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Working from home as an adaptation strategy to heat: Comparing temperatures and workers' assessments for 203 offices and 107 homes

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ABSTRACT

This contribution considers whether working from home (WFH) can be an effective adaptation to increasing summer heat for office workers. The mixed-method study presents temperature data from 203 offices and 107 home workspaces in Southern Germany, along with survey data from >100 workers at both locations during a hot period in June 2023. Home workplaces had both lower mean temperatures and less occurrence of elevated temperatures or overheating (operationalised as degree hours above 26 °C and 30 °C) than passive offices. A comparison with mechanically cooled offices is offered, but should be interpreted cautiously due to the small N and energy saving measures being in place at the time. Measured temperatures had significant effects on workers' perceived heat stress and productivity in a mixed-effects regression model. Individual variables age, gender, general activity level and general thermal preference were also explored. Barriers for WFH were explored through stakeholder interviews. We conclude that flexible WFH can be a means to protect workers' health depending on the specific office and work situation, and could offer workers better adaptive options and potentially a slight psychological benefit.

1. Introduction

Climate change leads to more frequent, longer and more intense periods of hot weather [20]. Research efforts so far have understandably focused more on exposed outdoor workers [9,27], but increasing heat will also affect office workers. Office buildings can heat up considerably due to internal heat sources (lighting, electric equipment, potentially high occupant density) and solar gains from glass façades ([5]). Heat can influence workers' health and safety, as well as reduce their productivity.

For workers' health, guidelines for occupational safety give upper temperature limits, e.g. hourly rest periods starting at 31 °C Wet Bulb Globe temperature (ISO Standard 7243, see [27]). German Technical Rules for Workplaces *recommend* heat protection measures from air temperatures of 26 °C onwards (suggested measures include adaptation of clothing rules and working hours, use of fans, effective ventilation and shading, cool-down periods) and *mandate* them from 30 °C onwards (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin [7]).

It is generally assumed that there is an optimum temperature range for productivity, and that productivity decreases at higher temperatures. Prior studies have found workers' productivity to decrease starting at about 23–25°C [17,44], with magnitudes of 6.6% self-reported productivity loss at 26–28 °C [45] or 10% at 30 °C [44]. However, a newer review of 35 studies [38] found productivity losses to be lower than 5% and calls into question whether there is a relationship between temperature and work performance at all. The relationship is apparently not clear-cut. Still, severe overheating for long periods can be assumed to influence workers' health and productivity, both leading to losses of working hours [16].

Aside from the magnitude of heat exposure, which further factors influence the health and thermal comfort of office workers? Chronically ill as well as elderly individuals are physiologically more vulnerable to heat due to limited thermoregulation [26]. Older people are also more likely to have cardiovascular or respiratory illnesses which increase risk [6]. Many studies assume age thresholds of 65 or 75 years [13]. It has been suggested that women have slightly higher comfort temperatures and feel cool more quickly, but a review of both climate chamber and field studies found no definite proof of this [50]. However, women appear more sensitive to temperature deviations, especially in cooler environments, and are more often dissatisfied with temperatures [41]. Similarly, while there was no evidence that older people had significantly different comfort temperatures, their acceptable range appears smaller and they, too, are more sensitive towards temperature changes [50] and possibly prefer higher temperatures [42]. Health and comfort

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are also influenced by thermal history / acclimatization, both long-term and short-term [10,37,55], which is in turn influenced by the amount of exposure – e.g. how much time is spent outside. Other physiological variables include obesity and fitness level. Obese individuals were less tolerant of heat when performing physical exercise in different study settings ([50]: 5.4; [56]), and obese office workers had cooler comfort temperatures in field studies under hot conditions [19,40]. Aerobic fitness and training improve cardiovascular function and sweating and have a strong impact on tolerance to heat [14].

A change of workplace cannot alter any of these individual physiological variables, but could temperatures and thermal comfort be assessed differently when working from home? A range of psychological or contextual factors has been studied in thermal comfort research. The adaptive theory of thermal comfort [11,34] has pointed out that in field studies of passive, naturally ventilated office buildings, people report thermal comfort in a broad spectrum of temperatures. The adaptive approach highlights actions that workers take to ensure their comfort, such as using blinds, fans and doors to adjust themselves and their thermal environment. These measures have been called behavioural adaptation, user controls, affordances or adaptive opportunities [4]. When workers *feel* they have control over their environment, they tend to have higher thermal comfort [30,49] – even when they do not use the adaptive opportunities [57]. There might simply be more adaptive opportunities at home than in the office, for example regarding clothing adjustment or nighttime ventilation. The perceived control might also be higher. Workers may feel they have more control at home – where they share the space with no or few others – as perceived control is lower when there are more people in the room [43]. Additionally, it might be easier to negotiate adaptative measures with household members than with work colleagues. Controls at home might also be easier to understand and use [24]. People appear to adjust their expections of comfort to the environment [8,39], and might be more 'forgiving' of their homes. The context of being at home might in itself be a psychological variable. Oseland [36] showed that in winter, the same subjects had lower 'neutral' temperatures and felt warmer in their homes than at the office or in a climate chamber, with clothing, metabolic activity and adaptive actions controlled for.

The few studies performed to date on work from home (WFH) thermal comfort and productivity generally found medium to high satisfaction with the thermal environment at the home workplace [32]. When the percentage of satisfied participants is also given, the distribution ranged from slightly below 50 % to nearly 90 %, pointing to a more heterogenous perception of individual workers ([32]: 7). Workers generally gave positive assessments of indoor air quality at home, and in a few studies reported higher satisfaction than those in offices ([32]: 8–9). When air quality was measured in WFH studies (CO_2 concentration/total volatile organic compounds as well as relative humidity averages), values were below the recommended thresholds, but intermittent peaks surpassed recommendations, indicating that WFH spaces might not be consistently or adequately ventilated ([32]: 4). Regarding productivity in WFH situations, studies found weak links between satisfaction with the thermal environment and perceived productivity [2], and no statistically significant correlation between satisfaction and perceived ability to concentrate, work on creative tasks or communicate [47]. Kawakubo and Arata [25] included measurements and found that measured air temperature and humidity were not significantly correlated with the participants' assessment of their comprehensive productivity, but that perceived WFH productivity significantly increased with satisfaction with the thermal environment. In conclusion, prior studies on WFH have found good satisfaction rates – possibly higher than in offices – and weak or no links between productivity and thermal satisfaction or measured temperatures. In the recent systematic review by Manu et al. [32], only 4 of the 41 reviewed studies had measured temperatures. None of them focused on summer heat. To our knowledge, there are so far no contributions that have compared indoor temperatures in offices and home workspaces during hot weather. Additionally, most studies had been conducted near the surge of the Covid-19 pandemic. In the long term, perceptions could change as regular WFH becomes the new normal.

Potentially, WFH could be a way to increase workers' heat protection, thermal comfort, satisfaction and productivity. Therefore, this contribution aims to (a) measure and compare temperatures and workers' assessments at both offices and home workspaces, and (b) discuss whether WFH can be an effective way to adapt to increasing summer heat. For this, we will introduce the mixed-method study design and our sample of office and from-home workers in the following Section 2., present results of both temperature measurements and workers' assessments in Sections 3.1, 3.2 and delve deeper into possible explanations for the latter in Section 3.3. Additional stakeholder interviews were conducted to explore the barriers of WFH in the surveyed offices, which are presented in Section 3.4. Section 4. discusses implications of the findings.

2. Methods

This mixed-methods study was conducted in 2023 and aimed to assess heat exposure and adaptation in offices and homes through both temperature measurements and worker surveys. The study was conducted in Germany's Southern state Bavaria, with most of the participants working in the state capital, Munich.

2.1. Recruitment process

As workers would be responding to the study during their working time, the recruitment process first focused on companies. Different channels were used to spread the study invitation: newsletter and website of the regional Chamber of Industry and Commerce, direct e-mail to members of the ‚Munich business climate pact', direct inquiry to large companies or public bodies in the city (e.g. university, municipal administration), as well as personal contacts. Companies were incentivized with an evaluation and recommendations for heat adaptation. When company representatives had expressed interest, they were then asked to disseminate a study invitation among all employees through either internal newsletters or the company intranet. The invitation described the research project and asked interested workers to get in touch with the researchers directly, to avoid any social pressure to participate. Participants were incentivized with a personal evaluation of their temperature data, as well as the chance to take part in a prize draw (25 shopping vouchers/donations of 50€). They were guaranteed anonymity and that only company-wide results from the study would be communicated. Neither participants nor their colleagues or superiors knew who else participated in the study (unless participants talked of it among themselves). Informed consent according to faculty ethics guidelines was obtained from all participants.

We previously had set a sample size of 100 participants but received an unexpected amount of interest and therefore increased the sample to 200, in the end surveying 210 participants. The participants came from 20 companies of various sizes and from different sectors (commercial enterprises, non-profits, public bodies). Although attention was paid to address different types of companies during the recruitment process, the final distribution of participants and companies can be described as a convenience sample.

Workplaces had different characteristics, with both mechanical cooling and passive, i.e. naturally ventilated building typologies (see

Table 1
Overview sample characteristics.

Sample characteristics		N	%
Age	25–35	45	21.4
	36–45	47	22.4
	46–55	54	25.7
	56–70	64	30.5
Gender	Female	139	66.2
	Male	69	32.9
	Diverse	1	0.5
Education	(Technical) university degree	170	81.0
	Completed vocational training	29	13.8
	Other degree	10	4.7
	No degree	1	0.5
Office size (m^2)	5–15	43	20.6
	16–20	63	30.1
	21–30	65	31.1
	31–90	18	8.6
	100–200	20	9.6
Office: number of occupants	1 person	69	32.9
	2 persons	76	36.2
	3 persons	28	13.3
	4–50 persons	37	17.6
Satisfaction with heat protection at the workplace	(Rather) satisfied	73	35.3
	Partly satisfied	54	26.1
	(Rather) dissatisfied	80	38.6
Heat adaptation options at offices	Possibility to work from home	189	90.0
	Possibility to adjust working hours	180	85.7
	Windows for manual ventilation	177	84.3
	Interior shading	142	67.6
	External shading (self-controlled)	140	66.7
	Localised fan close to the body	91	43.3
	External shading (automatically controlled)	45	21.4
	Air conditioning	36	17.1
	Automatic ventilation system	34	16.2
	Radiant cooling (ceiling)	31	14.8
	Central fan (e.g. ceiling fan)	9	4.3
Work from home (WFH) frequency	(Almost) every day	14	6.7
	Several times a week	95	45.7
	Several times a month	56	26.9
	Several times a year	19	9.1
	Never	24	11.5
WFH location	Dedicated room (study)	78	42.4
	Living room	62	33.7
	Bedroom	19	10.3
	Kitchen	10	5.4
	Other rooms	15	8.2

Table 1). It is important to note that domestic buildings in Germany typically do not feature air-conditioning, even new constructions.[1]

2.2. Study design and data collection

An initial survey took place during a cool period between 17.4.−31.5.2023. The participants were visited at their office workplaces and personally interviewed (duration 40–50 min) on their living and working situation, sociodemographics, as well as available heat protection. The trained interviewers placed a temperature logger at the workplace of each participant to demonstrate the correct setup. Participants were also given a temperature logger for their home workplace when they stated they work from home 'several times a week' or '(almost) every day'. The loggers record air temperature at 15 min intervals and have a measurement accuracy of ± 0.5 °C; loggers for home workplaces additionally recorded humidity.[2]

The summer survey was started as soon as the German Meteorological Service had issued a prediction of four consecutive workdays over 30 °C air temperature for Munich. From 20. to 23.6.2023, the participants were sent an online survey to answer shortly before the end of each workday (duration 5–10 min, questionnaire hosted on the platform *SoSci Survey*). Topics of the questionnaires included thermal comfort, heat stress, satisfaction, productivity, and adaptive measures taken. Participants were asked where they had worked on each day of the survey. Those who had worked at other (unspecified) locations (20, 10, 13 and 3 workers on days 1–4 respectively), and/or who had switched between workplaces (29, 28, 30 and 20 workers on days 1–4), were excluded from further analysis. Table 2 gives an overview for the number of participants as well as weather conditions during the four survey days.

In 2024, additional qualitative interviews were conducted to further explore the possibilities of WFH as an adaptation strategy to summer heat and possible barriers. For this, the researchers approached the 8 companies where more than 10 workers had participated, offering a presentation and discussion of study results. Company representatives

[1] 6 participants stated they have air-conditioning at home. However, participants often confused mechanical ventilation with air-conditioning. For office buildings, we fact-checked with company representatives, but participants' statements on their equipment at home could not similarly be verified. Some workers may have installed AC units in their homes, but the real number could be even lower than 6.

[2] 20 of the office and 10 of the WFH loggers (i.e. roughly 10%) were tested in the same room and the manufacturer's claims found to be accurate.

Table 2
Survey participation and weather conditions, all weather data from Munich central weather station [33].

Survey day	Day 1: Tuesday, 20th June 2023	Day 2: Wednesday, 21th June 2023	Day 3: Thursday, 22nd June 2023	Day 4: Friday, 23rd June 2023
Mean temperature (24 h, measured at 2 m)	24.5 °C	23.8 °C	24.4 °C	18.7 °C
Maximum temperature	32.2 °C	28.3 °C	33.6 °C	24.8 °C
Mean humidity	58.3 %	62.9 %	64.3 %	67.5 %
Participants in passive offices	79	82	73	45
Participants in air-conditioned offices	10	13	8	8
Participants working from home (WFH)	34	38	44	62
Total	**123**	**132**	**125**	**115**

were asked to invite those responsible or relevant for heat protection. All 8 companies participated, sending between 1 and 6 representatives from building management, worker protection, employee representatives and company management. After presenting the study results and answering the company representatives' general questions, researchers invited the audience to discuss the topic of WFH specifically, following an interview guideline (questions: How is WFH organized in your company? How would this be applicable to the situation of a heatwave – for example, can employees work from home at short notice? From your point of view, what are the main barriers to WFH at your company? Are there any 'hard limits' as well?)

2.3. Data analysis

The initial survey in spring assessed the properties of participants' homes and offices, their health and well-being, as well as their general thermal preference. The online summer survey was delivered to each participant's work e-mail shortly before the end of their workday. It asked the participants to review their workday in regard to their thermal sensation, satisfaction with temperatures, perceived heat stress and perceived productivity, as well as the actions they had taken this day to adapt to heat and whether these had been helpful.

After the summer, 203 workers sent back the temperature loggers from their offices, and 107 also from their workplaces at home. The logs were normalized (rounding each log to the next 15 min interval), cropped to the relevant period of observation in R, and selected indicators such as daily mean temperature were exported for further analysis together with the survey data.

The variables presented in Table 3 were selected for further statistical analysis in SPSS and R. A mixed-effects model with workers' assessment of heat stress and perceived productivity as dependent variables was used to test the effect of temperatures and different physiological and psychological factors (see 3.3).

Lastly, the qualitative interviews with company stakeholders were recorded, transcribed and analysed using qualitative content analysis with MAXQDA software.

Table 3
Overview of variables used for later statistical analysis.

Variable name	Question wording, response options / additional explanation
1. Data collected in the spring survey	
Gender	Female/male, 1 participant who had answered 'diverse' was excluded from analyses pertaining to gender.
Age	Studies often use 65 or 75 years as thresholds for heat risk. Due to the current German retirement age, only 4 participants were aged 65 or higher. Therefore, the upper quartile (oldest 25% of participants) was computed as 'higher age'. This includes workers aged 56 years or above.
Thermal preference	„Do you generally prefer cooler or warmer temperatures?“ 1=generally prefer cool to 5=generally prefer warm.
Activity level	„Think about a typical workweek (including the weekend, i.e. all 7 days). In all, for how long do you move a) moderately (e.g. quick walking, gardening, cycling), and b) vigorously (e.g. jogging, mountain hiking, swimming)?" Total activity was computed as moderate + vigorous activity * 2, according to WHO guidelines ([51], p. 32), and converted into hours for easier comprehension of results.
2. Temperature and humidity data	
Temperature workplace	Temperatures were measured continuously. The statistical analysis used a daily mean of the temperature measured at the workplace where each participant had worked on the survey day.
Relative humidity (WFH)	Due to study budget constraints, humidity was only measured in home workplaces.
3. Data collected in the summer survey (questionnaire at the end of each workday)	
Thermal sensation	"Overall, how did you perceive the temperature at your workplace today?" −3=cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot (ASHRAE 7-point scale).
Temperature satisfaction	"Overall, how satisfied were you with the room temperature at your workplace today?" 1=Dissatisfied, 2=Rather dissatisfied, 3=Neutral, 4=Rather satisfied, 5=Satisfied. Adapted from the ASHRAE 7-point thermal satisfaction scale, as the original wording of 'thermal environment' is not easily understood in German.
Air quality satisfaction	"Overall, how satisfied were you with the air quality at your workplace today?" 1=Dissatisfied, 2=Rather dissatisfied, 3=Neutral, 4=Rather satisfied, 5=Satisfied.
Heat stress	"How strongly did you feel stressed by heat at your workplace today?" 1=Not at all, 2=Rather not, 3=Partly, 4=Rather strongly, 5=Very strongly.
Productivity	"Overall, how did you perceive your productivity today?" 1=Very bad, 2=Rather bad, 3=Mixed, 4=Rather good, 5=Very good.
Adaptive satisfaction	"Overall, how satisfied were you with your options to adapt to temperatures at your workplace today?" 1=Dissatisfied, 2=Rather dissatisfied, 3=Neutral, 4=Rather satisfied, 5=Satisfied. Due to an unknown issue either none of the WFH participants responded to this question on days 2–4 or their answers were not computed. Therefore, this variable could not be entered into statistical analysis.
Adaptive measures taken and their perceived effectiveness	"What did you do today to make your workplace comfortable?" Catalogue of adaptive measures with three options per measure: 1=used, but did not help against heat, 2=used and helped against heat, 3=not available or not used.

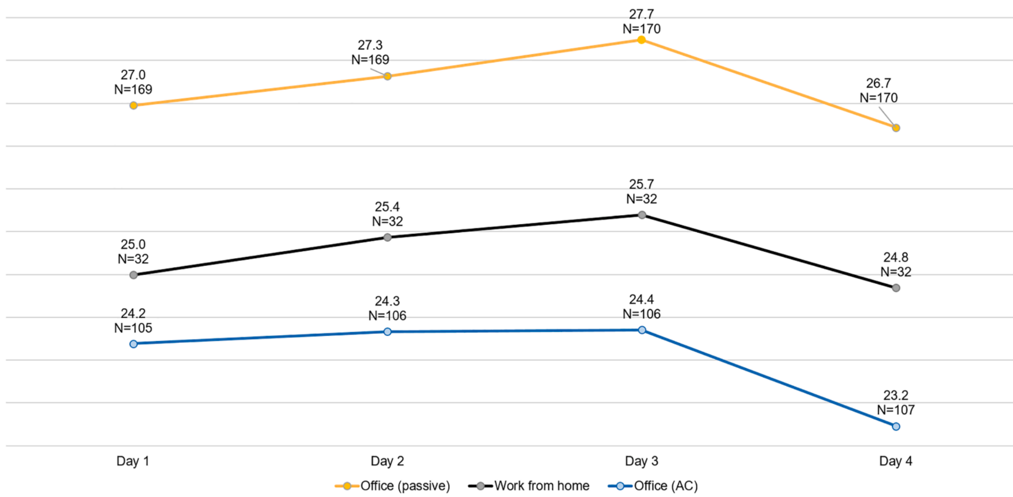

Fig. 1. Daily mean indoor air temperatures during the survey.

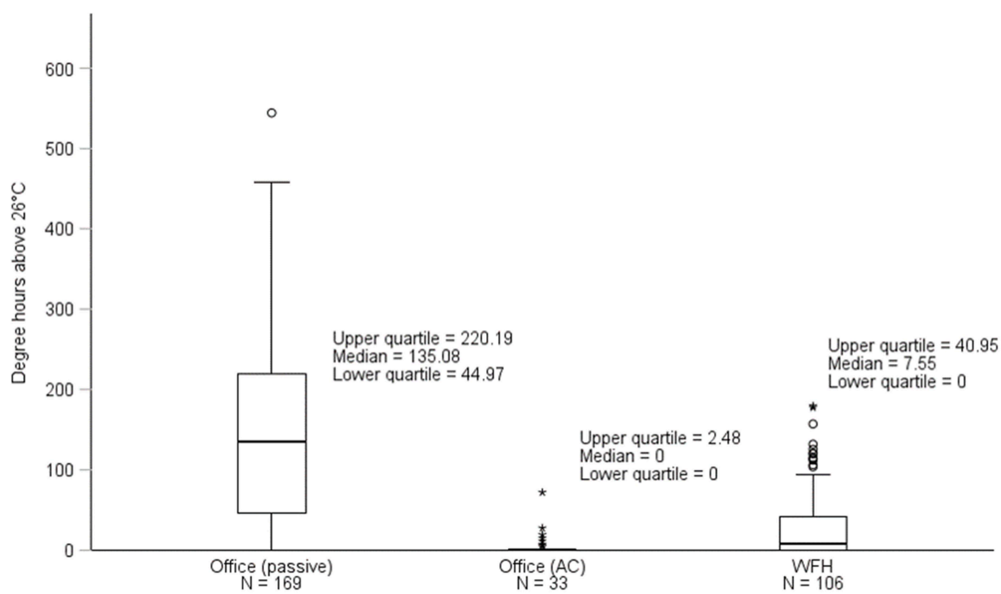

Fig. 2. Boxplots for degree hours above 26 °C indoor temperature during the measured four-day period (96 h total).

3. Results

3.1. Measured temperatures and humidity

Mean measured temperatures were highest in passive offices (i.e. naturally ventilated buildings without mechanical air conditioning), notably lower in homes and lowest in air-conditioned offices (Fig. 1). It should be noted that two of the three mechanically cooled office buildings in the survey had increased setpoints for summer indoor temperature due to the surge in energy prices following Russia's invasion of Ukraine. Average temperatures for the AC group would therefore be somewhat lower in a 'normal' year.

As 26 °C air temperature is a relevant figure in German worker protection laws (see Introduction), 'degree hours above 26 °C air temperature'[3] was used as an indicator for elevated temperature. Mechanically cooled offices had the lowest number of degree hours (Fig. 2). 25% of home workplaces had more than 40 degree hours, but the lower 50% had 7.55 or fewer degree hours, and 31.1% ($n = 33$) never surpassed 26 °C. Only 3.6% ($n = 6$) of passive offices never exceeded 26 °C, with the median at 135.08 and a maximum of 544.56 degree hours above 26 °C. This shows that the majority of passive offices were in temperature ranges where employers are advised to take effective cooling measures by worker protection guidelines. However, heat protection is only *mandatory* from 30 °C air temperature onwards. In 35.5% ($n = 60$) of passive offices, degree hours over 30 °C were logged, but most were overheated only little or periodically: 20.7% ($N = 35$) of all passive offices had under 10° hours, 8.9% ($n = 15$) had between 10 and 30 degree hours, and 5.9% ($n = 10$) had high or very high values of 30 to 170.58 degree hours. Of the home workplaces, only 7.5% ($n = 8$) ever exceeded the limit of 30 °C, with up to 5.13 degree hours.

In home workplaces, the humidity was also measured. At 53.2, 55.3, 57.1 and 53.6% respectively, mean humidity during the four days was well within international guidelines (ASHRAE: 65%, DIN EN 16,798–1:2022 for summer: 70% maximum). 2–5 workplaces exceeded

[3] A degree hour is counted when the threshold temperature (in this case 26 °C) is exceeded by 1 Kelvin for one hour. For example, a value of 3 degree hours could indicate 27 °C during three hours or 29 °C during one hour.

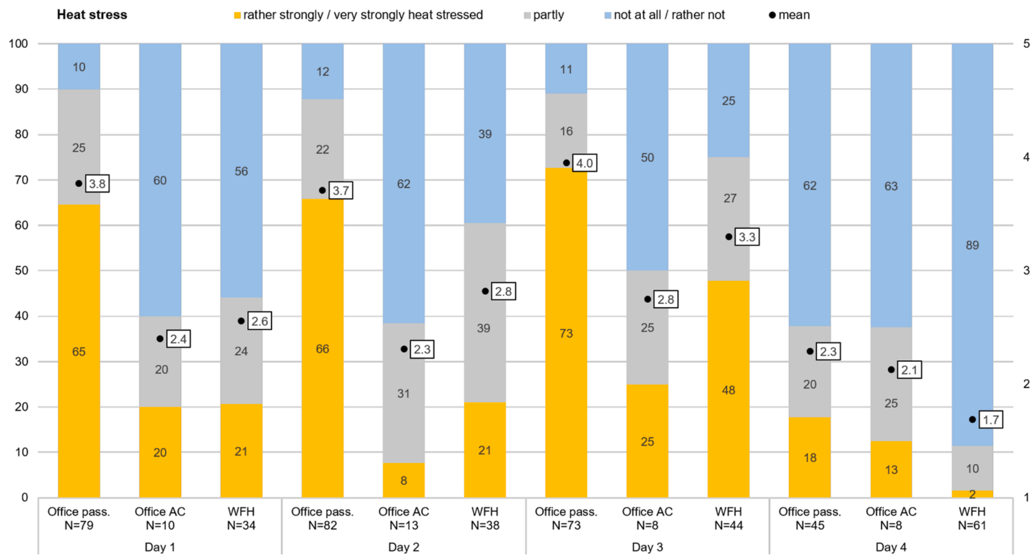

Fig. 3. Distribution of perceived heat stress across the four days (1=not at all, 2=rather not, 3=partly, 4=rather strongly, 5=very strongly heat stressed).

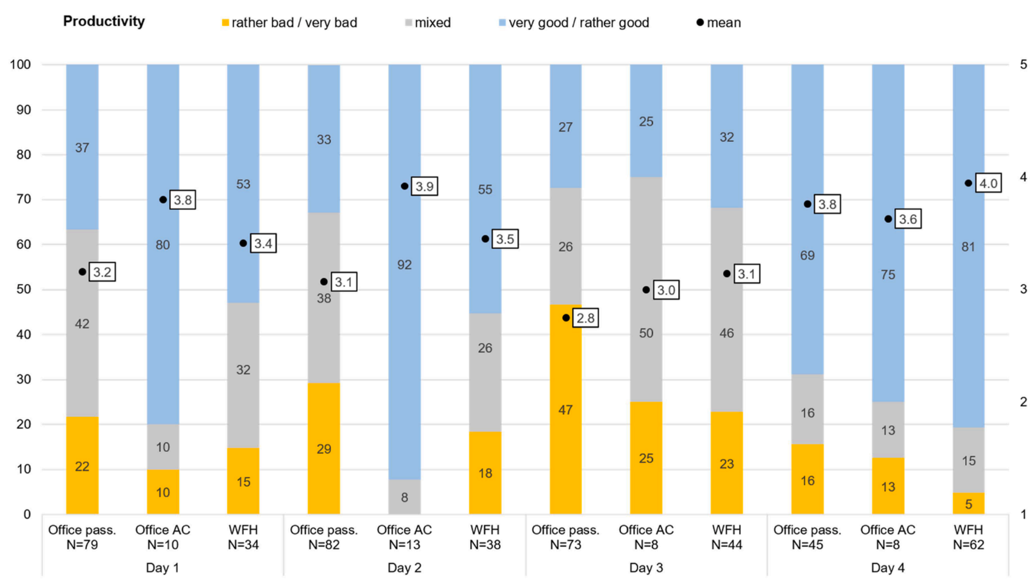

Fig. 4. Distribution of perceived productivity across the four days (1=very bad, 2=rather bad, 3=mixed, 4=rather good, 5=very good).

the 65% limit on different days, and one of them exceeded the 70% limit.[4]

3.2. *Workers' assessments at different locations*

At the end of each workday, participants were asked to rate different aspects of their experience: thermal sensation, temperature satisfaction, air quality satisfaction, heat stress and productivity. The distribution of participants' assessments for heat stress and productivity is shown in Figs. 3,4 for each of the three workplace types across the four days, along with mean values for comparison. The distribution for thermal sensation, temperature satisfaction and air quality satisfaction can be viewed in the supplementary material ((Appendix, Figs. A1, A2, A3).

The distributions show that participants in passive offices perceived their workspaces overwhelmingly as hot or (slightly) warm on the three hot days, felt heat stressed, and were (rather) dissatisfied with temperatures as well as air quality. Even on the fourth, cooler day of the survey, 49% of participants in passive offices were (rather) dissatisfied with temperatures and air quality, and 18% felt heat stressed.

Air-conditioned offices were mostly perceived as cool, neutral or (slightly) warm. Of the 8 to 13 participants each day, only two felt heat stressed and three were dissatisfied with temperatures (days 1 and 3).

On the hottest day, home workplaces were perceived as 'hot' by up to a fifth of workers, as (slightly) warm by up to 68%, and up to 53% were (rather) dissatisfied, with 48% feeling heat stressed. Still, 25% of WFH participants did not feel heat stressed and almost a third was (rather) satisfied with temperatures.

Self-reported productivity was mostly good or mixed on days 1, 2 and 4. On the hottest day, most participants reported mixed or bad productivity, with about a third of participants at each location feeling productive.

[4] Contrary to our expectations, only one of these 'humid workspaces' was located in a kitchen. The rest were from a dedicated WFH room, living room, and in one case from a cellar. The cellar workspace exceeded 70% humidity on three days – a trade-off between effective heat adaptation and air quality standards / possible mould growth.

Table 4
Mixed-effects regression for perceived heat stress.

Effect				
Fixed effects	Estimate	*SE*	*t-statistic*	*p*
Intercept	−5.459	0.939	−5.815	<.001
Workplace temperature	.334	0.033	10.108	<.001
Thermal preference 2, ‘rather cool’ [a]	−0.182	0.228	−0.796	.427
Thermal preference 3, middle category	−0.230	0.221	−1.043	.298
Thermal preference 4, ‘rather warm’	−0.374	0.220	−1.699	.090
Thermal preference 5, ‘warm’	−0.473	0.268	−1.765	.078
Higher age group	0.179	0.148	1.203	.230
Gender (female)	0.127	0.140	0.908	.364
Hours total weekly activity	−0.003	0.006	−0.479	.632
WFH	−0.231	0.129	−1.796	.073
Random effects	edf	Ref.df	*F-statistic*	*p*
Participant ID	78.64	149	1.165	<.001

R-sq.(adj) = 0.498, Deviance explained = 60%, GCV = 0.993, Scale est. = 0.790, *N* = 433.
[a] Reference category for 2 – 5 is Thermal preference 1 = ‘cool’.

Table 5
Mixed-effects regression for perceived productivity.

Effect				
Fixed effects	Estimate	*SE*	*t-statistic*	*p*
Intercept	7.963	.800	9.959	<.001
Workplace temperature	−.0176	0.028	−6.251	<.001
Thermal preference 2, ‘rather cool’ [a]	0.046	0.199	0.230	.818
Thermal preference 3, middle category	−0.017	0.193	−0.089	.929
Thermal preference 4, ‘rather warm’	0.107	0.192	0.557	.578
Thermal preference 5, ‘warm’	0.090	0.234	0.386	.700
Higher age group	−0.071	0.130	−0.550	.582
Gender (female)	−0.086	0.122	−0.705	.481
Hours total weekly activity	−0.001	0.006	−0.187	.852
WFH	0.074	0.108	0.690	.491
Random effects	edf	Ref. df	*F-statistic*	*p*
Participant ID	85.59	149	1.413	<.001

R-sq.(adj) = 0.403, Deviance explained = 53.3%, GCV = 0. 690, Scale est. = 0.538, *N* = 434.
[a] Reference category for 2 – 5 is Thermal preference 1 = ‘cool’.

3.3. Explaining workers’ assessments

To test and quantify the effect of measured temperatures as well as different physiological and psychological factors on workers’ heat stress and productivity assessments, we conducted a mixed-effects regression. Fixed effects include workplace temperature, general thermal preference, higher age group, gender, hours of weekly activity and working from home (WFH) (see Table 3 for detailed overview of questions and answer options). To account for individual variability between participants not explained by the fixed effects, participant ID was introduced as a random effect. Workers’ assessment of heat stress (Table 4) and productivity (Table 5) were selected as the dependent variable.

The regression model (Table 4) shows that with each Kelvin increase in workplace temperature, participants’ heat stress assessment increased on average by 0.334 units. This effect is statistically highly significant. Participants’ general thermal preference (‘Do you *generally* prefer cooler or warmer temperatures?’) was connected to their heat stress assessment: the ‘warmer’ their general thermal preference was, the lower the participants tended to rate their heat stress. Those who generally prefer the warmest temperatures (Thermal preference 5) rated their heat stress almost half a scale point lower (−0.473) than the participants with the ‘coolest’ thermal preference (reference group Thermal preference 1). Female participants and participants from the highest age group (upper quartile, 56 years or older) on average reported higher heat stress. With each additional hour of weekly physical activity (values ranging from 0 to 65 weekly hours[5]) the heat stress assessment was reduced by −0.003 units. Out of these individual characteristics, only the effect of thermal preference was statistically significant at the 10% level. Lastly, workers on average perceived less heat stress when working from home (WFH) than when in the office, with temperatures held constant (statistically significant at the 10% level). The smooth term for individual participants (ID) is highly significant, confirming that there is a large variability in heat stress assessment between individuals that could not be explained by the fixed effects in this regression model. In all, the model can be considered a good fit with an adjusted R^2 of 49.8% and 60% deviance explained.

The same mixed-effects regression for perceived productivity (Table 5) again shows a highly significant effect of measured temperatures, although the effect size is lower: productivity was on average rated 0.176 units lower with each Kelvin increase in workplace temperature. The individual factors gender, age and activity level influence perceived productivity slightly negatively, but effect sizes are quite small. WFH participants as well as those with ‘warmer’ general preference (4 or 5 on the five-point scale) on average reported slightly higher productivity. None of these effects reached statistical significance. The smooth term for individual participants (ID) is highly significant, confirming the heterogeneity in productivity assessment between individuals that could not be explained by the fixed effects in this regression model. The model had lower explanatory power for productivity than for heat stress, with an adjusted R^2 of 40.3% and 53.3% deviance explained.

3.4. Perceived control

One hypothesis gained from the literature on adaptive thermal comfort (see Introduction) would suggest that satisfaction is higher in WFH settings because the actual and/or perceived control is higher.[6] In the survey, workers were asked to check what they had done each day to increase their comfort at the workplace and rate the effectiveness of each measure taken. Table 6 shows the measures for each day.

[5] Note that in accordance with WHO guidelines one hour of vigorous activity was counted as two active hours, see Table 3.

[6] Participants were asked for their satisfaction with control options in the survey, but due to an unknown issue either none of the WFH participants responded to this question on days 2-4 or their answers were not computed. Therefore, the control perception has to be deduced from the effectiveness rating presented here, and control perception could not be entered into regression analysis.

Table 6
Heat adaptation measures taken by workers in offices and WFH settings during three hot and one cooler workday. †N<10 ††N<5. Total number of workers who participated in the survey: Day 1 N=123, Day 2 N= 132, Day 3 N=125, Day 4 N=115.

Measure	Day	N of workers who took this measure	Helped: % of workers who took this measure (total)	Helped: % of office workers	Helped: % of workers WFH
Adapt clothing	**1**	**96**	**79.2**	**73.0**	**90.9**
	2	99	74.2	71.2	81.8
	3	101	66.3	50.8	88.1
	4	69	91.3	83.9	97.4
Shade windows	**1**	**78**	**60.3**	**51.8**	**81.8**
	2	92	63.0	52.4	86.2
	3	94	54.3	36.4	79.5
	4	42	76.2	55.0	95.5
Adapt workday	**1**	**39**	**71.8**	**63.0**	**91.7**
	2	39	71.8	68.2	76.5
	3	45	75.6	63.6	87.0
	4	23	100.0	30.4	69.6
Ventilate	**1**	**80**	**61.3**	**58.5**	**73.3**
	2	84	52.4	50.0	61.1
	3	80	48.8	40.0	68.8
	4	97	89.7	82.6	96.1
Use fan	**1**	**30**	**73.3**	**74.1**	**66.7** ††
	2	42	64.3	64.9	60.0 ††
	3	45	62.2	58.8	72.7 †
	4	20	80.0	76.5	100.0 ††
Use a cooler room	**1**	**7**	**71.4**	**50.0** ††	**80.0** †
	2	9	88.9	100 †	75 ††
	3	9	88.9	66.7 ††	100 †
	4	3	66.7 ††	–	66.7 ††

Three trends are visible across the different adaptation measures. (1) The number of workers who used a measure increased with each hot day. The only exception is ventilation, which slightly decreased, probably because it ceases to be helpful when outdoor air becomes too warm. (2) Almost all measures were rated as more helpful in WFH settings than in offices, (3) perceived effectiveness of measures in general decreased with each hot day (1–3), but the decrease was much less pronounced in WFH settings. The numbers indicate that the same measures were perceived as more helpful at home. Anecdotally, this is consistent with workers' comments during the personal interviews, for example that their ventilation options in the office are limited because colleagues would complain about draft or papers on their desks getting disordered, or that clothing can be adapted more freely at home.

3.5. Modalities and barriers of WFH

As WFH increased worker satisfaction and, more importantly for heat protection, homes were in many cases objectively cooler than passive offices, the modalities and barriers of WFH were more closely studied with additional expert interviews presented in the following section.

189 of the 210 interviewed workers (90%) initially stated that they were free to work from home. However, during the hot period only between 42 and 70 participants (26–52% of each day's total participant number) did so. Anecdotally, some participants had mentioned during the initial interviews that although they can work from home, the rules governing this did not allow to flexibly react to hot days, e.g. because WFH days had to be set in advance.

Most companies organized WFH in one of two ways. The first is to allow a number of full WFH days either per week (e.g. 1 WFH day per week) or per month (e.g. 2 WFH days per week to distribute freely in one month, so that one could take up to 8 consecutive WFH days). The second is to allow a percentage of working time (40, 50, 60 or up to 100%), mostly based on a monthly period. However, two interviewees pointed out that employees wrongly understand the percentage and apply it on a weekly basis (i.e. 60%=3 WFH and 2 office days per week), whereas they could also apply it more flexibly to a whole month or a single day. This structure is relevant to heat adaptation: when the monthly ,allowance' of WFH days is used up, the rest of the month *has* to be spent at the office, regardless of temperature.

Hard limits to WFH are set by jobs that require physical presence: counselling (appointments with social services were usually made months in advance and could not be easily rescheduled), visits to municipality administrative offices, postal, technical and similar supportive services in the office building. Some financial, secretarial and counselling roles could at least partly be transferred to the home, but this was in several cases hindered by a lack of digitalization. Either there was no digital filing system and taking paper files home would be impractical and/or violate data protection laws, or workers were unwilling to switch to digital file management.

The potential of WFH for heat adaptation is also limited by workers' habits. Many have routine WFH days, organize their professional and private schedules accordingly and would therefore not change their routine due to the weather. This is somewhat supported by the fact that the highest number of survey participants worked from home on Friday (presumably a habit for many), regardless of outdoor temperature.

Another limitation can be the direct managers' willingness. In one case, it was commented that management did not correctly pass on information regarding WFH so that employees would stay at the office. However, most interviewees agreed that more flexible arrangements could be negotiated with the team or manager. One company had educated managers on the impact of heat on health to sensitize those that were not affected themselves.

In two cases (both public entities), interviewees explicitly mentioned equality. They emphasised that conditions for granting WFH due to heat must apply equally to all colleagues. In this view, if WFH depended on subjective evaluations of heat stress, it would lead to mutual mistrust: ,people will check their colleagues and say: Oh, now he's playing hooky again, it's unfair, he's been working from home for several days now although it's only 28 degrees.' To ensure equality, objective criteria such as official heat warnings or measured room temperatures would have to be introduced.

Interviewees also mentioned organizational innovations to adapt to summer heat. Two companies had introduced a desk-sharing system, one specifically to address unequal distribution of heat exposure between two building sides. The same company also tasked managers with organizing their team to better cope with heat (i.e. that some would work from home and thus free up cooler spaces in the office).

To conclude, these exploratory stakeholder interviews suggest several reasons for low WFH shares in the study: temporal allocation of WFH, cooperation of managers, a lack of digitalization and workers' ingrained habits are all barriers for using WFH to adapt to heat events. However, many interviewees appeared willing to consider organizational innovations to further the possibilities of WFH within the limits given by the respective workers' roles.

4. Discussion

96% of passive offices reached the threshold of 26 °C from which on worker protection guidelines recommend additional heat protection such as fans or relaxing clothing standards. 21% of passive offices ($n = 35$) also reached the 30 °C threshold from which on heat adaptation measures are mandatory. 9% of passive offices had longer or more intense overheating (10–30 degree hours above 30 °C) and 6% were severely overheated (30–171 degree hours). These values were reached even though the hot period was neither very pronounced nor very long. Home workplaces had lower mean temperatures. In 31% of homes, the 26 °C threshold was never reached. Only in 8% ($n = 8$) of homes, the 30 °C threshold was surpassed, and this only of short duration and magnitude. Humidity levels (only measured at home workplaces) were withing international recommendations. Air-conditioned offices were the coolest in the sample, never reaching 30 °C, and only some outliers reaching 26 °C.

The majority of workers in passive offices rated them as hot or (slightly) warm, felt heat stressed, and were dissatisfied with temperatures and air quality. A fifth of participants working from home perceived their workplaces as 'hot' on the hottest day of the study, 53% were (rather) dissatisfied and 48% felt heat stressed. Still, 25% of WFH participants did not feel heat stressed and almost a third was (rather) satisfied with temperatures.

A mixed-effects regression showed that measured temperatures had the largest and statistically highly significant effect on the heat stress assessment of participants. While not a surprising result, this corroborates the importance of measured temperatures not just for physiology but also for perception.

Age and gender had minor effects on the perception of heat stress. Women reported slightly more heat stress, which is in line with other studies that find women to be more critical of the thermal environment. The threshold for 'older' is usually at 65 years [50] or even higher [13]. Due to the sample of working individuals, the threshold here was set at the upper quartile, starting at 56 years. In spite of this lower threshold, we found participants of 56 years or older to feel slightly more heat stressed than their younger counterparts. Activity level also had a minor effect on heat stress perception. This is in line with former research showing that lean or fit individuals tolerate higher temperatures (see Introduction). Assessing participants' 'active minutes' throughout a typical week is suggested as a good alternative to other metrics commonly used such as fitness tests (as it is more field-compatible) or self-reported 'general physical strength' [18], and could be combined with and tested against BMI [14]. The activity level of this highly sedentary population might also be a metric for acclimatization – although acclimatization depends on the temperature of the environment, and we do not know how much of participants' weekly activity takes place outside or in other hot environments. None of these individual characteristics were statistically significant.

In this study, we enquired for 'general thermal preference' (generally prefer cooler / warmer temperatures) once, during the initial survey in spring. This is different to the usual usage of the term 'thermal preference' to indicate a desired change in temperature in the moment (cooler/warmer). Yang et al. [54] have used a similar general self-reported sentiment of subjects to group them into cold, warm und neutral preference. However, their questionnaire asked for preference in the summer season, whereas we did not specify further. Jacquot et al. [23] suggest categorizing subjects according to their thermal sensation votes into cool / warm preference as well as narrow / broad range preference. Although ours was quite a crude question (which could have many underlying variables), workers reporting generally warmer preferences on average reported significantly lower heat stress. This correlation is relevant as it could help to group workers into 'preference categories' quite easily, which could have potential benefits for better estimating energy consumption and improving heat adaptation. Workers who prefer warm temperatures could sit in more exposed zones of the building, e.g. depending on floor or orientation [12]. Realistically, this will not be practical in many situations as workers are grouped by team or simply by available space. Flexible workplace arrangements such as desk-sharing might increase adaptability in this regard. However, from the health perspective of heat adaptation, workers' self-assessed preference is not advisable as the only guiding factor since vulnerability to heat due to physiology or exposure is not always mirrored in higher risk perception of the individual [3].

The regression showed a slight 'psychological effect' of working from home even when measured temperatures and individual factors (see above) were held constant. Although we could not include control satisfaction in regression analysis due to a computing error, descriptive statistics (Table 6) suggest that behavioural adaptations were perceived as more effective at home than in the office. It is plausible that the workers can adapt more freely in their private household (e.g. remove more clothing, take a nap) whereas in the office they would be sanctioned by colleagues or supervisors for the same behaviours, or conflict with others who have different preferences for e.g. ventilation or shading. Higher satisfaction with controls and higher perceived control could be an explanation for the slightly higher satisfaction at home.

The connection between measured temperature and self-reported productivity was much less strong. Productivity was rated relatively well across all workplace types on days 1, 2 and 4, and mixed or (rather) bad on the third and hottest day. The effect of measured temperatures on perceived productivity was statistically significant, although lower than their effect on perceived heat stress. This is contrary to prior studies which found no statistically significant effect of measured temperatures on productivity [25,38]. Furthermore, the effect of temperature on self-reported productivity was linear and we found no 'threshold temperature' (unlike [17,44]). The effects of individual characteristics of participants (age, gender, activity level) were negligible. General thermal preference had a slight effect. Of course, adding an objective measure of productivity would have been preferable to only self-reported data. Yet, this is difficult in field studies and especially in knowledge work where output is tricky to quantify (in contrast to e.g. metrics such as 'number or length of processed calls' from call centre studies [35,46]). Commonly used psychological tests are difficult to use repeatedly due to learning effects. Therefore, many studies rely on self-reporting, for example by reflecting on the demands of a task (NASA Task Load Index) or giving a general assessment for a workday or even an entire season [45].

The qualitative interviews conducted with stakeholders from the participating companies showed several barriers to WFH as a method of flexible adaptation to summer heat. WFH is organized with 'budgets' – a number of days or a percentage of working time per week or month –, and workers' routines are often set regardless of temperature, e.g. WFH every Friday. Stakeholders discussed institutional barriers (certain office-based tasks, lack of digitalization) as well as cultural barriers such as managers' willingness or the expectation of equal WFH rules for all workers. These are some problem areas that could be addressed to allow for more flexible adaptation to heat. Either by slow changes from within institutional culture, or by government intervention. For example, the heat protection rules currently do not suggest WFH as an 'effective method of heat protection', and trade unions as well as labour ministry view the practice sceptically, including because often other ergonomic considerations are not met at home [53]. Social innovations that allow workers more flexibility depending on their heat exposure in the office and at home could be an additional tool for climate adaptation.

Lastly, some limitations and avenues for further research should be addressed. One limitation we would have expected due to the study design is a self-selection of workers dissatisfied with thermal conditions at their workplace. But as the distribution (see Table 1) shows, only 39% of surveyed workers were (rather) dissatisfied with heat protection at the office. The recruitment process could have produced a potential bias in the sample. As the first step was reaching out to company representatives, there might be a bias towards somewhat proactive employers interested in the improvement of their employees' environment. Another plausible self-selection bias is that participants are more likely to work from home when their home is thermally comfortable. This could have an effect on the presented assessments of WFH during the hot period. However, temperature loggers were handed out in springtime to all participants who stated they often WFH *in general,* not only during summer. Therefore, the possible self-selection bias during the three hot days is unlikely to have influenced the measured temperatures presented here.

A further limitation is that this study only measured air temperature. There are other relevant factors that influence thermal perception, such as air velocity, humidity and radiant temperature. It would be more informative to include these, e.g. by using wet-bulb globe temperature as a measure. At the same time, higher air velocity (e.g. through fans) is very effective in reducing heat discomfort and should be prioritized as a climate adaptation measure due to its low energy consumption – both in offices and in homes.

An analysis of the air-conditioned offices in this study is limited by two factors: only relatively few workers from air-conditioned offices participated in the summer survey (between 8 and 13 on the different days), and two of the three office buildings had increased summer AC setpoints to save energy in the wake of Russia's invasion of Ukraine. Both average temperatures and workers' assessments of AC offices in this study should therefore be interpreted with caution.

As the survey was sent to workers at the end of each workday, participants were asked to give an average rating for their entire day. In the study, this rating was complemented with a qualitative method asking for fluctuations throughout the day. Preliminary analysis shows that participants' estimated average for their day is consistent with their reported fluctuations. We will discuss this in a forthcoming paper. The timing and duration of heat stress also has implications for health and energy consumption. The distribution of degree hours suggest that heat stress in homes was more of a temporary discomfort to which workers can adapt through behaviour, while many offices produced a constantly hot environment. Spending time in adverse thermal conditions is not unhealthy per se and could even have positive effects for metabolic health [28,48]. When the temporal distribution is considered, active cooling could be applied selectively for those times where workers are most susceptible to heat [29].

Working from home could be a good method of heat adaptation for workers who have warmer offices and comfortable conditions at home. If companies situated in passive buildings could sufficiently react with temporary WFH to periods of overheating, and therefore reduce the number of building retrofits with air-conditioning systems [31] – or limit the cooling load for existing AC systems –, WFH could potentially save cooling energy and thus indirect CO_2 emissions [22]. Currently, domestic cooling is negligible in Germany as in other Central and Northern European countries [21]. However, this balance could change depending on domestic AC ownership. If more households adopt WFH, depending on affluence the AC ownership rate would grow further [1]. From an energy consumption standpoint, air-conditioned offices with high occupant density should be more energy efficient than individual households with self-installed air-conditioning units. For the US, based on a time-use survey and assuming standard values for indoor temperatures, Wu et al. [52] found that 'space heating and cooling dominated the GHG emissions under WFH, together accounting for 37.15% of the total footprint.' Of course, the broader picture of WFH vs office's energy consumption or emissions depends on a host of other factors including transportation [15]. Future studies could explore how different scenarios of AC market penetration as well as WFH adoption would impact energy consumption and peak loads in summer.

In future research, more attention should be paid to gender and care dimensions in heat adaptation and work. For example, women might be more likely to work part-time or switch between office and WFH – does this lead to more flexibility or stress? It could make a difference whether children are at home (both for productivity and heat adaptation, as getting up and doing housework or childcare frequently could increase metabolic heat production). Additionally, some heat adaptation recommendations are less feasible for child carers: for example, starting very early or working late might not be feasible with schedules of childcare institutions or schools. These aspects should be integrated into future questionnaires.

5. Conclusion

This study presented temperature measurements and workers' assessments from conventional offices and home workspaces during a hot period in the summer of 2023. Home workplaces had both lower mean temperatures and less occurrence of elevated temperatures or overheating (operationalised as degree hours above 26 °C and 30 °C respectively) than passive offices. These are novel findings as temperatures while working from home (WFH) have not been studied to date with respect to hot weather.

Workers' self-reported heat stress was significantly influenced by workplace temperatures. Individual characteristics age, gender and activity level had minor, statistically not significant effects, all in line with prior research. The notable effect of general thermal preference ('generally prefer warmer / cooler temperatures') on heat stress assessment could potentially be of interest in grouping workers along their stated preference. There was a slightly negative effect of WFH on heat stress assessment (with temperatures and individual factors held constant), which could possibly be explained by the higher perceived efficacy of adaptation measures at home.

Perceived productivity was also significantly influenced by measured temperatures, although with lower effect sizes. Other variables were negligible.

Although interviews with stakeholders from the participating companies showed various institutional and cultural barriers, we suggest that flexible working from home (WFH) could be an asset for climate adaptation of office workers.

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CRediT authorship contribution statement

Amelie Bauer: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix

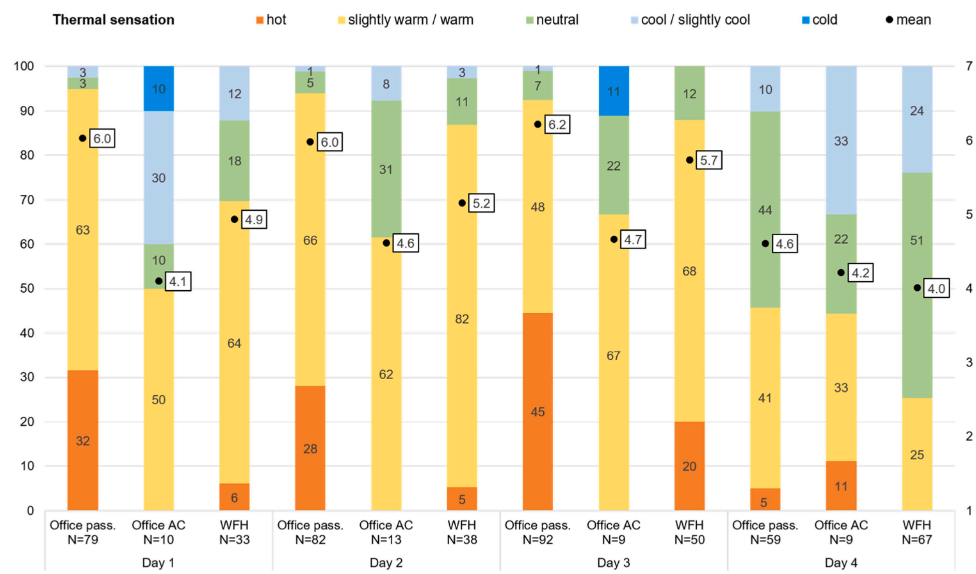

Fig. A1. Distribution of thermal sensation across the four days (% in bars, mean values in boxes; 1=hot, 2=warm, 3=slightly warm, 4=neutral, 5=slightly cool, 6=cool, 7=cold).

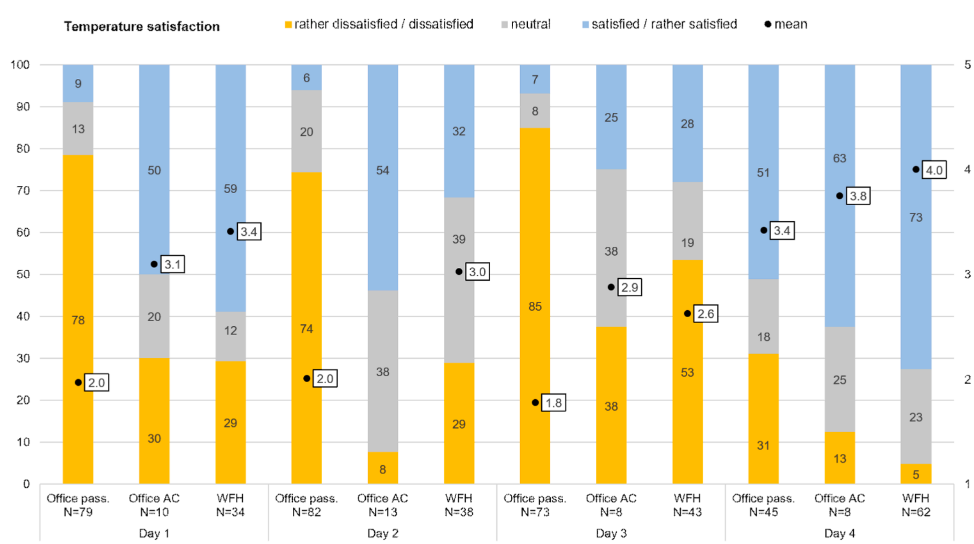

Fig. A2. Distribution of temperature satisfaction across the four days (1=dissatisfied, 2=rather dissatisfied, 3=neutral, 4=rather satisfied, 5=satisfied).

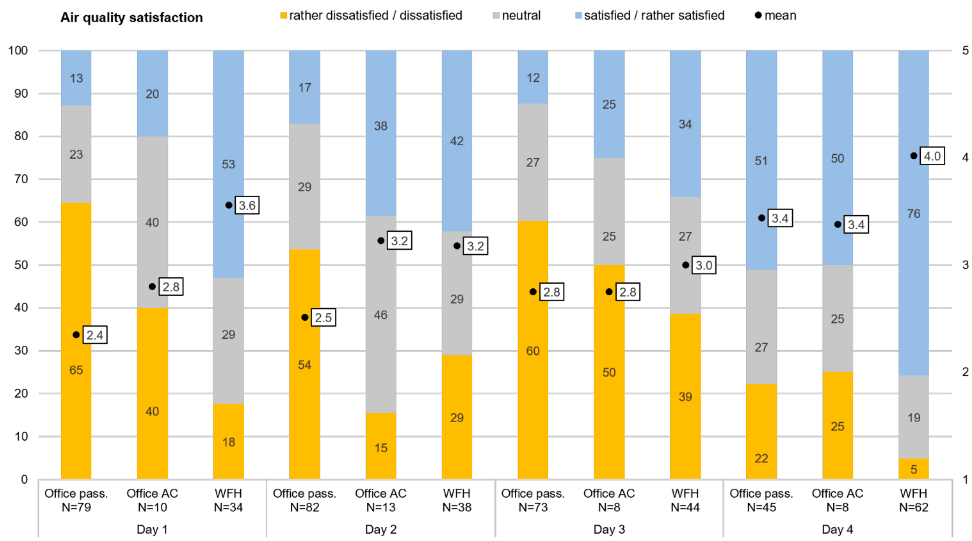

Fig. A3. Distribution of air quality satisfaction across the four days (1=dissatisfied, 2=rather dissatisfied, 3=neutral, 4=rather satisfied, 5=satisfied).

Data availability

Data will be made available on request.

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