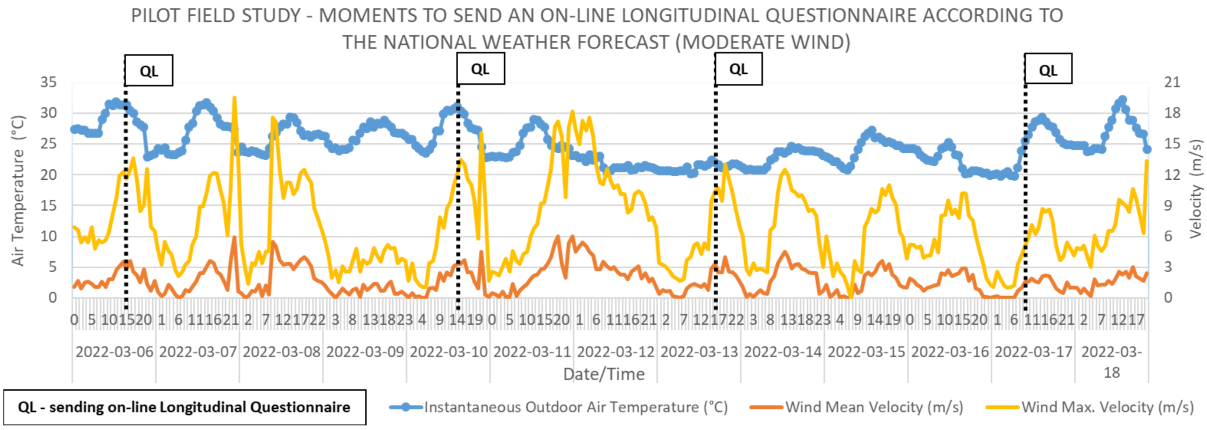
Figure C 3 – Positioning of HOBO devices for long-term monitoring



Source: elaborated by the author

Regarding the moments at which responses were given, 36/52 corresponded to the same day of sending, while the other responses were given one (7/52) or two (9/52) days after requesting. The gap is probably due to busy schedules or staying less at home since the participants understood that questionnaires should be completed at home. The researcher sent messages to participants manually in the pilot, and the response rate was considered satisfactory. The use of weather forecasts to estimate the occurrence of windy days has worked and was maintained in the field study. Some residents who responded on the same day commented that the weather was windy, reflected in their air movement evaluation (acceptable and enough air movement, preference to keep current air movement) on the questionnaire. The reference values of mean and maximum wind velocities – around 3 m/s and within 6-12 m/s, respectively – are illustrated in Figure C 4. Mean values corresponded to a light breeze on Beufort Scale, while maximum values represented a moderate to strong breeze. On a day scale, the highest velocity values were frequently observed in the afternoon, arguably the favourite moment to schedule visits and send online questionnaires (QL) considering environmental conditions only.

Figure C 4 – Overview of the outdoor conditions during the pilot



Source: elaborated by the author

The summer of 2022 in Florianópolis had hot-dry and mild-humid days, apart from the typical hot-humid days, which led to varied thermal comfort responses in the pilot (for example, feeling slightly cool or slightly warm in a naturally ventilated environment). In contrast to Florianópolis, the weather in São Luis is characterised by slight variations in temperature, wind and precipitation, especially in the hot-dry season. The typical day of this season in São Luis (sunny and potentially windy) likely happen repeatedly throughout the season. The assumed implications of climate on the field study protocols are less interference of the weather conditions on scheduling visits and sending online questionnaires to interact with residents (1) and less variation on the overall thermal comfort evaluation (2).

C.2. Instruments for collecting data from subjects

An interview script and two questionnaires were developed for the field survey and tested in the pilot study. The instruments were tested in terms of comprehension (if easy to respond to or not; the meaning of the content), extension (if too lengthy or not) and boredom (whether the repetitiveness of questions would affect the answers given). The interview script and a point-in-time questionnaire were applied during the visit to each home, while an online questionnaire (QL) was adopted during monthly monitoring. The final versions of each instrument are available in the following appendices: APPENDIX E – Semi-structured interview script; APPENDIX F – Point-in-Time (Instant) Survey Questionnaire (IQ); APPENDIX G – Long-term Comfort Survey Questionnaire (Online).

By interviewing the residents, the researcher sought to learn about their overall perception and evaluation of the thermal environment in their homes – particularly regarding the adoption of natural ventilation as a thermal comfort strategy – their routines of occupancy and use of active adaptive strategies – mainly fans and air conditioners. The underlying questions behind the interview script were as follows:

- Do residents pay attention to the thermal environment, the seasonal variations, and the adaptations to heat/cold they undertake? i.e. Are they indifferent to or bothered by the thermal environment and its nuances?
- Do residents perceive/adopt the air movement of natural ventilation as a thermal comfort strategy in a hot and humid climate?
- What are residents' thoughts about the available active adaptations (equipment, if available) to mitigate thermal discomfort? How do they perceive this specific energy cost?

Five questions regarding thermal and air movement evaluation were requested five times (within the interview script, in 5-10 minutes) in a Point-in-Time Survey Questionnaire (IQ). This questionnaire aims to capture possible changes in the evaluation due to variations in thermal conditions – particularly air velocity – which participants could perceive during the interview. Therefore, the final sample for the point-in-time evaluation (votes to each question) would be five times the number of participants. In the pilot study, there were 50 votes (10 participants * 5 repetitions in the questionnaire). A final air movement evaluation was proposed by the end of the interview. The point-in-time questionnaire was filled in to evaluate respondents' perception of constant/fluctuant airflow and overall satisfaction with air movement conditions throughout the conversation. According to the experience in the pilot, there was no need to make changes to this questionnaire for the field survey, as it was well understood and did not cause fatigue to the respondents. The same applied to the questions on the interview script.

Following the visit, long-term thermal environment monitoring occurred on residences for a month. Meanwhile, a comfort survey questionnaire (QL) was sent to participants via WhatsApp (online) to get their feedback regarding thermal and air movement conditions – the same point-in-time questions asked in IQ during the visit. As it was sent repeatedly, the conciseness and the time required to fill it in were observed. Repeated sending was needed to increase the sample size of valid questionnaires – those which were filled in when participants were at home. The QL questionnaire intended to collect data to answer the following questions:

- Is the overall comfort evaluation from naturally ventilated / free-running rooms different from the air-conditioned rooms? What are the main differences?
- The decision to adopt a climatisation strategy (natural ventilation / free running/air conditioning) is influenced by outdoor/indoor thermal conditions? Is the occurrence of breezy wind (outdoors) relevant somehow to operating homes naturally ventilated? Or is the current climatisation strategy more associated with residents' costumes and routines?

The five point-in-time questions requested within the interview in IQ were also in QL – except when participants reported that they were in air-conditioned rooms. The two questions about air movement sensation and preference were excluded in this case. The final sample size of thermal and air movement evaluation questions would be a sum of the samples from the IQ (collected during the visit) and QL (via online sending). The additional information obtained in the QL questionnaire was used to characterise respondents: where in residence they were, which clothing and activity corresponded to theirs, and which equipment – if any – was turned on at the time of reply.

The motivations to adopt a primary climatisation strategy (natural ventilation or air conditioning) in the rooms were approached in an open question in the pilot ("Please briefly describe the main reason why the room is [not] currently naturally ventilated"). The reason for this approach was twofold: (1) to have an overview of which responses would be given as reasons to adopt or not and (2) to evaluate respondents' willingness to write their responses instead of selecting from a list of responses (closed-ended options), especially in a scenario of repeated sendings. Regarding reason #2, it was observed that writing an answer was not a problem in general since it was missing in only 2 out of 50 valid questionnaires. However, it was also observed in many cases that a single respondent had given similar answers to this question, which would corroborate to turn it into a closed-ended question in the field study.

Considering the #1 reason, the answers to this question were categorised and presented as follows. When rooms were naturally ventilated (NV), 11 out of 35 respondents justified their choice by simply arguing that the windows or doors were open, which was deemed by the researcher as a routine of keeping them open in the residences. 14 out of 35 mentioned indoor/outdoor climate conditions, including air temperature (whether mild or extreme) and breeze (presence or absence). Finally, 8 out of 35 cited other aspects such as personal preference, health, energy savings, and the feasibility of keeping windows/doors open at home. When air-conditioning (AC) was running, the majority cited as reasons to turn it on were the outdoor climate conditions (8 out of 15 responses), followed by any impediments to keeping windows or doors open (6 out of 15 responses). The main impediment cited was rain, leading occupants to close windows at a given moment. This categorisation was turned into the list of responses to this question in the QL questionnaire to be applied to the field survey.

Another aspect modified in the final version of the QL questionnaire is the list of dress code options. The dress code options presented in the pilot came from the research conducted in Florianópolis by Ramos (2020) in 2017 and 2018. The present pilot study was carried out in the summer of 2022. The dress code option corresponding to the highest clothing insulation (0.96 clo according to ASHRAE 55 (2020) Standard, Table 5-2, Figure C 5) was not used by any respondents. Considering the climate conditions of São Luis, this dress code option was excluded from the QL questionnaire.

Figure C 5 – Option 5 of the dress code

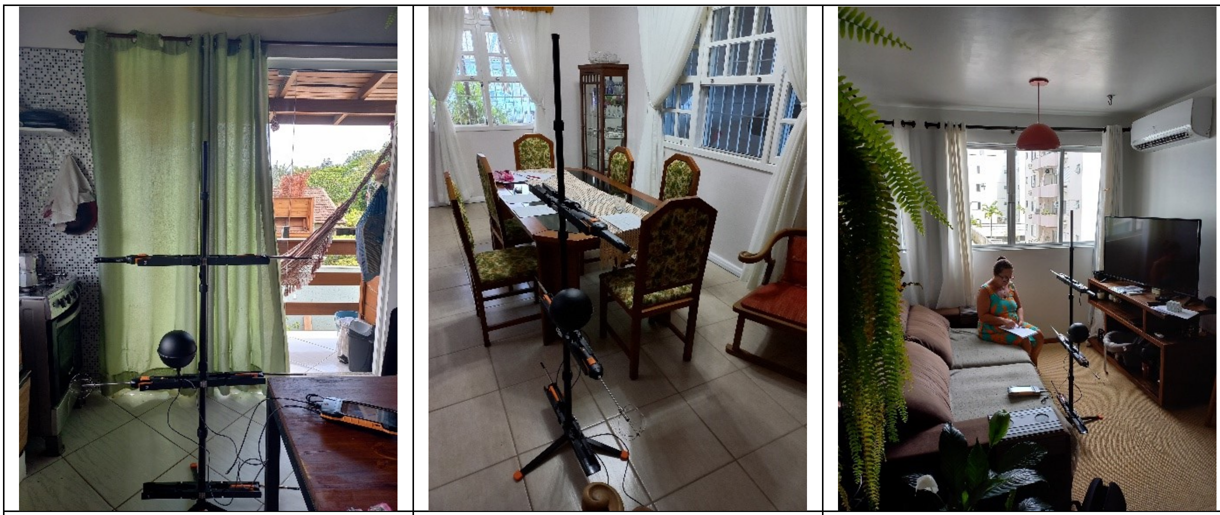
Source: Ramos (2020)

C.3. Instruments for measuring indoor physical variables

The pilot study adopted a TESTO 400 IAQ and comfort kit to measure air and globe temperature, relative humidity and air velocity. Three thermal anemometers TESTO 405i were coupled in the kit's tripod to conduct air temperature and (unidirectional) air speed measurements in three representative heights according to a recommendation in ASHRAE 884 Report (1997). Omnidirectional air velocity measurements were obtained via a turbulence probe with cable. Since only one probe was available, it was placed at the intermediate height (0.6m from the floor for seated posture) – the same applied to the black globe, following instructions from ISO 7726 (1998).

Unidirectional hot-wire anemometers were positioned based on the predominant direction of indoor airflow in each room – horizontal or vertical flows. In naturally ventilated rooms, air movement came from doors or windows (and could be occasionally supported by a pedestal fan). In contrast, the airflow descended in an air-conditioned living room (Figure C 6c). Some rooms had a terraced area connected through a door, which was open to allow air circulation (Figure C 6a). If there was no terraced area or the doors were not open, windows were open instead (Figure C 6b).

Figure C 6 – Illustration of the representative window/door configurations which would influence airflow distribution in residences



a) Door opening configuration (NV)	b) Window opening configuration (NV)	c) Closed windows/doors (AC)

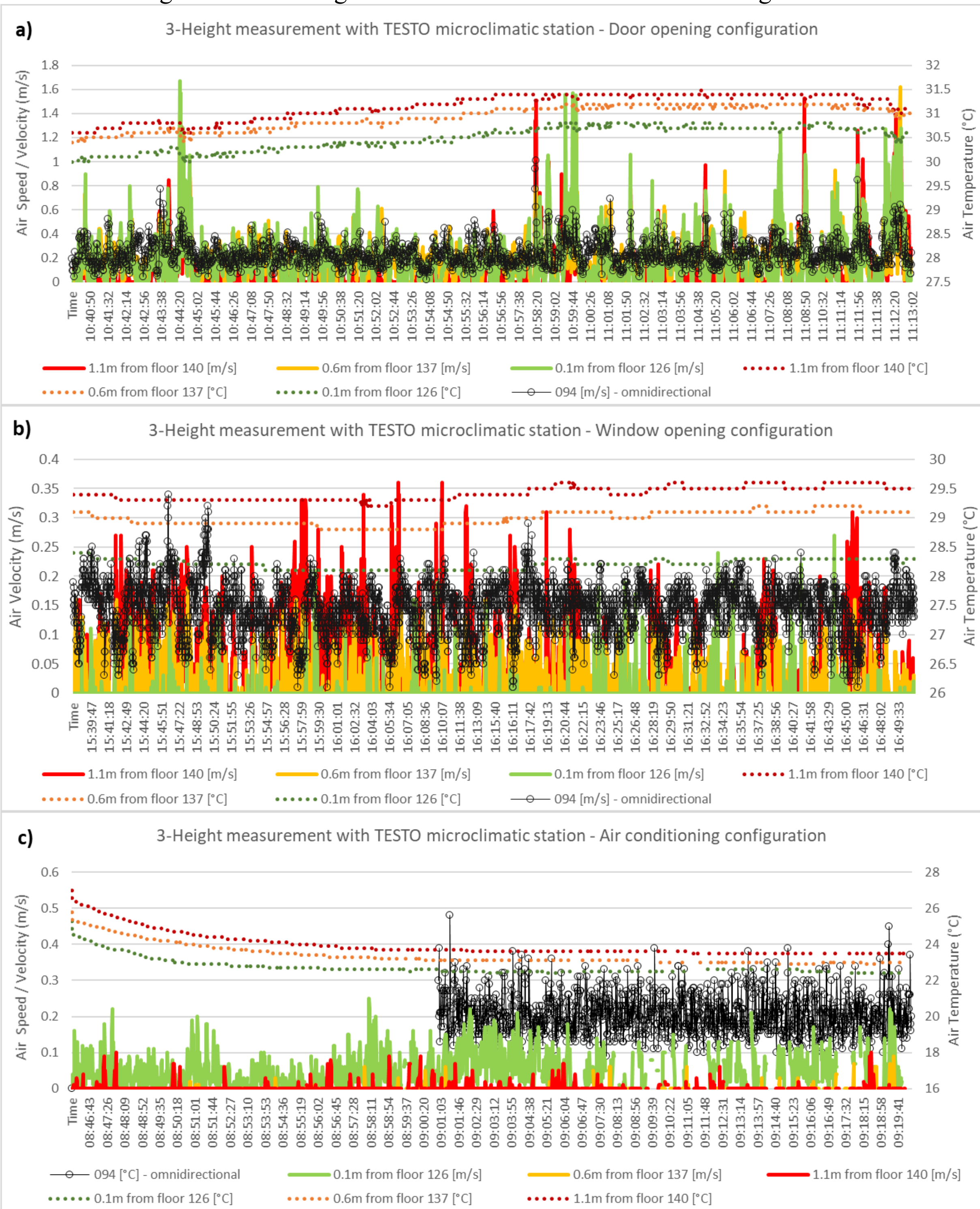
Source: elaborated by the author

Air temperature and speed/velocity measurements from thermal anemometers (uni and omnidirectional) were compared for each setup shown in Figure C 6. The results are presented in Figure C 7. Vertical gradient temperature was typically below 1 °C in naturally ventilated rooms, as illustrated in Figure C 7a and b. The vertical gradient temperature did not exceed 2 °C in the only room with air conditioning turned on during the visit. All vertical gradients were within the acceptable range of 3 °C for seated people from ASHRAE 55 (2020) Standard.

The issues of directionality and positioning of anemometers were analyzed based on airspeed/velocity measurements. On the one hand, the omnidirectional probe is very sensitive to the lowest air velocity range (0-0.20 m/s), which means that its readings never equal zero in those real environments. On the other hand, the omnidirectional probe did not capture the highest values, probably due to a lower response time. Typical opening configurations in naturally ventilated rooms also influenced the measurements, as open doors favoured more homogeneous readings among 3-height unidirectional sensors. A more significant difference between 3-height air speeds was observed in open window configurations, and the highest readings were recorded at 1.1m from the floor (Figure C 7b).

Concerning the impact of directionality over the magnitude of airspeed measurements and the diversity of opening configurations in real settings, as seen in the pilot, it is nearly impossible to ensure that a single positioning of unidirectional anemometers would represent current indoor airflow conditions properly. There is a trade-off between getting the resultant air velocity vector (more suitable with omnidirectional sensors) and obtaining faster air speed readings for amplitude analysis (minimum and maximum values in a single direction). In this context, it was decided to proceed to the field study with three omnidirectional air velocity sensors to be manufactured and checked against TESTO sensors as depicted in APPENDIX H – Measuring Instruments.

Figure C 7 – 3-Height measurements obtained in each configuration



Source: elaborated by the author

APPENDIX D – Consent Form for Participation in the Field Study

Field study: Thermal comfort at home

Welcome to this survey!

We invite you to take part in the survey entitled "Thermal comfort at home", which is part of a PhD research in the Architecture and Urbanism Academic Doctoral Degree Program (PósARQ) at the Federal University of Santa Catarina (UFSC) under the responsibility of Carolina Buonocore, Msc, and supervision of Prof. Roberto Lamberts, PhD.

Through their participation, we seek to understand how people feel about the thermal environment they experience at home, particularly in hot weather, and the role of natural ventilation in this process. We will generally ask questions about thermal comfort, natural ventilation, home routines and equipment to improve the environment.

How does the research work?

The researcher will interview you at your place of residence. She will request to record the interview to transcribe the information provided after the researcher's visit. The interview will last approximately 30 (thirty) minutes, during which time temperature, humidity, and airspeed measurements will be obtained with appropriate instruments. After the interview, the researcher may request permission to take measures in other house rooms for the duration of the visit. Before leaving, the researcher will request permission to install portable air temperature and humidity meters (HOBOs), which must remain in the home for approximately 4 (four) weeks. During this interval, the researcher will send online questionnaires periodically to the residents. For sending and eventual communication, it will be necessary to provide a contact (telephone or e-mail, according to preference). On the occasion of the first visit to the home, photographs will be taken only with the consent of the resident(s) and only to record the arrangement of the measuring instruments installed in the rooms.

Risk and benefit assessment

The benefits of participating in this research are educational and scientific. Along with the other participations, your contribution to this research will be fundamental to understanding (1) the impact of air movement from natural ventilation on the thermal comfort of residents in hot weather and (2) how natural ventilation can be valued in the context of thermal comfort and conscious energy consumption for cooling in homes.

The possible risks and discomforts arising from participation in this research are minimal and listed below: (1) tiredness or boredom when answering the requested questions and (2) breach of confidentiality regarding the information provided. To minimise the discomfort of tiredness or boredom, the questionnaires and the interview script were planned as briefly as possible, with a minimum number of questions and objective answers. A data confidentiality breach is possible, even if remote, involuntary or unintentional. The researcher will take all necessary care to ensure that this does not occur, storing the data in a private and not shared cloud. While transcribing the data, it will not be possible to identify any information that refers to you individually (name, contact, home address, etc.).

Participants' rights

There will not be any remuneration for your participation in this research, and there will be no expenses for you. In case of any foreseen or unforeseen costs or damages demonstrably resulting from your participation in this research, there will be reimbursement or compensation according to the current legislation (Civil Code, Law 10.406/2002, Articles 927 to 954). The researcher assures that the study participant will receive all necessary assistance throughout the research. The assistance provided includes the clarification of doubts regarding the functioning of the study and the measuring equipment through the researcher's contacts provided at the end of this term.

The responsible researcher undertakes to prepare and conduct the research under what is recommended by Resolution CNS No. 510/2016, which deals with the ethical precepts and protection of participants in scientific research involving human beings. This consent form was prepared based on the provisions of the Resolution above. Should there be any doubts on your part regarding your rights as a research participant, don't hesitate to get in touch with the Ethics Committee in Research with Human Beings (CEPSH/UFSC) by phone (48) 3721-6094 or by e-mail at cep.propesq@contato.ufsc.br (Physical address: Rua Desembargador Vitor Lima, nº 222, 7th Floor, Room 701 - Reitoria II. Trindade, Florianópolis). The CEPSH is an interdisciplinary, deliberative, consultative and educational collegiate body linked to the Universidade Federal de Santa Catarina, but independent in decision-making, created to defend the interests of research participants in their integrity and dignity and to contribute to the development of research within ethical standards.

What else is essential to know?

This research was approved by the Ethics Committee on Research with Human Beings (CEPSH/UFSC) under the CAAE identifier no. 58653622.8.0000.0121. Participation in this study is voluntary, anonymous and may be interrupted at any time without any prejudice to the participant. You are also reserved the right not to answer any questions you consider irrelevant. All information provided will be kept confidential and applied exclusively to the analyses of this research. In case of damage to the meters installed in the home (HOBOs), it will not imply cost to you. It is recommended that you keep your copy of this term to have easy access to the information of this research. However, should there be any doubts or requests regarding the study, do not hesitate to communicate with the researcher in charge through the contacts: (48) 99817-0011 (Telephone/WhatsApp) / carolina.buonocore@posgrad.ufsc.br (e-mail).

Thank you in advance for your valuable collaboration!

Obtaining consents

☐ I allow voice recording during the interview under the conditions described above

☐ I allow the recording of photographs of the equipment installed in residence under the conditions described above

Tick "Take part in the survey" to start

☐ Take part in the survey

Signed, on ___/___/2022,

Carolina Buonocore (in charge of the researcher)	____________________________(participant)

APPENDIX E – Semi-structured interview script

First contact (via personal contact or message): an invitation to participate in the research and sending of the scanned TCLE (consent form) for information

[Check temperature, humidity and wind conditions (external - INMET) in the previous week as soon as the date of the visit is defined].

Identifier code of the residence:

Type of residence:

Identification of the resident(s):

Date of visit:

- Ask for the indication of one or more rooms that are well ventilated in the perception of the resident(s) {if there is not a place considered ventilated, indicate another area according to the resident's criteria}; request authorisation to carry out the research (interview + instant questionnaire) in one of these rooms {give priority of choice to the resident}. Suggest that participants feel at ease in the place where they decide to stay during the research;
- Ensure the interviewee(s) are willing to participate at that time.
- The signing of TCLE (online or hard copy, as preferred); request permissions - voice recording and photos (focus on windows/equipment/measurement setup).

[Positioning of SENSU microclimatic station - pen drive connected]

SENSU app: Open the COM port, then "Start Save".

TESTO drive:

[Deliver printed IQ survey questionnaire to participants]

- Requesting responses to activity and dress questions in the IQ

[Interview starts - interviewee(s) sitting down]

Time of voice recording:

Part 1 - Introduction and general information on the participants

- Explanation of the topic, objectives and general guidelines (what participation entails, how much time will take etc.);

Resident				
Contact				
IQ participation?				
Longitudinal survey participation?				

Part 2 - Your perception of the residence

Let's talk about your thermal comfort at home.

1) Generally speaking, how is the internal environment? Regarding air temperature, humidity, ventilation, sunlight...?

    a) Do you notice significant variations from room to room?

    b) Are there any rooms that stand out because of these aspects?

    c) Do you notice variations depending on the season/season of the year?

    d) Considering your experience, do you judge today to be a typical or expected day regarding the thermal environment?

[Request IQ answer 1] Time PC/cell: Voice Record:

2) In general, do you feel comfortable when you are at home?

    a) And specifically, are there any non-recurring or unusual situations that make you feel more or less comfortable?

    b) Do you take action when faced with thermal discomfort? If yes, which one(s)?

3) I will propose the following questions, talking specifically about natural ventilation. Please think carefully about how natural ventilation behaves in this residence.

    a) How would you rate your residence in this respect? {Would you say it is well, poorly ventilated?}

    b) Is the existing natural ventilation satisfactory, and does it meet your needs? {What do you like most? And what do you dislike the most?}

Diagnosis **{select options}:** the respondent **(prefers/dislikes)** natural ventilation

    c) Do you notice differences between rooms in the house? And between seasons/seasons of the year?

    d) How do you judge natural ventilation today? More or less ventilated than expected, according to your experience?

[Request IQ answer 2] Time PC/cell: Voice Record:

4) Now, I propose an exercise: choose factors that, in your opinion, are reasons to adopt or not adopt natural ventilation in your home, thinking about your reality. I ask you to select up to 5 reasons among those listed [on the back of the IQ sheet] and to list from 1 to 5 - number 1 being the most decisive.

   a) Reasons to ADOPT natural ventilation

Reasons to ADOPT natural ventilation	**Order**
Appreciation of the outdoors	
Favourable scenario (my house is well-ventilated)	
Thermal comfort (cooling the body by the air movement)	
Respiratory diseases and allergies	
Cooling energy saving	
Feasibility of keeping windows or doors open	
Environmental impact	
Limitations to the use of air-conditioning	
Personal preference (I like natural ventilation)	
Air renewal in the room(s)	
Other:	

   b) Reasons NOT to ADOPT natural ventilation

Reasons NOT to ADOPT natural ventilation	**Order**
Unfavourable scenario (my house is poorly ventilated)	
Unfavourable climatic conditions (extremely hot/low humidity/no wind)	
Thermal discomfort (absence/insufficiency of air movement)	
Impediments to opening windows or doors (unwanted solar radiation/use of blinds/strong wind/rain/insects/noises/odours/privacy/safety etc.)	
The disturbance caused by wind (noise/objects falling/unwanted cooling)	
Need or preference for air-conditioning	
Personal preference (I'm not too fond of natural ventilation)	
Other:	

   c) [At the end] are there any questions or comments about this exercise?

[Request IQ answer 3] Time PC/cell: Voice Record:

Part 3 - House Routines

The information requested below will be used throughout the longitudinal {monitoring} survey, which will run for four weeks. It will be used to understand if, how and why natural ventilation is present or absent in your home routine.

5) Concerning long-stay rooms (bedrooms, home offices, living rooms),

   a) How many are there, who uses them, and at what times/shifts?

   b) Are they naturally ventilated? If yes, for how long?

Resident				
Room 1				
Schedule				
Room 2				

Schedule				
Room 3				
Schedule				

Diagnosis **{select options}:** the **current room is (NV / NV+FAN / AC)**, and this **(is/is not)** a routine of the resident(s) in this room and at this time.

c) Are there any specific times or times that are an exception? If yes, what are they?

d) Do you usually stay at home during the week and at weekends?

e) What kind of activities do you usually do at home? {Domestic chores? Resting?}

f) What kind of clothing do you usually wear at home?

[Request IQ answer 4] Time PC/cell: Voice Record:

6) Now let's talk about the equipment you have at home. Fans and air-conditioners.

a) Do you have any of this equipment? If yes, in which rooms? *{For a non-fixed fan, do you usually move from room to room?}*

b) Is there a routine for use? Or does it vary as needed? {Or does it vary for other reasons you may mention?}

c) And outside the home, do you use this equipment (AC)? In which places and for how long, approximately?

Equipment	Air conditioning	Fan
Room 1		
Schedule		
Room 2		
Schedule		
Room 3		
Schedule		

d) {How do you perceive the energy costs for using this {comfort-specific} *equipment* in your home? Choose the one that best applies to you from the alternatives below.

_______(...)_______ cost in relation to the total energy consumed at home:
☐ very low ☐ low ☐ neither high nor low ☐ high ☐ very high

[Request IQ answer 5] Time PC/cell: Voice Record:

[Request completion of the final evaluation post-IQ repeated answers]

Part 4 - Information for characterising the sample

To finalise the interview, I will ask for some information to characterise the sample I am researching. Please mark the option that applies to you(s) in the final part of the individual questionnaire. [Request completion IQ]

7) Sex
8) Age
9) Education
10) Family income

11) Are there any residents with respiratory problems (e.g. rhinitis/asthma) in the house?

12) Are there any residents with partial or total impairment of body thermoregulation (e.g. menopause/andropause) in the household?

Is everything OK with the experience? Are there any other comments to be made? (Doubts, curiosities, suggestions, criticism)

[Interview and IQ ends]

End time recording:

Voice recording:

SENSU app: (copy .csv data to excel then)

TESTO:

We can recall the continuation of the research [longitudinal - how it will work]

- Request permission to visit the rooms of the house cited by the residents [Guided visit - measurements with the microclimate station in places indicated as most ventilated, if any; placement of HOBOs];

- Request permission for photographic records of the installed equipment.

Equipment	HOBO (code)		Microclimatic station (nº)	
Room 1				
Installation/Withdrawal times				
Room 2				
Installation/Withdrawal times				
Room 3				
Installation/Withdrawal times				

Annotations/Croquis

- Main windows' orientation

APPENDIX F – Point-in-Time (Instant) Survey Questionnaire (IQ)

Guidelines:

- Should be gradually filled in at the time of the semi-structured interview and simultaneously to the measurements with SENSU microclimate station in residence;
- Begins before the interview, with the first two questions on activity and clothing;
- Interviewees should answer Questions 1 to 5 five times during the interview ("answer" columns). The interval between answers should be at least 5 minutes and no longer than 10 minutes, totalling an estimated 30-50 minutes of interview time. After responding to "answer 5", ask for responses to questions 6 and 7;
- Ends with four questions referring to the characterisation of the sample.

[Start]

- What type of activity were you doing about half an hour ago?

____

- What are you wearing at the moment?

____

Please mark with an "X" the alternative corresponding to your response to each of the five questions below when asked in 5 different moments (answers R1 to R5).	**Answer R1**	**Answer R2**	**Answer R3**	**Answer R4**	**Answer R5**
Question P1: How do you rate the condition of air movement now?					
Unacceptable due to too much air movement					
Acceptable and too much air movement					
Acceptable and enough air movement					
Acceptable and little air movement					
Unacceptable due to little air movement					
Question P2: What is your preference regarding air movement at this time?					
More air movement					
Stay as is (no change)					
Less air movement					
Question P3: How do you judge the environment at this moment?					
Very unpleasant					
Unpleasant					
Slightly unpleasant					
Neither pleasant nor unpleasant					
Slightly pleasant					
Pleasant					
Very pleasant					
Question P4: What is your preference right now?					
To be warmer					
To stay as I am (not changing anything)					
To be cooler					
QuestionP 5: What is your thermal sensation at this moment?					
Cold					
Cool					
Slightly cool					
Neutral					
Slightly warm					
Warm					
Hot					

Final Evaluation *[after Answer 5]*
<u>Over the past 30 minutes,</u>
{**Question P6**} Did you perceive the air movement as
☐ More constant ☐ More fluctuating
{**Question P7**} The condition of air movement you experienced was
☐ Unsatisfactory ☐ Satisfactory

Reasons to ADOPT natural ventilation (Question 4 from interview)	**Order**
Appreciation of nature and the external environment	
Favourable scenario (my house is well-ventilated)	
Thermal comfort (cooling the body by air movement)	
Respiratory illnesses and allergies	
Cooling energy saving	
Feasibility of keeping windows or doors open	
Environmental impact	
Limitation to the use of air-conditioning	
Personal preference (I like natural ventilation)	
Air renewal in the room(s)	
Other:	

Reasons for NOT ADOPTING natural ventilation (Question 4 from interview)	**Order**
Unfavourable scenario (my house is poorly ventilated)	
Adverse climatic conditions (extreme heat/low humidity/wind regime)	
Thermal discomfort (absence / insufficient air movement)	
Impediments to opening windows or doors (unwanted solar radiation, use of blinds, strong wind, rain, insects, noise, odours, privacy, security etc.)	
Inconveniences caused by winds (noise/objects falling/unwanted cooling)	
Need or preference for air-conditioning	
Personal preference (I'm not too fond of natural ventilation)	
Other:	

Sample Characterisation
Finally, please check the options that apply to you.

Sex
☐ Male
☐ Female
☐ I prefer not to answer

Age
☐ Under 25 years old
☐ Between 25 and 34 years old
☐ Between 35 and 54 years old
☐ Over 55 years old
☐ I prefer not to answer

Education
☐ Primary school
☐ Secondary education (incomplete)
☐ Secondary education (complete)
☐ Higher (incomplete)
☐ Higher (complete)
☐ Postgraduate (incomplete)
☐ Postgraduate (complete)
☐ I prefer not to answer
☐ Do not know the answer

Family income
☐ Up to R$ 1,100 (up to 1 minimum wage)
☐ From R$ 1,100 to R$ 2,200 (between 1 and 2 MW)
☐ From R$ 2,200 to R$ 4,400 (between 2 and 4 MW)
☐ From R$ 4,400 to R$ 11,000 (between 4 and 10 MW)
☐ From R$ 11,000 to R$ 17,600 (between 10 and 16 MW)
☐ Over R$ 17,600 (over 16 MW)
☐ I prefer not to answer
☐ Do not know the answer

APPENDIX G – Long-term Comfort Survey Questionnaire (Online)

Public Title: Thermal comfort at home
What to know in this questionnaire: What climate control strategy is used when answering the questionnaire? Is the choice driven by measurable environmental variables (indoor/outdoor environmental conditions)? What is the difference between the comfort ratings of those using natural ventilation and those using air conditioning at the time of response?

Guidelines:

- Submission via smartphone and short completion time (maximum 2 minutes);
- Criteria for selecting the times of submission: according to the routine of the resident(s) (days and times that they are theoretically at home), also consider the intensity of the wind (wind speed > 3m/s from INMET - weather forecast and weather Meteograms - https://previsao.inmet.gov.br/);
- Monitoring of related environmental variables: indoor air temperature and humidity (HOBO), indoor air speed (measured on the day of the visit) and outdoor variables (INMET - weather system - https://tempo.inmet.gov.br/).

[Start]

Welcome! Once again, thank you for taking the time to participate in this survey!
You are invited to complete a quick (2-minute) online questionnaire.

Kindly provide the last four numbers of your telephone: ________
{The researcher will use this information to identify which residence/room corresponds to the evaluation given in this questionnaire}

Are you at home at this time?
☐ Yes {continue participation}
☐ No {end participation, but compute the number of occasions}

Which environment are you in right now?
☐ Living/dining room
☐ Office
☐ Bedroom
☐ Kitchen
☐ Balcony/garden
☐ Other: ___________

Is the environment you are in, being naturally ventilated? (Are the windows or doors open? Is natural ventilation allowed in?)
☐ Yes
☐ No

Condition YES (Naturally Ventilated)	Condition NO (not Naturally Ventilated)
Is there a fan running? ☐ Yes ☐ No	Is there a fan running? ☐ Yes ☐ No
	Is there an air conditioner running? ☐ Yes ☐ No
Thermal Comfort Assessment: Air movement (Questions 1/2 - IQ) Thermal environment (Questions 3/4/5 - IQ)	Thermal Comfort Assessment: Thermal Environment (Questions 3/4/5 - IQ)
Among the options below, please indicate the one that best represents the main reason why this room is naturally ventilated **right now**: ☐ Household habit or routine ☐ Pleasant temperature and or humidity on the day/time (mild) ☐ The day/time is ventilated ☐ Energy saving concern ☐ Air renewal and or health concern ☐ There is no air conditioning equipment, or it is not possible to use it ☐ Other: ______________________	Among the options below, please indicate the one that best represents the main reason why this room is not naturally ventilated **right now**: ☐ Household habit or routine ☐ Unpleasant temperature and or humidity on the day/time (extreme) ☐ The day/time is not ventilated ☐ Preference to use air-conditioning ☐ Interference from outdoor environment (rain/sun/strong wind/privacy/safety/ pollution/insects/noise) ☐ Other: ______________________

Please choose the option that most closely resembles the activity you are performing at this time.

☐ Rest (sitting/lying)

☐ Home-office work (writing, typing)

☐ Housework (cooking, tidying up)

☐ Physical exercise

Please select the option that best represents your current dress code (if you do not identify it, use the length of the clothing and the area of the body it covers as a reference for approximation).


Option 1


Option 2


Option 3

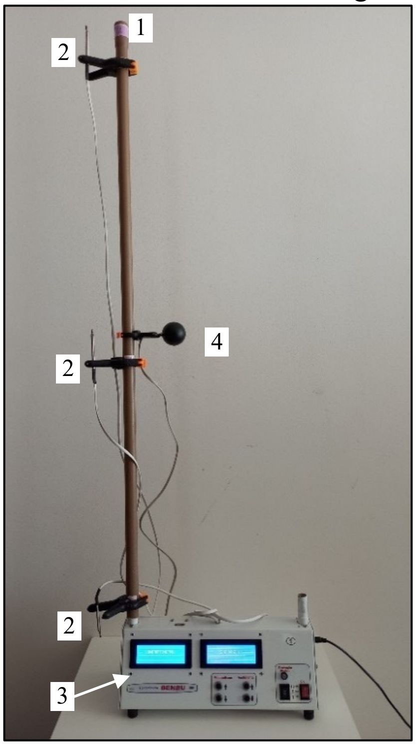

Option 4

[End]

APPENDIX H – Measuring Instruments

Two microclimatic stations (SENSU model, Figure H 1) were used to measure and record the indoor environmental variables throughout the field study campaign. The microclimatic stations included sensors to measure the indoor air temperature (Ta), black globe temperature (Tg), relative humidity (RH), and air velocity (Va). SENSU station has three omnidirectional air velocity sensors and one sensor to measure the other variables. A team from the Laboratory of Porous Media and Thermophysical Properties (Department of Mechanical Engineering at the Federal University of Santa Catarina, Brazil) developed the microclimatic stations and calibrated their sensors. The manufacturer provided information about the measurement range and accuracy of the sensors, as depicted in Table H 1.

Figure H 1 – SENSU microclimatic station

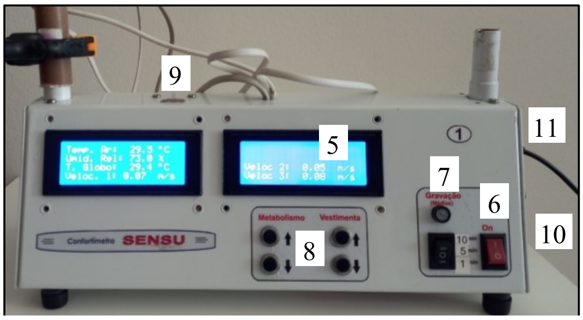


- Mechanical part

1 - Support
2 - Va sensors (0.1 m / 0.6 m / 1.1 m)
3 - Ta / RH sensors (0.1 m)
4 - Tg sensor (0.6 m)

- Electronics

5 - Display
6 - On/Off button
7 - Recording button
8 - Metabolic rate / clothing button (inactive)
9 - USB storage device connection
10 - AC/DC to USB connection
11- Power plug



Source: elaborated by the author

Table H 1 – Sensors included in the SENSU microclimatic station

Variable	Description	Measuring Range	Uncertainty
Air Temperature (Ta)	Thermo resistor	0 to 90 °C	0.2 ºC (95% CL)
Globe Temperature (Tg)	Thermo resistor Black globe, d=40mm	0 to 90 °C	0.2 ºC (95% CL)
Relative Humidity (RH)	Hygrometer, capacitive	5 to 98%	3%
Air Velocity (Va)	Thermal anemometer, omnidirectional	0.02 to 3 m/s	3% (95% CL)

Source: elaborated by the author

H.1. Pre-field study procedures

The researcher conducted measurements in partially controlled experimental setups before beginning the field campaign. The first two measurements were carried out in an air-conditioned room in the Civil Engineering Department building (Figure H 2). Measuring instruments manufactured by TESTO were adopted as a reference in those procedures. The information about TESTO probes is described in Table H 2. Their measuring cycle is set to 1 second by default, while the sensors in SENSU have a measuring cycle of 1 minute (one mean value per minute). Two types of portable anemometers were used in the tests. However, only the unidirectional hot-wire anemometers (TESTO 405i) could be moved to the place of research to make periodical checks on the readings from SENSU stations.

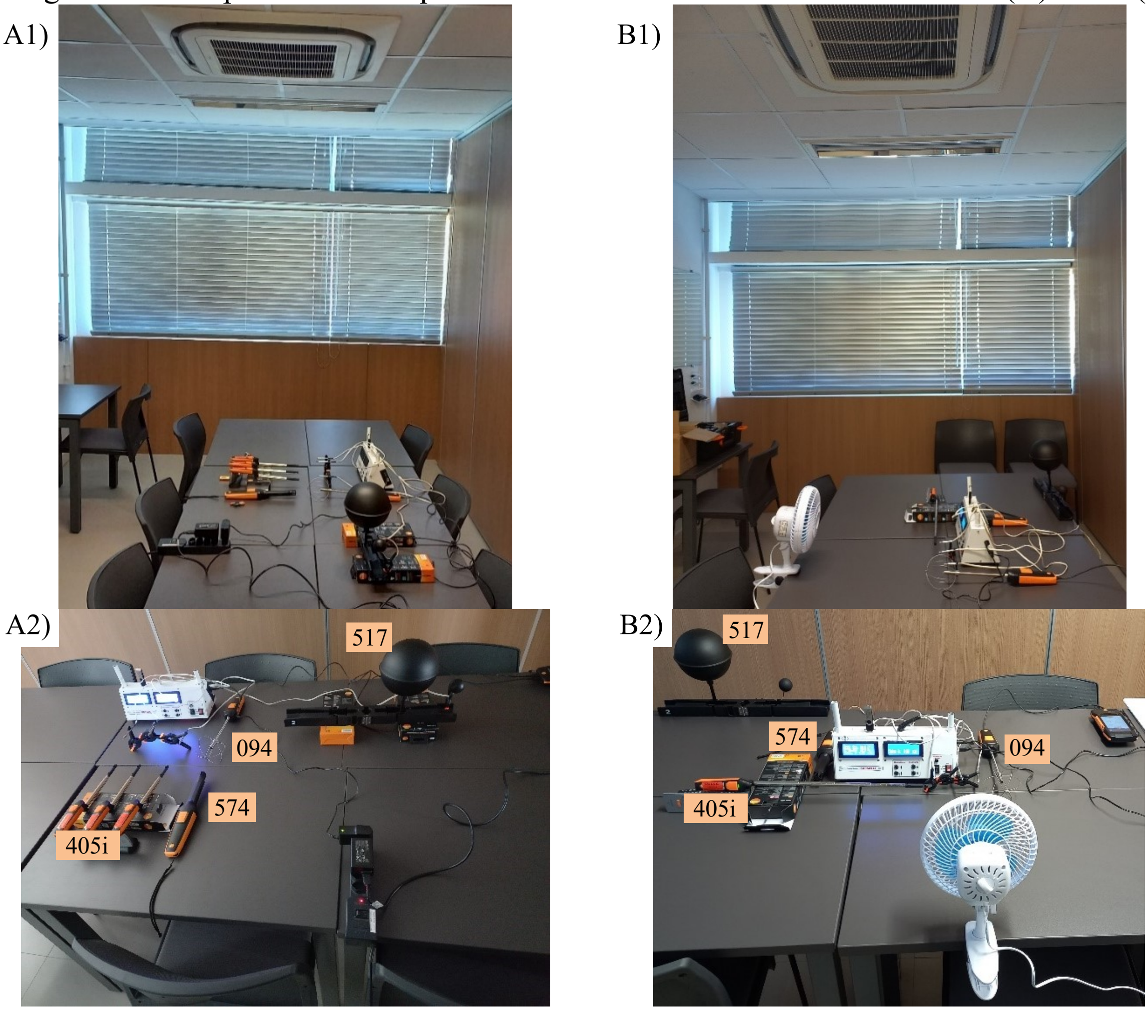
Table H 2 – TESTO probes adopted in test measurements

Description	Variable	Measuring Range	Accuracy
CO_2 probe (TESTO 574)	Air Temperature (Ta) Relative Humidity (RH)	0 to +50 °C 5 to 95%	±0.5 °C ±3% (10-35%RH) ±2% (35-65%RH) ±3% (65-90%RH) ±5% (Remaining Range)
Globe thermometer d = 150mm (type K, TESTO 517)	Globe Temperature (Tg)	0 to +120 °C	-40 to +1000 °C (Type K) Standard EN 60584-1
Turbulence Probe (TESTO 094)	Air Temperature (Ta) Air Velocity (Va)	0 to +50 °C 0 to 5 m/s	±0.5 °C ± (0.03 m/s + 4% of m.v.)
Thermal anemometer (TESTO 405i)	Air Temperature (Ta) Air Velocity (Va)	-20 to +60 °C 0 to 30 m/s	±0.5 °C ± (0.1 m/s + 5 % of m.v.) (0 to 2 m/s) ± (0.3 m/s + 5 % of m.v.) (2 to 15 m/s)

Source: TESTO (2022).

The measurements with SENSU 1 started with no additional air movement sources other than the air-conditioner, as illustrated in Figure H 2A. The air-conditioner setpoint was set to 24 °C with minimal air velocity. In this scenario, all four variables (Ta, Tg, Va and RH) were monitored for 30 minutes – excluding the initial minutes recorded – and the results are shown in Figure H 3. Air velocity readings from TESTO anemometers were quite different due to their directionality – TESTO 094 is omnidirectional, while TESTO 405i units (labelled 126, 137 and 140) are unidirectional. Thus, air velocity readings from SENSU were expected to follow the former TESTO probe. This trend was confirmed in the measurements carried out so far, stressing the importance of directionality in capturing the magnitude of the air velocity.

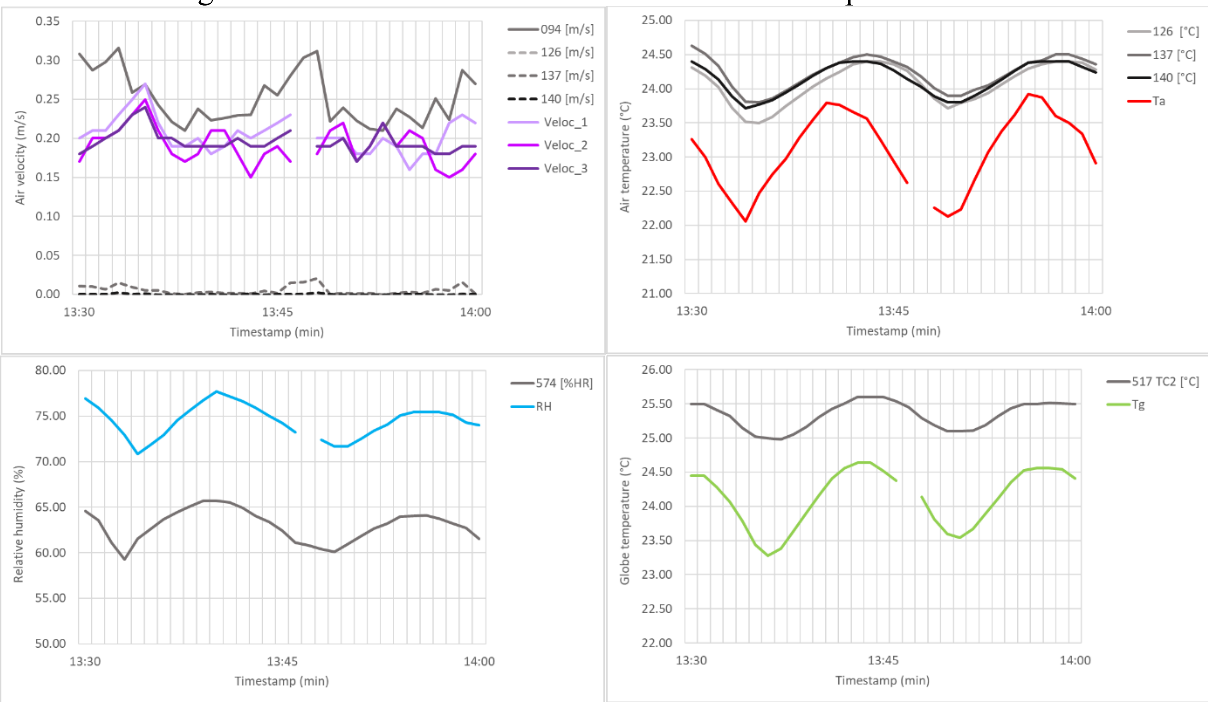
Figure H 2 – Experimental setups in an air-conditioned room with SENSU 1 (A) and 2 (B)



Source: elaborated by the author

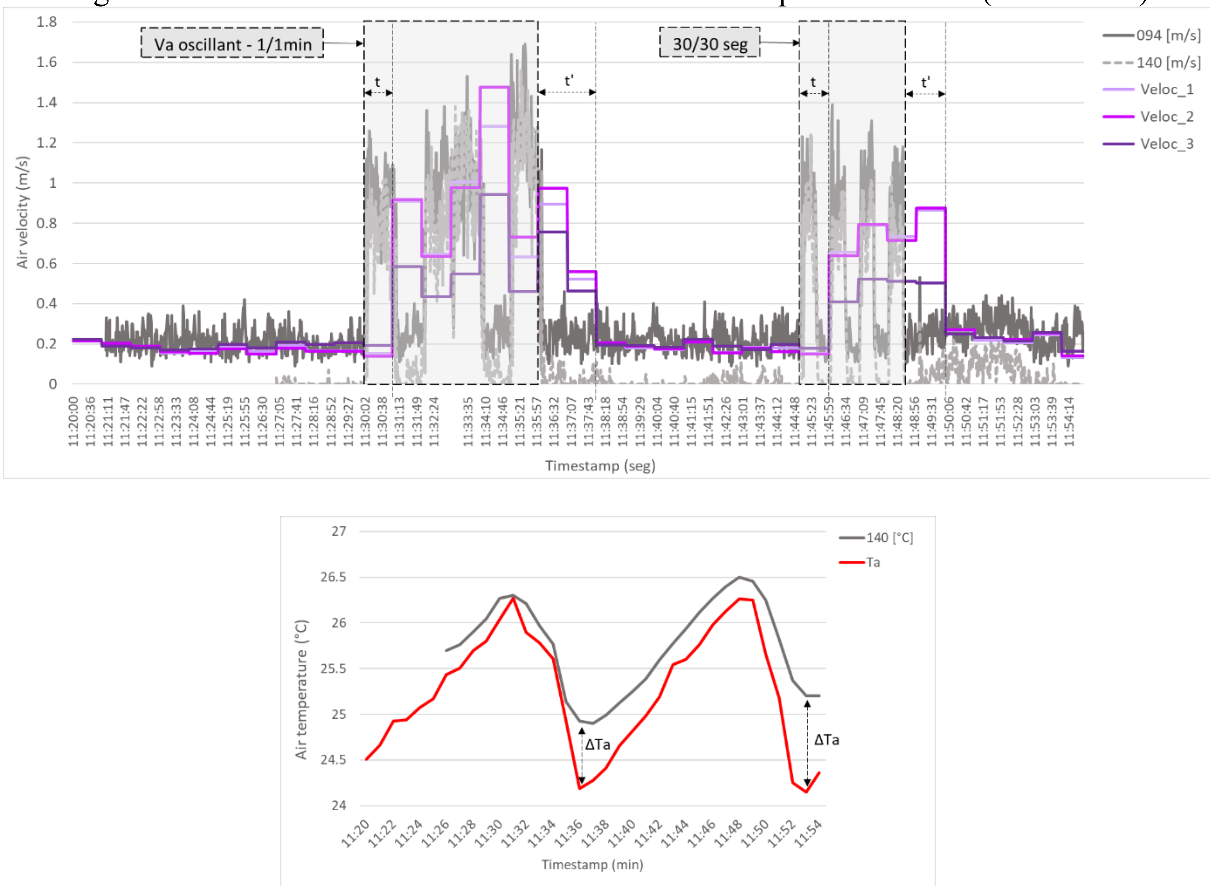
A small fan was added to the setup made for SENSU 1, similar to that illustrated in Figure H 2B. The aim was to produce well-defined airflow patterns and to check the temporal resolution of air velocity sensors from SENSU (labelled veloc_1, veloc_2 and veloc_3). The air-conditioner setpoint was altered to 26 °C, and the fan was turned on/off for 1 minute and 30 seconds. The result is depicted in Figure H 4. It could be noted that the sensors from TESTO responded immediately to the increased airflow, while the ones from SENSU took 1 to 2 minutes to respond to increase/decrease (t and t’). Moreover, the amplitude of air velocity registered in SENSU is relatively lower, as expected. The air temperature measured with SENSU was very close to the TESTO reference in this setup (ΔTa in readings < 0.5 °C except for Ta < 25 °C) compared to the previous setup.

Figure H 3 – Measurements obtained in the first setup for SENSU 1



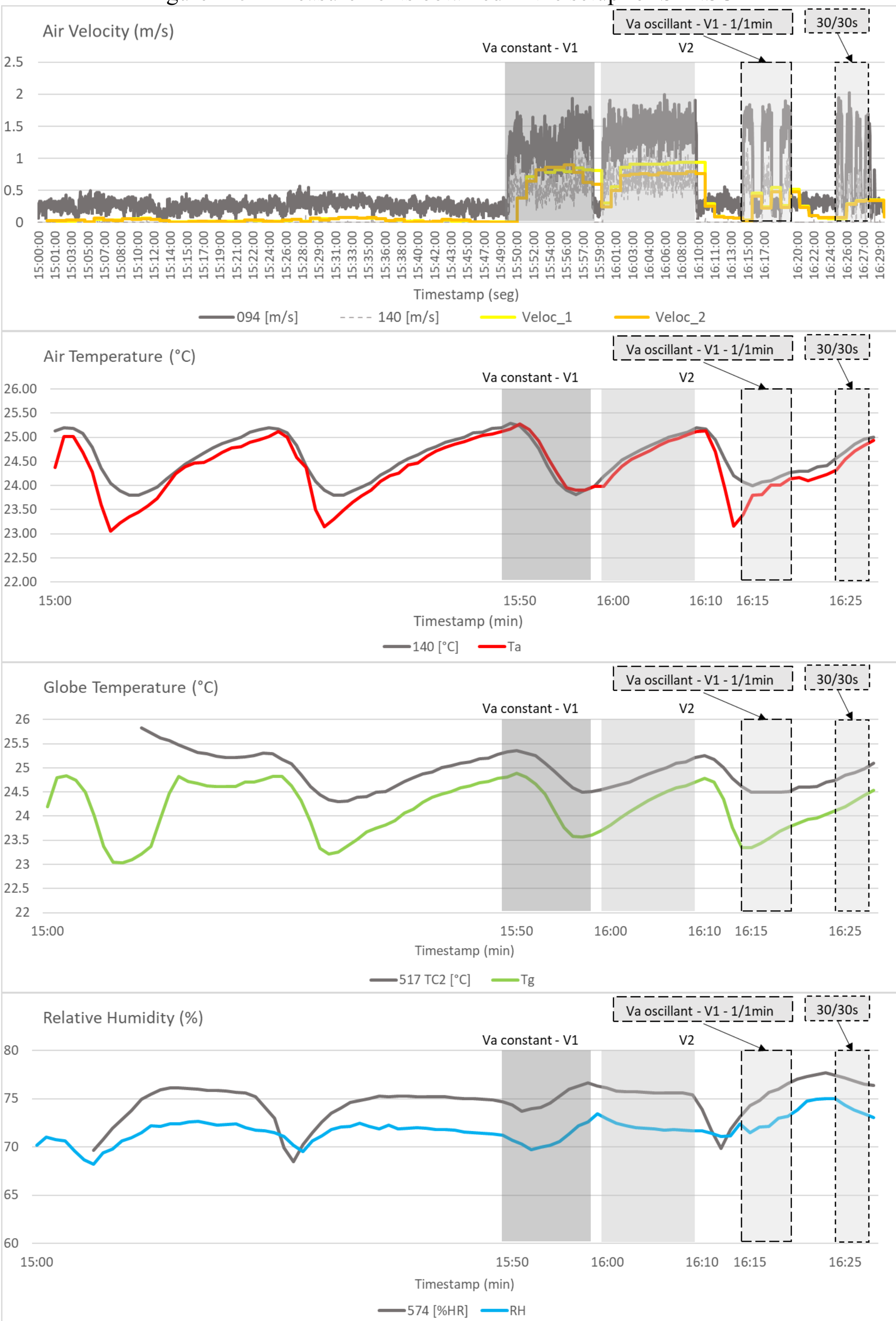
Source: elaborated by the author

Figure H 4 – Measurements obtained in the second setup for SENSU 1 (detailed Va)



Source: elaborated by the author

Figure H 5 – Measurements obtained in the setup for SENSU 2

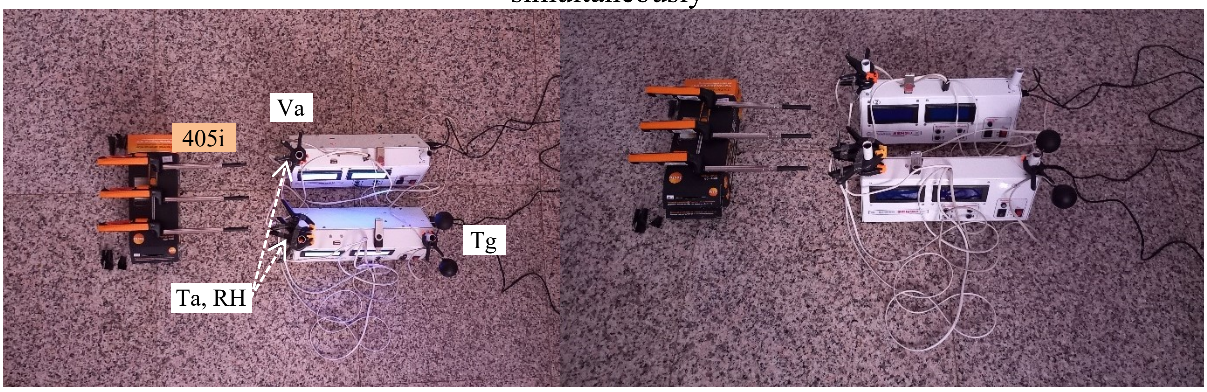


Source: elaborated by the author

The measurement procedure with SENSU 2 lasted one hour and a half, starting without additional airflow sources (air-conditioning set to 25 °C and minimal air velocity). Then two sequences of increased and constant airflows – V1 and V2 from fan setup – were carried out, followed by a sequence of the fan on/off (1 minute on /1 minute off) and ended with a sequence of the fan on/off (30 seconds on /30 seconds off). In Figure H 5, the air velocities registered by SENSU 2 were relatively lower than the ones from the TESTO reference (094) and close to the values read by the unidirectional device (140). The same trend regarding response time and amplitude of air velocity measurements was observed in SENSU 1 and 2.

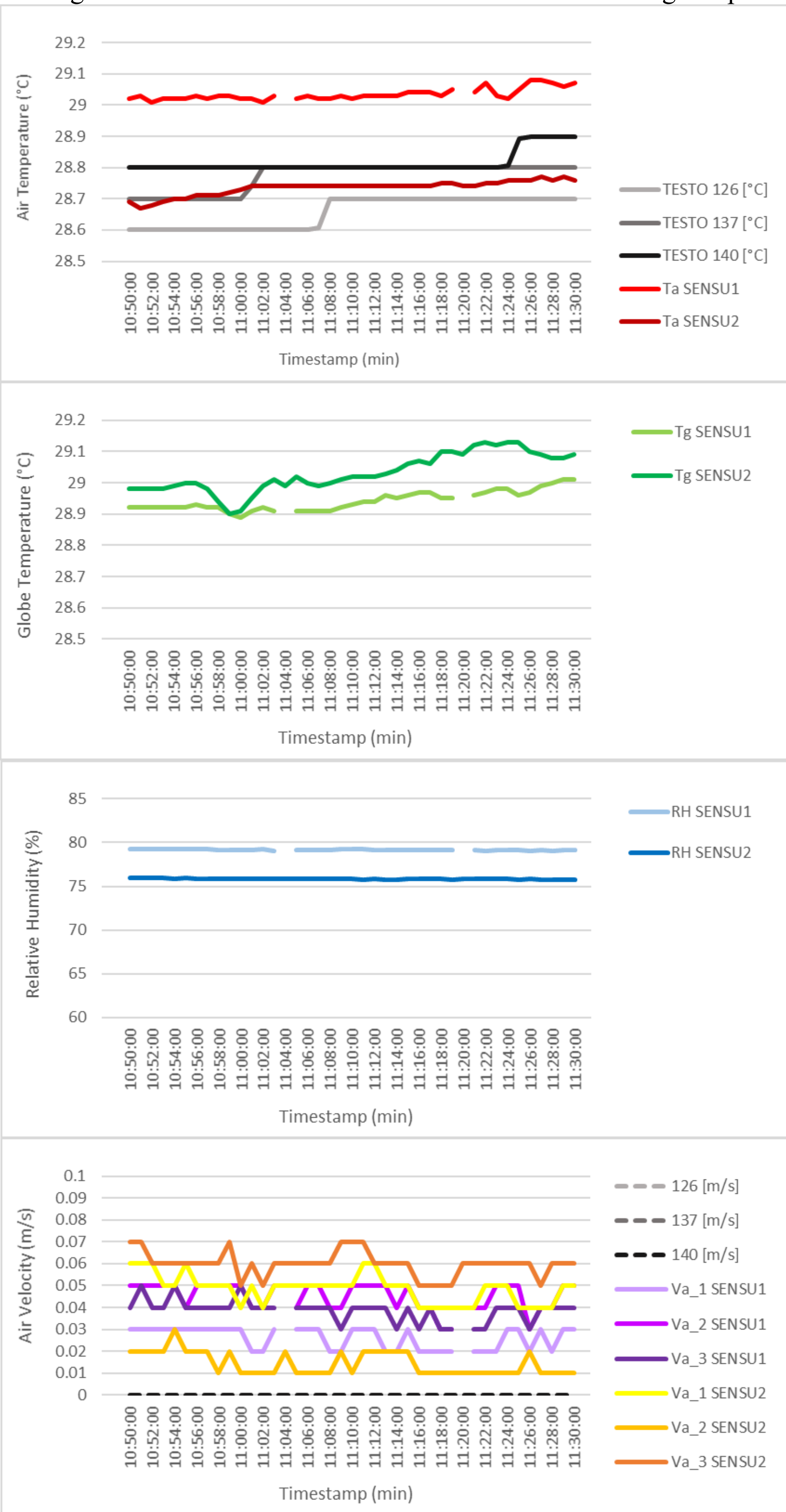
After conducting measurements with the microclimatic stations separately, a free-running and enclosed room measurement was conducted with SENSU 1 and 2 at the same space and time. The room was unoccupied, the door and the window were closed, and there were no short-wave radiation or air movement sources. The setup is illustrated in Figure H 6, and the results of a 40-minute measurement – excluding the initial minutes – are depicted in Figure H 7. In this nearly still air environment, air temperature, globe temperature, relative humidity and air velocity readings were within 0.3 °C, 0.2 °C, 3% and 0.05 m/s, respectively.

Figure H 6 – Experimental setup in the free-running room with SENSU 1 and 2 simultaneously



Source: elaborated by the author

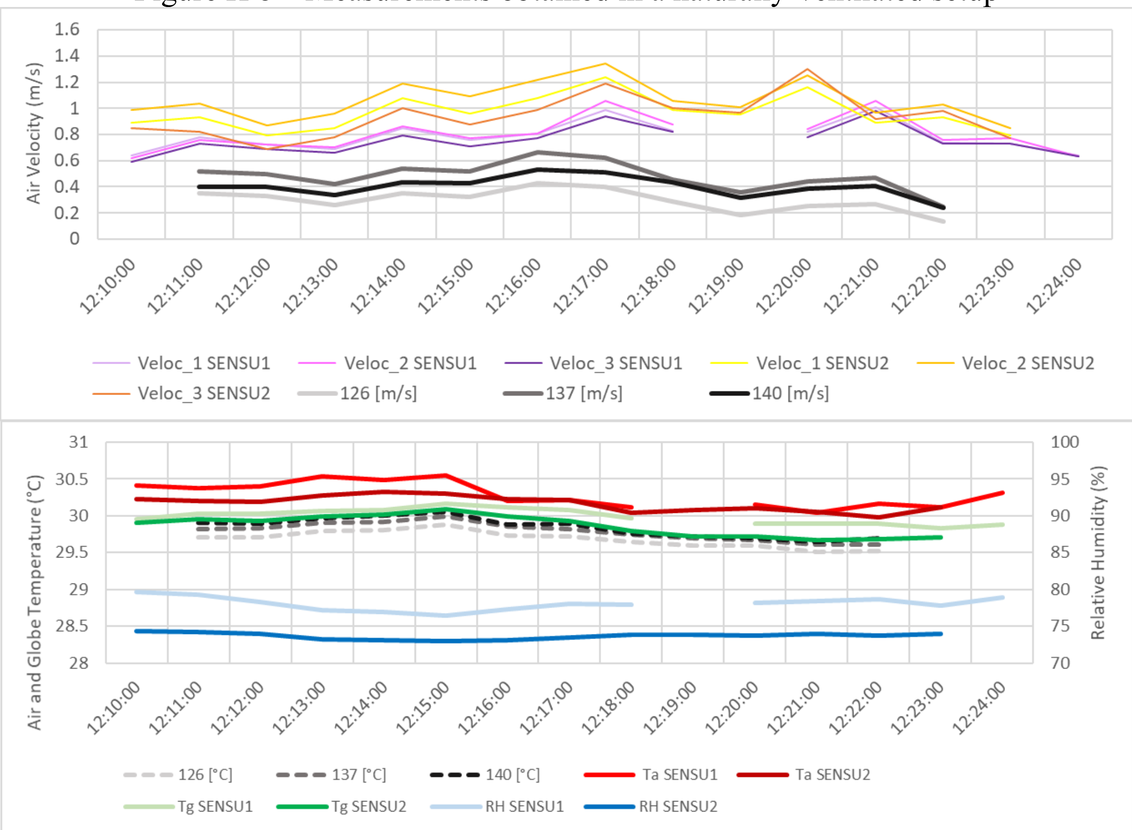
Figure H 7 – Measurements obtained in the free-running setup



Source: elaborated by the author

After measurements were carried out, some points should be discussed. Although the researcher partially controlled the experimental setups, controlling the air movement inside the rooms was nearly impossible, particularly under simultaneous air-conditioning and fan on. Thus, the objective of the tests with increased air movement was not to obtain similar air velocity readings from different sensors but to observe the behaviour regarding response time and amplitude. Moreover, the occurrence of cold air draughts in the conditioned environment could have contributed to the differences observed in air temperature (> 0.5 °C), globe temperature (> 0.5 °C) and relative humidity (> 3%) readings between SENSU and TESTO sensors. The most remarkable differences were noted when indoor air temperatures were below 25 °C (TESTO reference). In the case of globe temperature, it must be highlighted that the characteristics of black globes – diameter and manufacturing material – could determine the differences in measurements due to the inertia and the effect of convection in each black globe.

Figure H 8 – Measurements obtained in a naturally-ventilated setup



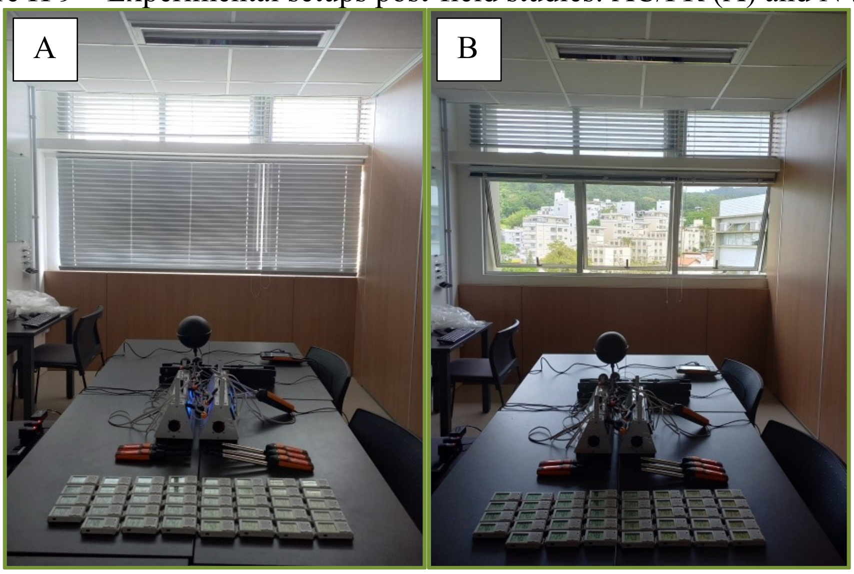
Source: elaborated by the author

Thermal environmental conditions observed in actual naturally-ventilated rooms during the field study campaign are expected to be diverse from the ones observed in the setups. Therefore, a new measurement was conducted throughout the operation of natural ventilation in an actual room in São Luis before the field study campaign. The doors and windows were open, and thus there was no control over air movement in the room. The result of this measurement, excluding the first minutes recorded, is shown in Figure H 8. Under air motion in a warm environment, the differences in air temperature and relative humidity readings could increase to 0.5 °C and 5%, respectively. In comparison, globe temperature values recorded by SENSU 1 and 2 remained within 0.2 °C. It is concluded that air motion in air-conditioned and naturally-ventilated setups impacted the sensors' readings. However, the differences remained within acceptable thresholds of required accuracies in ISO 7726 (1998).

H.2. Post-field study procedures

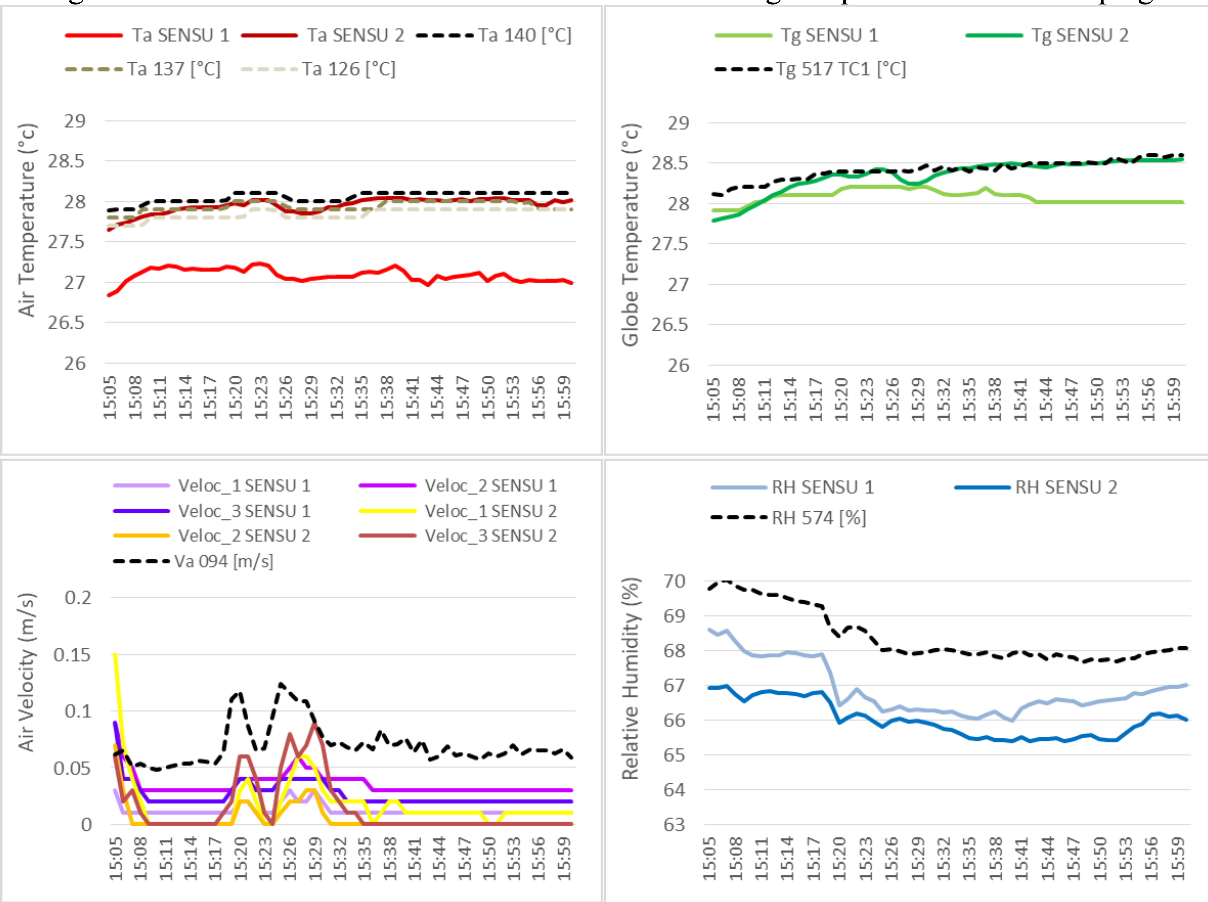
After the field campaign's conclusion, the researcher conducted measurements in partially controlled experimental setups. The measurements occurred in December/2022 in the same air-conditioned room in the Civil Engineering Department building. Measuring instruments manufactured by TESTO were adopted as a reference to check the readings from SENSU microclimatic stations and HOBOs. Three setups were organised: AC (setpoint = 25 °C with minimal air velocity, windows/doors closed), FR (AC turned off, windows/doors closed), and NV (AC turned off, windows/doors open). The lights were turned off, and there was no occupancy during the measurements. The setups are illustrated in Figure H 9.

Figure H 9 – Experimental setups post-field studies: AC/FR (A) and NV (B)



Source: elaborated by the author

Figure H 10 – Measurements obtained in the free-running setup after the field campaign



Source: elaborated by the author

In the free-running (FR) scenario, all four variables collected in SENSU (Ta, Tg, Va and RH) were monitored for approximately one hour – excluding the initial minutes recorded – and the results are shown in Figure H 10. Regarding the readings registered in SENSU microclimatic stations, it was observed that the air temperature measurement from SENSU 1 (Ta SENSU 1) was reasonably different from the reference sensors (TESTO 126, 137 and 140), extrapolating the range of ±0.5 °C previously stipulated in ISO 7726 (1998). This trend was confirmed in AC and NV scenarios. Therefore, a correction to Ta SENSU 1 was evaluated within the data measured throughout the field campaign. Periodic checks on the readings from SENSU stations were conducted in São Luis under an FR scenario (windows/doors closed and protected from sunlight, no mechanical equipment turned on). The respective corrections to Ta from SENSU 1 were adopted in the measurements conducted during October/2022 (see Table H 3). From the experimental setup conducted in December (Figure H 9 and Figure H 10), the other variables were considered to be within the acceptable ranges from ISO 7726 (1998), and so were the air temperature and relative humidity readings from the HOBOs.

Table H 3 – Difference in readings between reference (TESTO) and SENSU sensors

Δ Air Temperature	**Aug**	**Oct**	**Nov**	**Dec**
Δ(Ta TESTO 137 - Ta SENSU 1)	-0.4 °C	0.6 °C	0.8 °C	0.8 °C
Δ(Ta TESTO 137 - Ta SENSU 2)	0.3 °C	0.1 °C	0.2 °C	0 °C

Out of the required range for t_a (class comfort)

Source: elaborated by the author