An assessment of the thermal conditions and users' thermal adaptability in air-conditioned offices in a hot climate region

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Abstract

Indoor thermal condition is a global concern that plays a major role in the wellness, comfort, and satisfaction of office workers. The thermal environment was evaluated in an office building in a hot region using subjective and objective measurements. Considering the former, a questionnaire was distributed to the employees to assess their thermal perceptions. Specialized instruments were used for the objective measurements to monitor thermal parameters following the guidelines of ASHRAE-55 and ISO-7730. A total of 220 employees took part in the survey, and 207 valid questionnaires were included in the analysis. According to the subjective assessment, the thermal votes of the employees were between (cold) to (slightly warm), and the majority were thermally comfortable and accepted the environment. This implies that a temperature of 22.8 ± 1.2°C appears to be a comfortable range. Using the Griffiths method, the comfort temperature (Tc) was calculated as 23.5 ± 1.9 °C. Additionally, the employees ranked 11 indoor factors that influence their work productivity. Noise conditions were ranked as the most important factor. The results of the reported study provide a base for further research and useful information on the comfort temperature of office buildings in hot regions.

Keywords - Thermal adaptive model, hot climate, comfort temperature, office buildings

1. Introduction

Considering the increasingly overheating climates, indoor thermal conditions become a global concern due to their role in the wellness, comfort, satisfaction, and productivity of buildings' users [1]. Thus, maintaining comfortable work environments is essential considering the long daily and continuous use of offices. However, achieving indoor comfort requirements is directly related to energy consumption [2]. On the other hand, it is difficult to identify a satisfactory environment for all users because of the regional and subjective nature of thermal comfort, as it depends on individual, cultural, and climatic differences [3], [4]. However, acceptable environmental conditions can be predicted for the majority of occupants using the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) [5]. If the thermal condition of any space is satisfactory for more than 80% of the occupants, then the space is considered an acceptable thermal environment [6]. Inefficient thermal conditions can affect the occupants and lead to discomfort. To avoid such issues, thermal conditions can be controlled through heating, ventilation, and air conditioning HVAC systems and building design (i.e. building façade and insulation) [7].

Maintaining thermally comfortable environments in hot regions such as the Arabian Gulf region is highly dependent on energy-intensive air-conditioning systems. With the absence of regional thermal guidelines and standards, it is difficult to achieve optimal thermal conditions with sustaining energy. The researchers from the Arabian Gulf region tend to follow the international standards designed for other climatic regions such as [5], [6], [8]; thus, the influences of cultural background, climate, and users' preferences and expectations are not precisely addressed. Added to this, there is a lack of research in the thermal comfort field in the Arabian Gulf region, especially in office environments. Indeed, searching published literature from the Gulf Cooperation Council (GCC) region using the Scopus database and the keywords (thermal AND comfort AND offices AND building AND GCC) returned three studies only [9]–[11]. This highlights the need to evaluate and understand thermal comfort conditions in work environments in the region more thoroughly. Up to the authors' level of knowledge, there is no published research evaluating thermal conditions in office buildings in Oman. The study at hand attempts to fill this gap of knowledge by evaluating the thermal environment of university offices considering the users' thermal sensations, preferences, comfort, acceptance, and adaptability. The importance of the study evolves from its findings that can be used as a base to minimize the energy demand by adjusting the set point temperature of the air conditioning system based on the comfort range of the users, as mentioned in [12].

2. Methods

The offices of Sultan Qaboos University, Oman, were selected as the case for the evaluation reported in this paper. The university is in Muscat city, which is characterised by its hot arid climate based on the Koppen-Geiger climate classification. However, the city's proximity to the Indian Ocean resulted in hot humid conditions [13]. The offices' thermal conditions were evaluated using subjective assessment and objective measurements. For the former, a paper-based questionnaire was distributed to the employees. Table 1 displays the main themes of the questionnaire. For the objective measurements, specialised instruments were used to monitor indoor air temperature (T_a), relative humidity (RH), air velocity (AV), and globe temperature (T_g) following the guidelines of [5], [6], [8] as summarised in Table 2. The instrument was placed at the centre of each office at a height level of 1.1 m from the seated employees. The data was logged at a 1-minute interval. Simultaneously, the employees evaluated their perceptions of the indoor thermal environment using the questionnaire. The survey was conducted during a relatively warm period from 5th March 2023 to 18th April 2023. Moreover, the mean radiant (T_r) and operative (T_o) temperatures were calculated using equations (1) and (2) [14] and the comfort temperature (T_c) was calculated using Griffiths method using equation (3).

$$T_r = [(T_g + 273)^4 + (1.2 \times 10^8\, d^{-0.4})\, v^{0.6}\, (T_g - T_a)]^{0.25} - 273 \quad (1)$$
$$T_o = 0.5\, T_a + 0.5\, T_r \quad (2)$$
$$T_c = T + (0 - TSV) / G \quad (3)$$

Where d is the diameter of the globe, which is 15 cm for the used sensor.

Table 1: The questionnaire themes

Theme	Questions
Demographic data	Employee gender, age and college or department
Thermal perceptions	Evaluation of thermal comfort, acceptance, sensation, and preference
Thermal history	Participants' activity levels, clothing levels, and adaptive actions
Ranking	Ranking 11 items that affect work productivity

Table 2: The accuracy of the sensor used in the physical measurements

Physical parameter	Air temperature	Globe temperature	Air velocity	Relative humidity
Accuracy	± 0.3 °C	± 0.3 °C	± 10 cm/s	1.8%

3. Results

The returned questionnaires were checked to ensure that only complete and consistent questionnaires were included in the analysis. Out of the 222 distributed questionnaires, only 15 were incomplete. Based on the participants' sensations and preferences, none of the questionnaires was inconsistent. Female participants were 111 forming 53.6% and male participants were 96 forming the remaining 46.4%. The participants covered a wide age range starting from 21 to above 65 years old as plotted in Figure 1. Most female participants clustered between 30 and 40 years old, whereas male participants were almost equally distributed over a wider range extending from 30 years old to 55 years old.

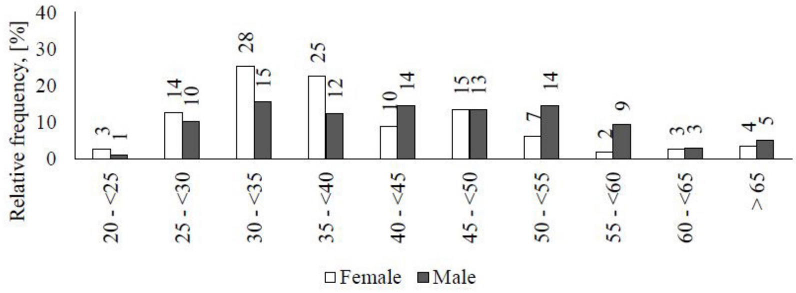

Figure 1: Participants' distribution based on their age and gender (labels are participants' numbers)

The participants were asked about their activities during the last 15 minutes before answering the questionnaire as indicated in Figure 2. More than 140 participants were sitting performing active work and more than 80 were passively sitting. Insulation levels were estimated based on participants' clothing and seat insulation [5], [6], [8] as displayed in Figure 3. Mean insulation level was 1 clo with the mean being 1.14 clo and 0.83 clo for female and male participants, respectively. Maximum and minimum levels were 0.44 clo and 1.96, respectively. It is noted that 58,47, and 40 participants clustered in insulation levels of 0.63-0.82 clo, 0.82-1.01 clo, and 1.01-1.20 clo, respectively.

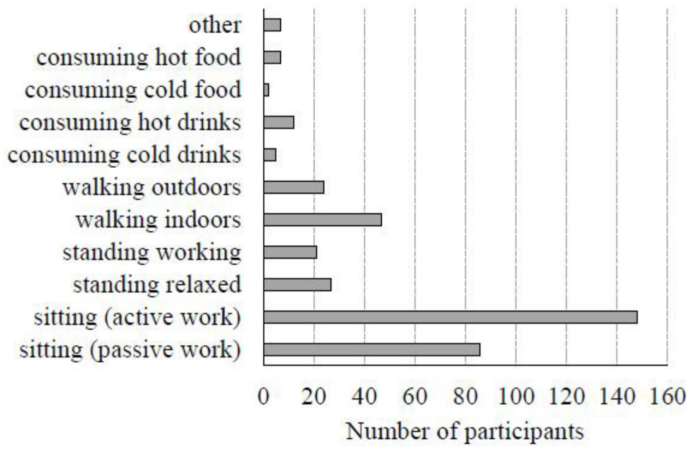

Figure 2: Participants' distribution based on their activity level 15 minutes before answering the questionnaire

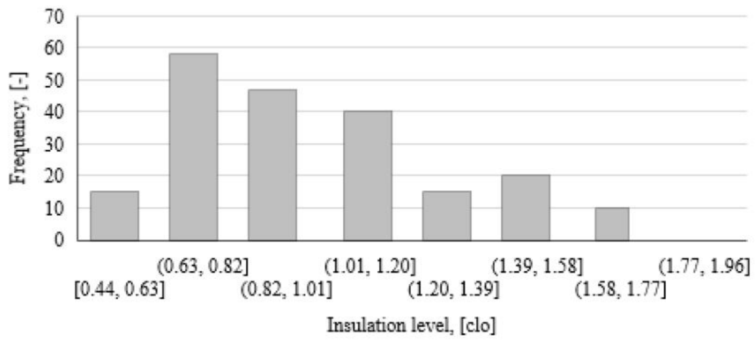

Figure 3: Participants' distribution based on their clothing level during the questionnaire

Table 3 displays some descriptive statistics of the measured physical parameters. Air temperature (Ta) ranged from 19.7 °C to 25.9 °C with a mean of 22.8 °C. Globe temperature (T_g) was recorded between 20.0 °C and 25.5 °C with a mean of 22.7 °C. The correlation between Ta and Tg is 0.95, which indicates an absence of radiant sources in the offices. Relative humidity (RH) fluctuated between 43.6% and 78.4% with a mean of 56.4% and air velocity (AV) extended from 0.0 m/s to 0.3 with a mean of 0.0 m/s. Both mean radiant temperature (T_r) and operative temperature (T_o) were calculated using the measured parameters. (T_r) ranged from 19.7 °C to 26.1 °C, and the mean was 22.8°C. The variation recorded for (T_o) was between 19.9 °C to 25.8 °C.

	T_a	T_g	RH	AV	T_r	T_o
Mean	22.8	22.7	56.4	0.0	22.8	22.8
Standard error (SE)	0.084	0.074	0.441	0.003	0.084	0.078
Median	22.8	22.6	55.8	0.0	22.8	22.7
Mode	22.4	23.1	57.7	0.0	22.4	21.8
Standard deviation (SD)	1.204	1.069	6.348	0.037	1.213	1.127
Range	6.2	5.5	34.8	0.3	6.4	5.9
Maximum	19.7	20.0	43.6	0.0	19.7	19.9
Minimum	25.9	25.5	78.4	0.3	26.1	25.8

Table 3: Descriptive statistics of the physical parameters

For the subjective evaluation, the participants were asked about their thermal comfort, environment acceptance, thermal sensation vote (TSV), and thermal preference vote (TPV). The relative frequency of TSV and TPV are plotted in Figure 4. The participant's sensations clustered in the (cool) category and the comfort range (i.e., slightly cool, neutral, and slightly warm), with 45.9% of votes in the (neutral) category. Moreover, 41.1% felt coldness sensations (i.e., cold, cool, and slightly cool), while 13.0% felt warmth sensations (i.e., hot, warm, and slightly warm). Considering thermal preferences, the participants clustered between (a bit cooler) to (a bit warmer), with 53.1% in the (no change) category.

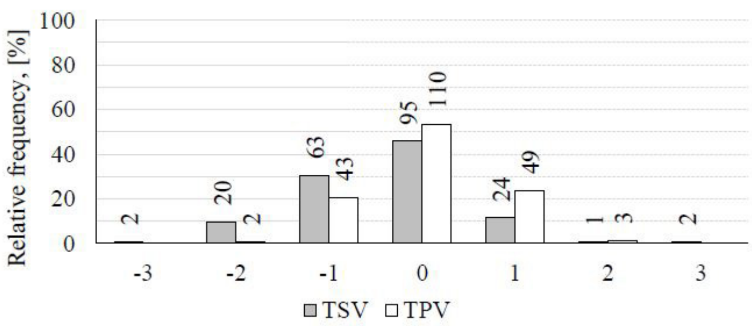

Figure 4: Relative frequency of TSV and TPV (labels are participants' numbers)

Figure 5 presents the thermal sensation distribution based on thermal comfort and acceptance. As noted, the votes clustered between (slightly warm) and (cool), despite comfort level or environmental acceptance. Forming around 91.8%, 190 of the participants evaluated their environments as acceptable. Yet, 180 reported being thermally comfortable. Considering the correlation between comfort and sensations, most participants were thermally comfortable accounting for 87.0%, while 13.0% were thermally uncomfortable. With reference to the distribution of sensations based on comfort, 50.6% of the participants who felt (neutral) were thermally comfortable. On the other hand, 40.0% of those who felt coldness sensations were thermally comfortable, while 9.4% felt warmth sensations. The number of thermally uncomfortable participants was relatively small and around 48.1% of them felt coldness sensations, whereas 37.0% felt warmth sensations and 14.8% felt (neutral).

The environment acceptance is presented in Figure 5 (b). The acceptance rate was high, of approximately 91.8%. Around 47.9% of them were (neutral), whereas 41.6% felt a coldness sensation and 10.5% felt warmth conditions. In addition, around 41.2% of the 8.2% who reported unacceptable environment were (neutral), whereas 41.2% and 35.3% and 23.5% felt warmth and coldness conditions, respectively. It is noteworthy that the percentage of the users felt (neutral) for comfort level and acceptance level was identical for both questions. On the other hand, the results indicated differences in the percentage of the participants who reported environment acceptance and comfort level.

The participants were asked about the behaviours they took to modify the offices' thermal conditions as displayed in Figure 6. Most participants did nothing in spite that around 12.1% were thermally uncomfortable and 7.1% evaluated the ambient environment as thermally unacceptable. Most of the participants opened doors and switched off/on AC. Among the 16 participants who opened the door, 87.5% were thermally comfortable and evaluated the environment as acceptable, whereas 12.5% found it uncomfortable and unacceptable. Considering those who switched on/off AC, 37.5% and 12.5% switched off AC reported uncomfortable and unacceptable conditions, respectively. In contrast, 10% who switched on AC were uncomfortable and did not accept their thermal environment. It is noteworthy that only 20 participants took more than one adaptive action.

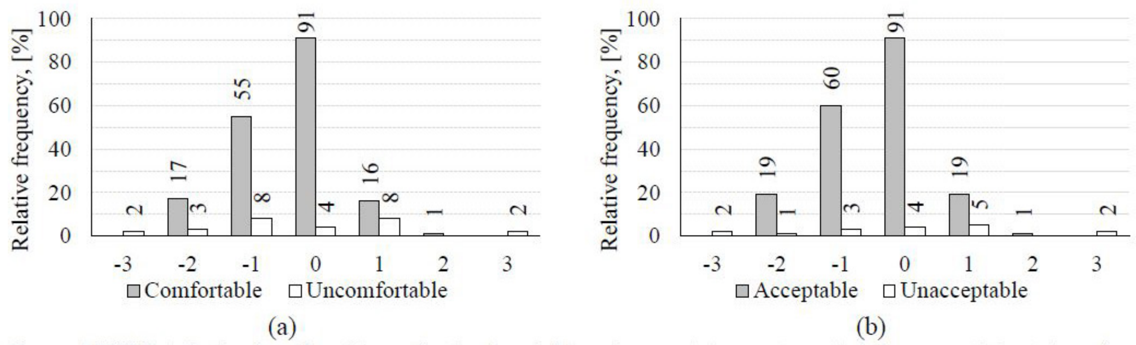

Figure 5: TSV distribution based on (a) comfort level and (b) environmental acceptance (labels are participants' numbers)

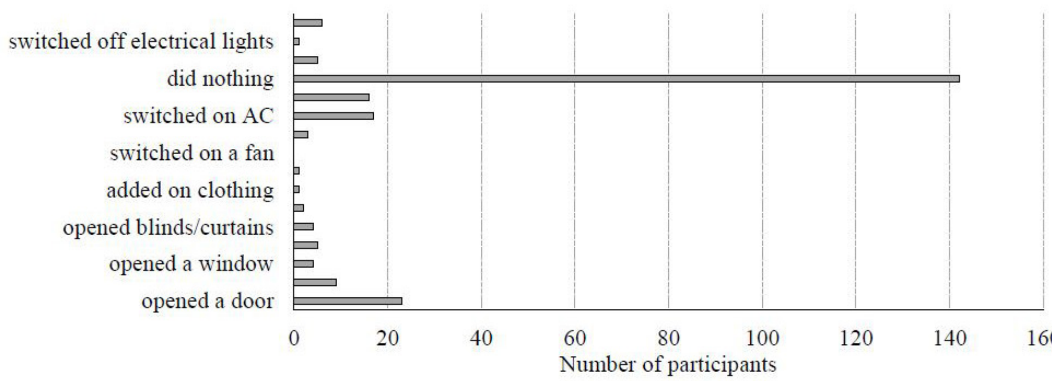

Figure 6: Adaptive actions taken by the participants

The last section of the questionnaire asked the participants to rank 11 factors that affect their work productivity from 1 to 11, where 1 represents the most important factor and 11 represents the least important factor. The results are presented in Figure 7. Considering (noise), it was selected by 67 employees as the first important factor, whereas 19 employees considered it as the second important factor. Considering all factors, (noise) was the most important factor followed by (privacy), (temperature), (cleanness), (lighting), (personal control), (air quality), and (workspace size). The least important factors were (external views), (furniture), and (indoor air movement) that were selected by an equal number of employees, i.e. 5 for each factor.

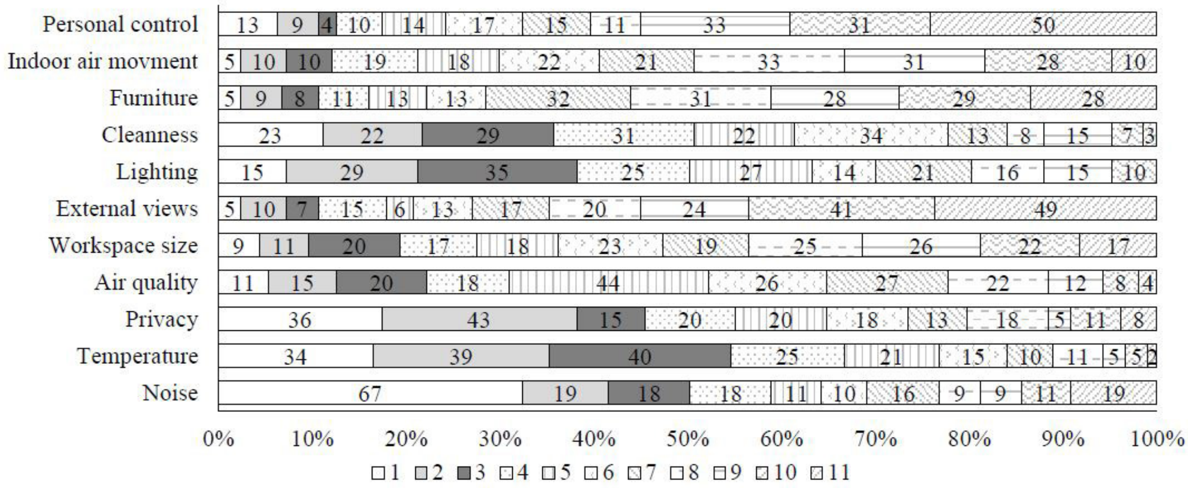

Figure 7: Importance of factors affecting work productivity, 1 = the highest, 11 = the lowest (labels are participants' numbers)

4. Discussion

The thermal sensations clustered between (cool) and (slightly warm), and most of the participants were thermally comfortable and accepted the environment, which implies that an air temperature of 22.8 ± 1.2°C is a comfortable range. The sensation clustered in a different range from the comfort range specified by ASHRAE. This is in line with the findings of [15], where people from hot regions define (neutral) to (cool) conditions as the comfort range. This is expected based on the subjective and regional nature of thermal comfort, which depends on different factors, including individual preferences and climatic and cultural background. The results indicated that the coldness condition is preferable among the investigated employees. Moreover, air temperature (Ta), operative temperature (To), and globe temperature (Tg) were moderately correlated to the participants' sensations. The correlations between each of these temperatures and thermal sensations were moderate as the correlation coefficient was 0.3 in each case. ASHRAE definition of thermal comfort does not distinguish between thermal comfort and thermal acceptance.

However, there was an apparent difference of around 4.8% between comfort and acceptance for the participants. Therefore, the one-way analysis of variance (ANOVA) was applied as presented in Table 4. It is obvious that there was not enough evidence to reject the null hypothesis and, thus, the 4.8% difference can be attributed to natural randomness.

Table 4: ANOVA results of the variations between thermal comfort and thermal acceptance

	SS	df	MS	F	P-value	$F_{criticl}$
Between groups	0.242	1	0.242	2.546	0.111	3.864
Within group	39.082	412	0.095			
Total	39.324	413				

Thermal comfort is directly influenced by insulation and activity levels, which affect heat exchange between people and the environment [12]. During the survey, the participants did not change their clothing; instead, their adaptation depended mainly on modifying their indoor environment, especially opening the door or switching on/off AC. It should be mentioned that windows are operable in a few offices in the university. It is observed that the clothing level for female participants is slightly high with an average of 1.14 clo, which is expected considering the cultural aspects of the society. The clothing level was weakly related to the operative temperature with a correlation of -0.035. Moreover, the noticeable number of participants who did nothing to change their thermal conditions despite being uncomfortable highlights the importance of increasing the awareness of the employees regarding the role of adaptive behaviour in achieving, or at least reducing the gap towards, thermal comfort.

Comfort temperature (Tc) was calculated using Griffiths' method as presented in Table 5. Different researchers apply this method as an alternative to regression analysis, using different slopes [16]–[19]. The method is recommended in the case of small data sets [20]. As noted, applying different slopes resulted in minor changes in the calculated comfort temperatures; a similar observation was reported by [17]. According to [16], [19], [21] a 0.5 slope resulted in a more accurate prediction. To ensure consistency with these studies, a slope of 0.5 was considered when calculating comfort temperature, which was found to be 23.5 ±1.9 °C in terms of operative temperature. However, due to the physiological and psychological differences between individuals, it is difficult to find an optimal comfort temperature, which emphasises the need for personal comfort models.

Table 5: Comfort temperature calculated by Griffiths' method

Griffiths' slope	T_a, [°C]	T_g, [°C]	T_r, [°C]	T_o, [°C]
0.5	23.4 ± 1.9	23.6 ± 1.9	23.6 ± 1.9	23.5 ± 1.9
0.49	23.4 ± 1.9	23.6 ± 1.9	23.6 ± 1.9	23.5 ± 1.9
0.48	23.4 ± 2	23.6 ± 2	23.6 ± 2	23.5 ± 2
0.47	23.5 ± 2	23.6 ± 2	23.6 ± 2	23.5 ± 2
0.39	23.6 ± 2.4	23.8 ± 2.3	23.8 ± 2.3	23.7 ± 2.3
0.33	23.8 ± 2.8	24 ± 2.7	24 ± 2.7	23.9 ± 2.7
0.3	23.9 ± 3	24.1 ± 3	24.1 ± 3	24 ± 3
0.25	24.2 ± 3.6	24.3 ± 3.6	24.3 ± 3.6	24.2 ± 3.6

5. Conclusion

The thermal environment of office buildings in a hot region was systematically evaluated using subjective and objective measurements. A total of 220 employees participated and 207 questionnaires were included in the analysis. The employees' thermal votes clustered between (cool) to (slightly warm), and most of them accepted the environment and were thermally comfortable. Accordingly, the temperature of 22.8 ± 1.2°C can be considered to be a comfortable range. Moreover, the employees cluster in a range that is slightly different from the comfort range specified by the ASHRAE can be explained by the fact that people from hot regions define (neutral) to (cool) as the comfort range. Considering the adaptive behaviour, the participants did not change their clothing; rather, they adapted to the thermal conditions by changing their indoor environment, such as opening doors and switching on/off the AC. Moreover, the noticeable number of employees who did nothing to change their thermal conditions despite being uncomfortable emphasises the need to educate employees about the role of adaptive behaviour in achieving thermal comfort. The comfort temperature (Tc) was calculated as 23.5 ± 1.9 °C using Griffiths' method. In addition, the employees ranked 11 indoor factors that affect their work productivity. Among the factors, noise conditions were ranked as the most important factor followed by privacy and thermal conditions.

6. Acknowledgment

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