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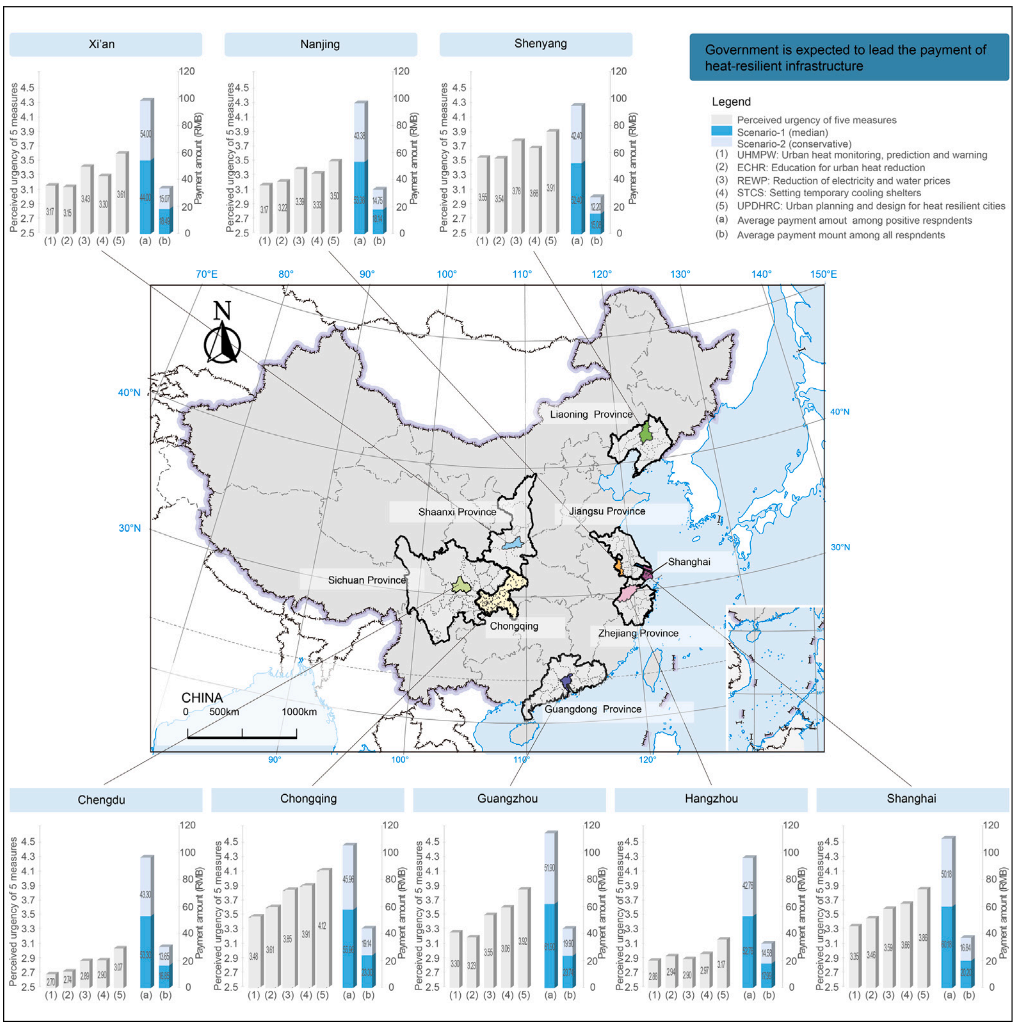
Government is expected to lead the payment of heat-resilient infrastructure



Bao-Jie He, Mingqiang Yin

baojie.unsw@gmail.com

Highlights

Actions to address heat-related challenges were moderately urgent

Development of mitigation and adaptation infrastructure was the most urgent

Shenyang respondents strongly expected the government to pay

Respondents from Guangzhou, Chongqing, and Shanghai paid the most

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Government is expected to lead the payment of heat-resilient infrastructure

Bao-Jie He[1,2,3,4,5,6,*] and Mingqiang Yin[1,2]

SUMMARY

Urban heat is severe in numerous cities, but the urgency of heat action and support for the development of heat-resilient infrastructure is unclear. To address these research gaps, this study investigated the perceived urgency of developing heat-resilient infrastructure and associated payment issues in eight megacities, in China using a questionnaire survey of 3758 respondents in August 2020. Overall, the respondents thought it was moderately urgent to take actions to address heat-related challenges. The development of mitigation and adaptation infrastructure is urgent. About 86.4% of the 3758 respondents expected the government to be involved in paying for heat-resilient infrastructure, but 41.2% supported cost-sharing among the government, developers, and owners. There were 1299 respondents willing to pay, resulting in an average annual payment of 44.06 RMB in a conservative scenario. This study is important for decision-makers to formulate plans on heat-resilient infrastructure and to release financial strategies for collecting investments and funds.

INTRODUCTION

Cities are experiencing many challenges, such as climate change, environmental deterioration, urbanization, population growth, economic development, and pandemics. Improving resilience to such challenges is a key approach to sustainable urban development. Cities have paid the most attention to building resilience to COVID-19 in the past three years,[1] while the arrival of the post-COVID-19 era offers opportunities to address many other challenges.[2] Many cities face urban heat challenges which have been recognized as one of the deadliest weather-related disasters.[3,4] Under extreme heat conditions, heat stress can easily exceed the threshold that people's bodies can withstand, leading to an increase in morbidity (e.g., dehydration, heat cramps, heat exhaustion, heat stroke)[5–7] and mortality (i.e., related to cardiovascular, cerebrovascular, and respiratory diseases).[8,9] The most notorious case was the European heatwave of 2003 which killed more than 70,000 people.[10] In addition, more than 2500 additional people in England lost their lives during the summer extreme heat period in 2020.[11] The heatwave from late June to mid-July 2021 caused approximately 660 Canadian deaths and 569 deaths in BC, Canada.[12] Given the nexuses of heat waves, urbanization, population growth, population aging, and rising baseline mortality, China has been undergoing a rapid increase in heat-induced human deaths since the 1980s, from 3,679 deaths per year in the 1980s to 15,500 deaths per year in the 2010s[13]

There is an urgent need to overcome urban heat challenges to mitigate urban heat problems on the one hand and reduce heat-induced impacts on the other. Many studies have explored urban heat problems in terms of heat-related heat impact assessment (e.g., morbidity and mortality),[8,9] environmental impact assessment (e.g., air pollution, energy, and water consumption),[14,15] development and implementation of cooling techniques and strategies,[16–19] development of decision-support tools,[20,21] and analysis of co-benefits, trade-offs, and unintended consequences.[22,23] However, there is a large gap between actual actions to address urban heat challenges and scientific studies.[24–26] This gap constrains the progress of urban heat mitigation and heat-induced impact reduction. Actual actions should be shared among civil society (e.g., national, state, and local governments; urban planners and designers; architects; engineers; enterprise managers; community managers; and citizens),[27–30] in addition to climate, epidemic, and medical scientists.[8,9]

One of the challenges relevant to collaborative actions is that few studies have explored the extent to which people can provide economic and social support and the associated factors that can affect people's

[1]Centre for Climate-Resilient and Low-Carbon Cities, School of Architecture and Urban Planning, Chongqing University, Shapingba, Chongqing 400045, China

[2]Institute for Smart City of Chongqing University in Liyang, Chongqing University, Liyang 213300, Jiangsu, China

[3]Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing 400045, China

[4]State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, Guangdong 510640, China

[5]Network for Education and Research on Peace and Sustainability (NERPS), Hiroshima University, Hiroshima 739-8530, Japan

[6]Lead contact

*Correspondence: baojie.unsw@gmail.com

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interests and behaviors. Borzino et al.[31] investigated people's willingness to pay for UHI mitigation in Singapore. Their results showed that the annual payment amount could account for 0.43% of Singaporeans' income, equivalent to $ 783.08 million SGD each year, and there could be some differences in the payment amount among residential and commercial precincts.[32] Zhang et al.[33] investigated people's willingness to pay for UHI mitigation via a green roof strategy in Beijing, China, and found that the average annual household payment was about 148.582 RMB. He et al.[25] investigated perceived urgency of the development of urban heat mitigation and adaptation strategies and public willingness to pay in Chongqing, China, indicating that the most urgent action should be urban planning and design for heat-resilient cities, followed by the establishment of temporary cooling facilities, with the payment amount of 19.10 RMB annually. Such studies have further revealed that people's willingness to pay can be affected by various factors, such as gender, education, income, health, living conditions, age, and occupation.[25,31,33] However, the regional influence, which could be associated with the severity of urban heat challenges, on the priorities of urban heat mitigation and adaptation techniques and strategies and the variability of people's economic and social support with regions have not been well revealed.

Therefore, this study aims to analyze the urgency of urban heat actions and people's support for heat-resilient infrastructure in different regions. In particular, a questionnaire survey was conducted in eight megacities in China to investigate people's perceived urgency of developing urban heat mitigation and adaptation techniques and strategies and the issues of payment for implementing them in cities and communities. The originalities of this article include an identification of the urgency of urban heat mitigation and adaptation techniques, an analysis of people's preferred payment patterns for collecting economic support, and an understanding of associated regional variability. Building upon the original findings, this study is important for decision-makers to formulate regional policies and plans on heat-resilient infrastructure implementation and to formulate financial strategies for collecting investments and funds.

RESULTS

Perceived urgency of developing heat-resilient infrastructure

Figure 1 shows the perceived urgency of developing structural and non-structural measures for sound heat-resilient infrastructure in eight megacities in China (3758 samples). The results showed that there were three tiers with perceived urgency. The first tier of the urgency is on structural measures in "mitigation" (average score:3.63) and "adaptation" (average score:3.42) which are related to the alleviation of heat-related impacts from the root and the immediate reduction and avoidance of heat-related risks and vulnerabilities. In particular, 61.4% of respondents thought it was urgent or very urgent to conduct urban planning and design for heat-resilient cities. About 53.1% of the respondents thought that temporary cooling shelters should be urgently developed. There was no statistically significant difference between the "mitigation" and "adaptation" measures.

The second tier of urgency is on non-structural measures in aspects of "operation & behavior" and "awareness and knowledge." The "reduction of electricity and water prices" and "education for urban heat reduction" gained average scores of 3.40 and 3.24 respectively, and no statistically significant difference was found between the two measures. About 51.6% of the respondents thought that electricity and water prices should be urgently reduced to enhance their capacity for extreme heat adaptation. About 53.3% of the respondents thought there was an urgent need to enhance education for better awareness and knowledge of addressing urban heat challenges.

The third tier is the development of an urban heat monitoring, prediction, and warning system for collecting, predicting, and disseminating extreme heat information. Nevertheless, its average score was 3.19, indicating that it was moderately urgent to develop this type of structural measure. Approximately 44.0% of the respondents suggested that urban heat monitoring, prediction, and warning systems should be urgently developed.

Payment issues on heat-resilient infrastructure

Figure 2 presents the public preferences for cost-sharing patterns, willingness to pay, and payment amount among the 3758 respondents. The results in Figure 2A indicate that 1548 respondents (41.2%) suggested that the cost of heat-resilient infrastructure should be shared by the government, developers, and owners. Following this, 27.8% of the respondents thought that the payment should be fully covered by the government, and 17.5% expressed the involvement of developers in sharing costs with the government. Only 7.1%

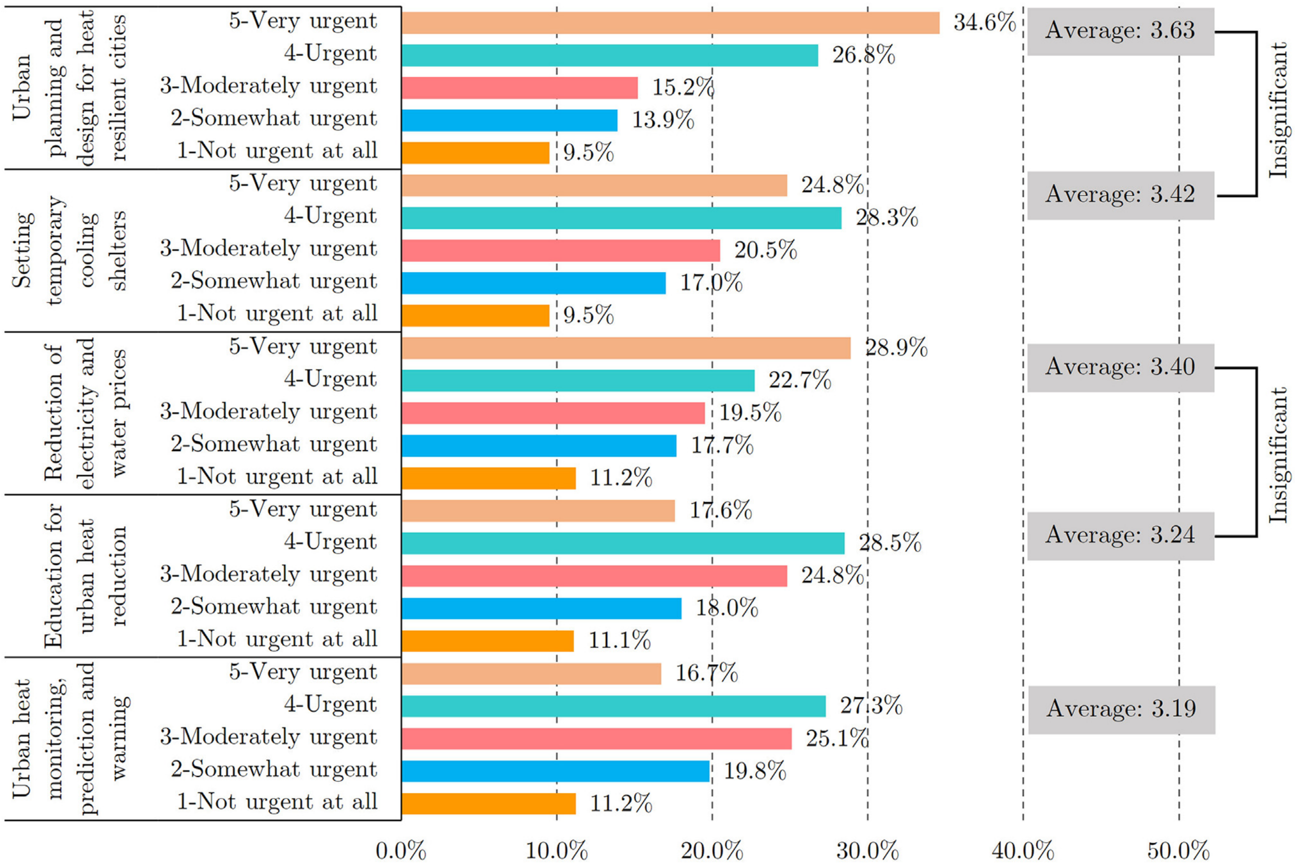

Figure 1. Perceived urgency of developing heat-resilient infrastructure

The urgency of urban heat monitoring, prediction and warning, the urgency of education for urban heat reduction, the urgency of reduction of electricity and water prices, the urgency of setting temporary cooling shelters, and the urgency of urban planning and design for heat-resilient cities.

and 6.5% of the respondents suggested "fully paid by developers" and "others", respectively. Overall, most respondents were rational to suggest that the government should play a leading role in investing in heat-resilient infrastructure, and that both developers and owners should be supportive of cost-sharing. Compared with owners, developers should play a more important role.

Figure 2B shows the respondents' WTP for a heat-resilient infrastructure. About 1389 respondents (accounting for 37.0%) were reluctant to pay. This number was higher than the number of respondents who were willing to pay (1299, 34.6%). In addition, there were 1070 respondents (28.5%) stood in a neutral position without preference for neither willingness nor reluctance. Such results indicate that at the current stage, it is not appropriate to involve individuals in payment, and actions for improving awareness and knowledge are needed. Moreover, it should be noted that 41.2% of the respondents supported cost sharing among the government, developers, and owners (Figure 2A), generating a gap with the result that only 34.6% of the respondents were actually willing to pay (Figure 2B).

The payment amount of the 1299 respondents who were willing to pay was analyzed, as shown in Figure 2C. Overall, 434 respondents, accounting for the highest proportion (26.8%), expressed their willingness to pay more than 80 RMB annually. There were 320 respondents showing an intention of paying 20-40 RMB, accounting for 19.8%. Approximately 18.9% and 18.5% of the respondents would like to annually pay 40-60 and 60-80 RMB, respectively. In comparison, 15.8% of the respondents paid less than 20 RMB annually. In the conservative scenario, there was an average annual payment of 44.06 RMB among the 1299 respondents and 15.22 RMB among the 3758 respondents. In comparison, in the median scenario, the annual payment was estimated to be 54.04 RMB among 1299 respondents, and 18.68RMB among 3758 respondents.

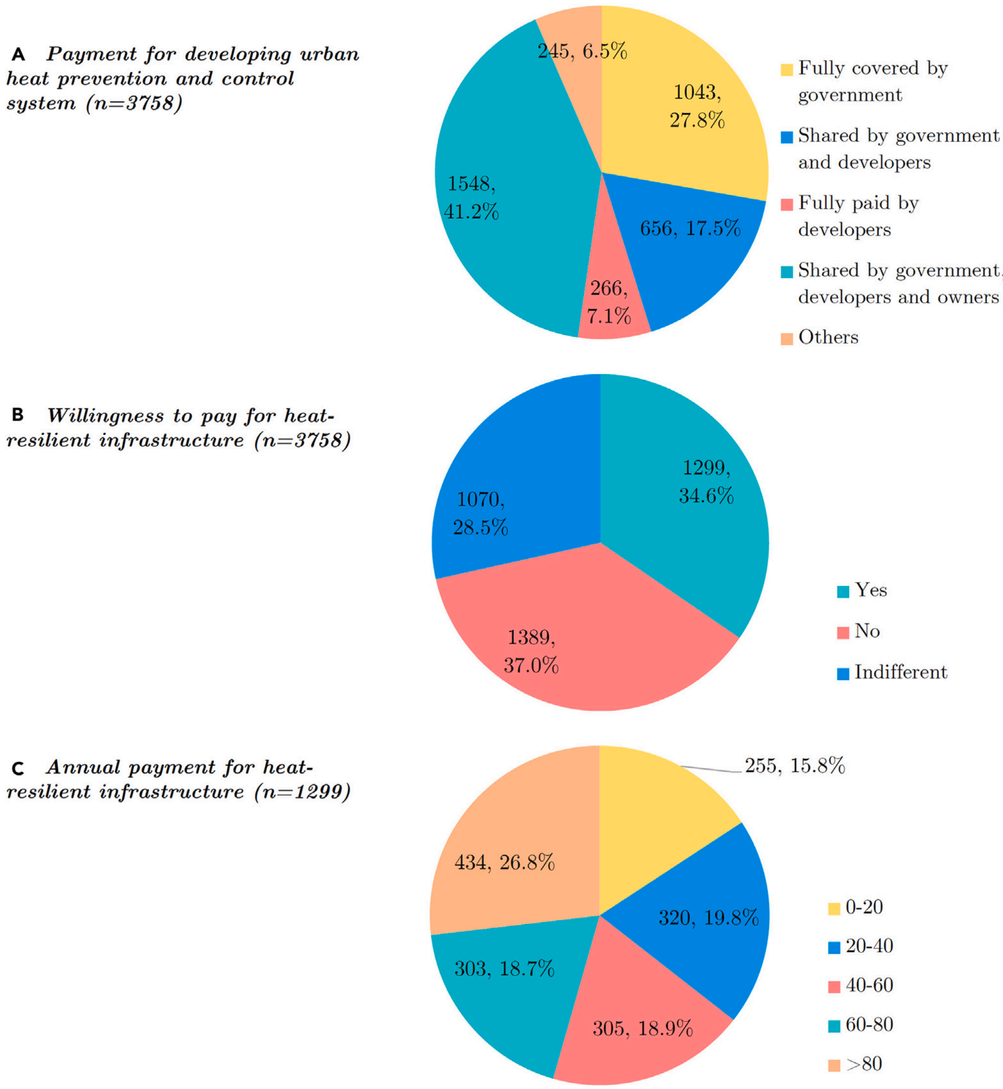

Figure 2. Payment issues of heat-resilient infrastructure among 3758 respondents

(A) Cost-sharing patterns for heat-resilient infrastructure. (B) Willingness to pay for heat-resilient infrastructure. (C) Annual payment for heat-resilient infrastructure.

Regional differences in perceived urgency of heat-resilient infrastructure

The perceived urgency of developing structural and non-structural measures was further compared. Figure 3 compares the perceived urgency of the five types of measures across megacities. For the urban heat monitoring, prediction, and warning system (Figure 3A), the urgency in Chengdu and Hangzhou was the lowest, ranking at "somewhat urgent" level with average scores of 2.70 and 2.88, respectively. This indicates that the urgency in these two cities ranked in the lowest tier. In all the other six megacities, it was moderately urgent to develop an urban heat monitoring, prediction, and warning system. Nevertheless, urgency in Shenyang was the highest (average score:3.55). This value is significantly higher than those of Chengdu (2.70), Hangzhou (2.88), and Nanjing (3.17). However, there was no significant difference among the urgency in Shenyang (3.55), Chongqing (3.48), Shanghai (3.35), and Guangzhou (3.30); therefore, the urgency in these four megacities ranked in the top tier. The urgency in Xi'an and Nanjing ranked in the middle tier, with average scores of 3.17 and 3.17, respectively. Meanwhile, the urgency in these two cities did not differ significantly from that in Shanghai (3.35) and Guangzhou (3.30).

Figure 3B shows the perceived urgency of enhancing education for urban heat reduction. The average scores of Chengdu and Hangzhou were 2.74 and 2.94, below the threshold of 3.00, indicating a "somewhat urgent"

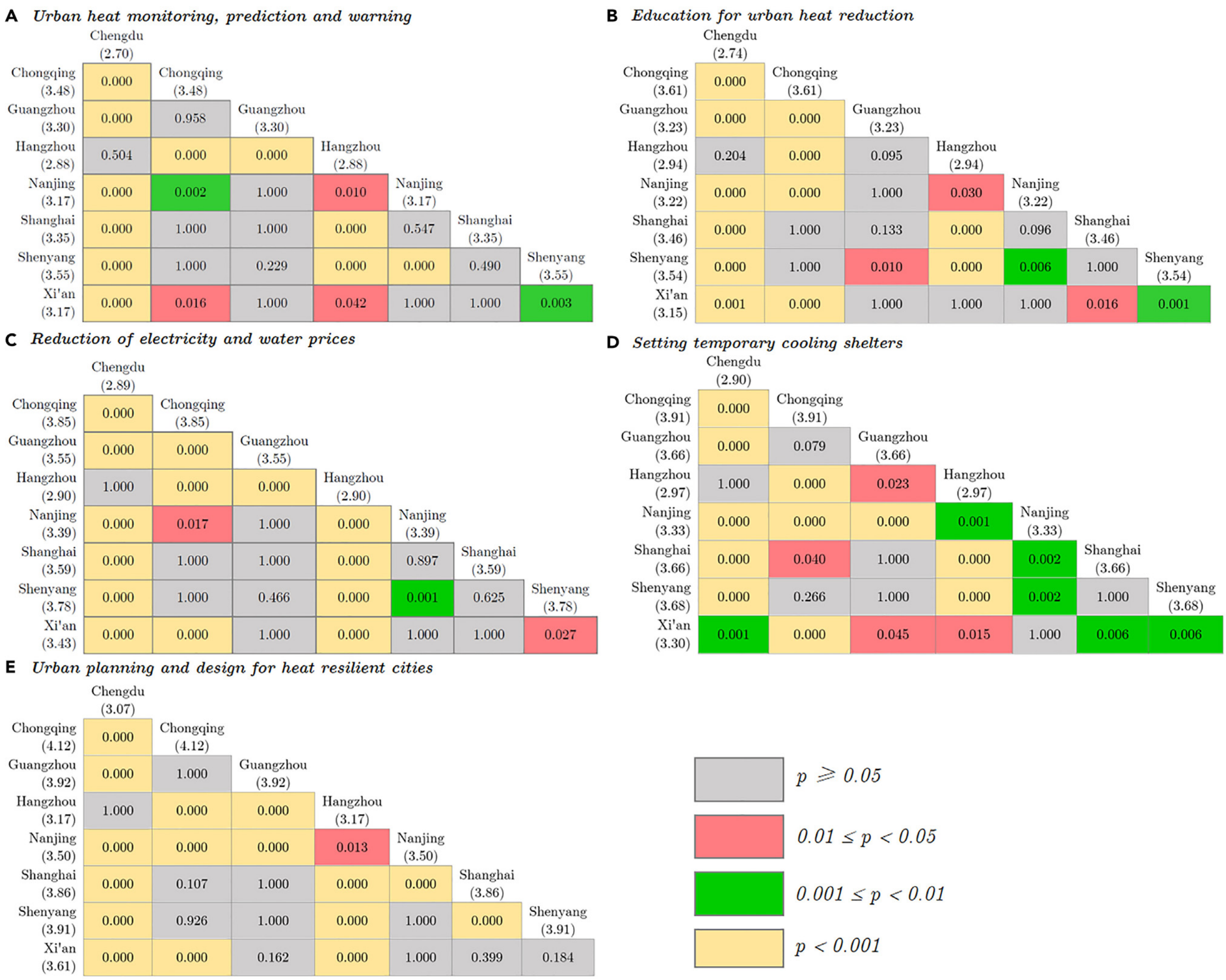

Figure 3. A comparison of the perceived urgency of heat-resilient infrastructures in eight megacities

(Note: The p-value is presented to show the significance of difference of the perceived urgency of five measures among eight cities). (A) Urban heat monitoring, prediction and warning. (B) education for urban heat reduction. (C) Reduction of electricity and water prices. (D) Setting temporary cooling shelters. (E) Urban planning and design for heat-resilient cities.

condition. Meanwhile, this suggests that perceived urgency in Chengdu and Hangzhou ranked in the lowest tier. In comparison, in all other megacities, the average scores were above 3.00, indicating "moderately urgent" conditions. Chongqing gained the highest score of 3.61, followed by Shenyang (3.54), and Shanghai (3.46). There was no statistically significant difference among the perceived urgencies in Chongqing, Shenyang, and Shanghai, suggesting that the perceived urgency of education for urban heat reduction fell into the first tier. The average scores for Guangzhou, Nanjing, and Xi'an are 3.23, 3.22, and 3.15, respectively. These scores also exhibited significant differences from Chongqing and Shenyang, suggesting that perceived urgency in Guangzhou, Nanjing, and Xi'an ranked in the middle tier.

Figure 3C shows the perceived urgency of reducing electricity and water prices from suppliers. Chengdu and Hangzhou gained average scores of 2.89 and 2.90, indicating a "somewhat urgent" situation and ranking at the lowest tier. In all other six megacities, it was "moderately urgent" to reduce electricity and water prices. Chongqing gained the highest average score of 3.85, ranking in the top tier, followed by Shenyang (3.78) and Shanghai (3.59). Guangzhou (3.55), Xi'an (3.43), and Nanjing (3.39) ranked in the middle tier. Regarding temporary cooling shelters (Figure 3D), both Chengdu and Hangzhou gained the lowest average scores of 2.90 and 2.97, indicating a "somewhat urgent" situation and ranking in the lowest tier. Chongqing gained the highest average score of 3.91, ranking in the top tier, followed

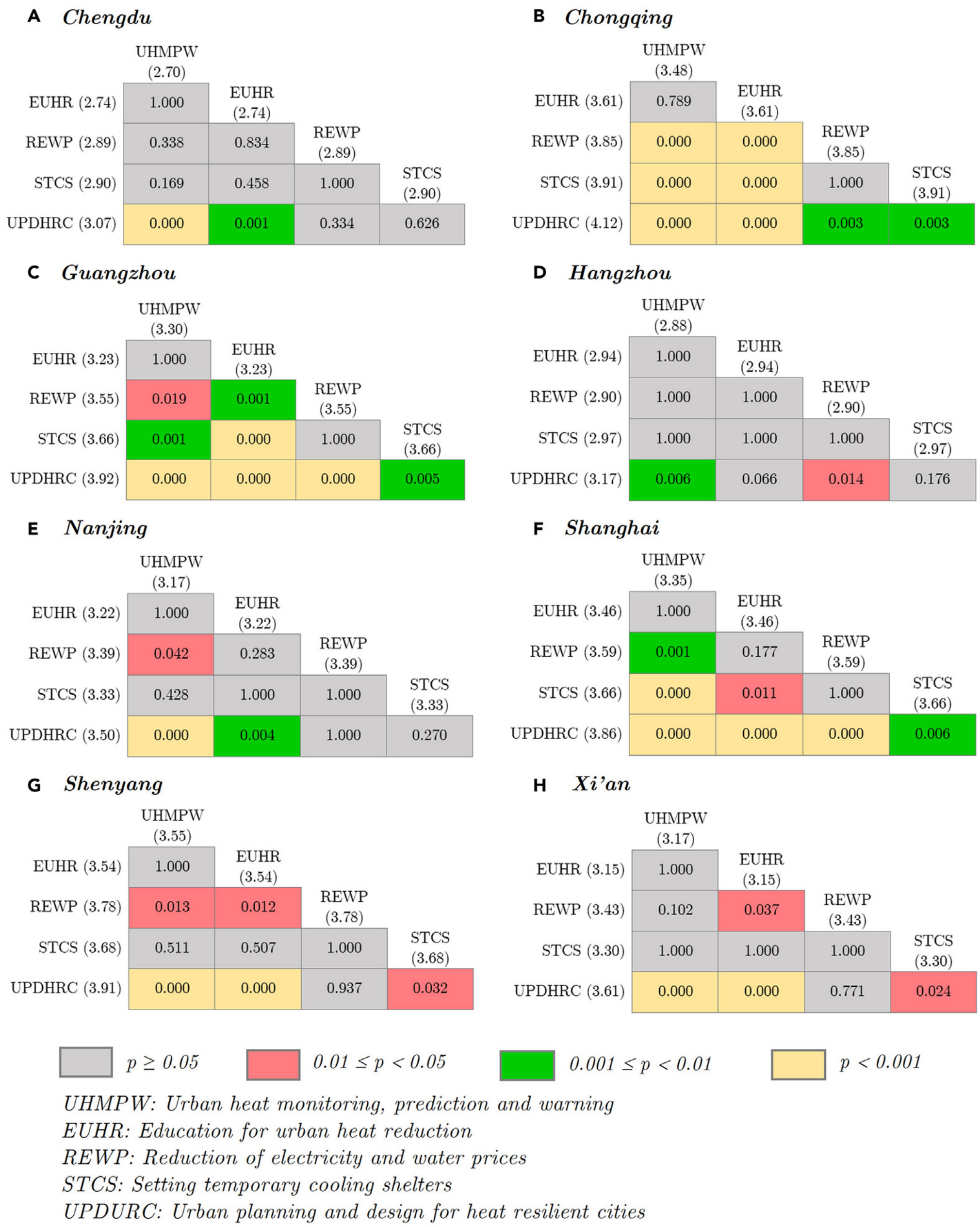

Figure 4. A comparison of the perceived urgency of five measures in eight megacities

(Note: The p-value is presented to show the significance of difference of the perceived urgency of structural or non-structural measures in specific cities). (A) Chengdu. (B) Chongqing. (C) Guangzhou. (D) Hangzhou. (E) Nanjing. (F) Shanghai. (G) Shenyang. (H) Xi'an.

by Shenyang (3.68) and Guangzhou (3.66). Shanghai (3.66), Nanjing (3.33), and Xi'an (3.30) fell into the middle tier. For the urban planning and design for heat-resilient cities, it was "moderately urgent" for all cities, and even "urgent" in Chongqing (4.12). Chongqing, Shenyang, and Shanghai ranked in the top tier, with average scores of 4.12, 3.91, and 3.86, respectively. Guangzhou (3.92), Xi'an (3.61), and Nanjing (3.50) ranked in the middle tier, while Chengdu (3.07) and Hangzhou (3.17) fell into the lowest tier.

Figure 4 compares the perceived urgency of different measures for each megacity. In general, the perceived urgency in each megacity was consistent with the overall sample of the eight megacities

Table 1. Regional variability of payment pattern among eight megacities

	Fully covered by government		Shared by government and developers		Fully paid by developers		Shared by government, developers and owners		Others	
Cities	Count	AR	Count	AR	Count	AR	Count	AR	Count	AR
Chengdu	165	0.6	92	−1.0	66	4.5	196	−3.7	55	3.2
Chongqing	137	−1.9	98	0.0	24	−2.8	281	4.6	22	−2.7
Guangzhou	99	0.2	72	1.6	11	−3.0	149	0.5	21	−0.4
Hangzhou	119	−2.9	107	1.8	58	3.8	208	−0.9	36	0.3
Nanjing	109	−2.0	87	1.0	28	−0.8	202	1.4	30	0.1
Shanghai	155	−0.7	107	0.6	29	−2.2	271	2.8	22	−2.9
Shenyang	188	8.7	40	−4.4	27	−0.4	126	−4.6	29	0.5
Xi'an	71	−1.4	53	0.3	23	0.6	115	−0.7	30	2.7

Pearson Chi-Square: 187.53 [a], p = 0.000.
a: 0 cells (0.0%) have expected count less than 5. The minimum expected count is 19.04.

(Figure 1). Both "urban planning and design for heat-resilient cities" and "setting temporary cooling shelters," the "mitigation" and "adaptation" structural measures, was thought of the most urgent among all eight cities except for Nanjing, Shenyang, and Xi'an. The "reduction of electricity and water prices" ranked third in value in all eight cities, except for Hangzhou, Nanjing, Shenyang, and Xi'an. In addition, urban heat monitoring, prediction and warning, and education on urban heat reduction are the least urgent. The case in Nanjing Shenyang, and Xi'an was that "urban planning and design for heat-resilient cities" was the most urgent, followed by the "reduction of electricity and water prices" and then "setting temporary cooling shelters." In Hangzhou, the "education for urban heat reduction" ranked third, while the "reduction of electricity and water prices" ranked fourth.

Regional differences in payment patterns in eight megacities

Regional variability in preference for payment patterns was further analyzed. The results in Table 1 indicate that there were significant differences among the respondents' preferred payment patterns from the eight megacities. For instance, respondents from Chengdu had a strong preference for "fully paid by developers" (AR = 4.5) and they strongly expected "other" payment patterns (AR = 3.2). In comparison, they did not support the cost-sharing pattern with the inclusion of the government, developers, and owners (AR = −3.7). On the contrary, respondents from Chongqing expressed a strong preference for cost-sharing patterns among the government, developers, and owners, which could include the public for payment (AR = 4.6). Meanwhile, they resisted the pattern of "fully paid by developers" (AR = −2.8) and "Others" (AR = −2.7). In Guangzhou, while it was difficult to assert their support for the cost-sharing pattern, the respondents excluded payments merely from developers (AR = −3.0).

Respondents from Hangzhou gave the priority to "fully paid by developers" (AR = 3.8), while they did not support the payment totally covered by the government (AR = −2.9). In Nanjing, the respondents disagreed with the government's responsibility for payment (AR = −2.0), but the results did not show their appreciated payment. The preferred payment pattern in Shanghai was akin to the one in Chongqing that people supported the cost-sharing pattern among government, developers, and owners (AR = 2.8), but they disagreed with the pattern of "fully paid by developers" (AR = −2.2) and "others" (AR = −2.9). In Shenyang, respondents suggested that the payment should be the business of the government (AR = 8.7), and they strongly disagreed with the cost-sharing pattern among either "government and developers" (AR = −4.4) or "government, developers and owners" (AR = −4.6).

Regional differences in willingness to pay for heat-resilient infrastructure

Table 2 compares the public willingness to pay for heat-resilient infrastructure among the eight megacities. The results indicate that the respondents from Chongqing were more active in paying (AR = 3.8), and they did not hesitate to make the decision (Indifferent: AR = −4.4). In Nanjing, respondents were not reluctant

Table 2. A comparison of respondents' willingness to pay for heat-resilient infrastructure in eight megacities

	Yes		No		Indifferent	
Cities	Count	AR	Count	AR	Count	AR
Chengdu	181	−1.7	220	0.7	173	1.0
Chongqing	234	3.8	211	0.3	117	−4.4
Guangzhou	135	1.6	121	−1.1	96	−0.5
Hangzhou	180	−0.2	183	−1.2	165	1.5
Nanjing	155	−0.3	137	−3.3	164	3.8
Shanghai	196	−0.6	222	0.6	166	0.0
Shenyang	118	−2.6	192	4.4	100	−1.9
Xi'an	100	−0.1	103	−0.6	89	0.8

Pearson Chi-Square: 59.72 [a], $p = 0.000$.
a: 0 cells (0.0%) have expected count less than 5. The minimum expected count is 83.14.

to pay (AR = −3.3), but this did not mean that they were supportive of the payment (AR = −0.3). The respondents from Nanjing were indifferent to payment (AR = 3.8). In comparison, respondents from Shenyang were reluctant to pay (AR = 4.4) and clearly stated their disagreement with the payment (AR = −2.6). In other cities, the respondents' preferences were not statistically significant. Table 3 further analyzes the variability of payment amounts among the eight megacities once the respondents would like to pay. Overall, there was no statistically significant difference among the payment structures ($\chi^2 = 31.713$, p = 0.286). Nevertheless, respondents in Guangzhou and Shanghai were positively willing to pay more than 80 RMB annually (AR = 2.4). In comparison, the respondents from Shenyang could not support a payment of 60-80 RMB annually (AR = −2.4).

Figure 5 presents the annual payment amount for each megacity in both the conservative and median scenarios. According to Figure 5A, the positive respondents in Guangzhou could pay the most, approximately 51.90 (61.90) RMB in the conservative (median) scenario. The payment amount in Shanghai ranked second, about 50.18 (60.18) RMB. Chongqing respondents could pay 45.96 (55.96) RMB. In comparison, the respondents from Shenyang paid the least, approximately 42.40 (52.40) RMB in the conservative (median) scenario. The respondents from Hangzhou and Chengdu paid the second and third least, at about 42.76 (52.76) RMB and 43.30 (53.50) RMB, respectively. With the consideration of all respondents (Figure 5B), payment amounts exhibited different patterns from the consideration of only positive respondents (Figure 5A). Guangzhou respondents could pay the most, about 19.90 (23.74) RMB in the conservative (median) scenario. Next, Chongqing respondents paid 19.14 (23.30) RMB, higher than the payment amount of 16.84 (20.20) RMB among Shanghai respondents. Shenyang respondents still contributed the least, about 12.20 (15.08) RMB in the conservative (median) scenario. Different from the case of positive respondents, Chengdu and Hangzhou paid the second and third least, at about 13.65 (16.81) and 14.58 (17.99) RMB, respectively.

DISCUSSION

Heat-resilient infrastructure was framed to assist in addressing urban heat challenges. Priorities of developing heat-resilient infrastructure and public willingness to pay were further understood through a questionnaire survey in eight megacities in China. The empirical results can help understand the possible drivers of public demand and investment on the one hand, and to support evidence-based decisions and policies related to heat-resilient infrastructure implementation on the other.

Prioritized actions and efforts for heat-resilient infrastructure

The most urgent action was to implement mitigation and adaptation strategies, but the least urgent action was to develop a sound urban heat monitoring, prediction, and warning system. The reason for this may be two-fold. The first is the development and soundness of structures or facilities. Urban heat has become a critical problem with climate change and urbanization, but society has not been well prepared, without the application and construction of urban heat mitigation and adaptation techniques and facilities.[26,34,35] In comparison, weather monitoring and forecasting systems have been well developed in each city, and people can access weather information through a variety of channels, such as online inquiry, TV/Internet news, community/family dissemination, phone call/message, and radio. As a result, people believe

Table 3. A comparison of payment amount among positive respondents in eight megacities

	0–20		20–40		40–60		60–80		>80	
Cities	Count	AR	Count	AR	Count	AR	Count	AR	Count	AR
Chengdu	31	0.8	37	0.6	31	−0.2	35	0	47	−1.0
Chongqing	36	0.1	41	−0.5	39	−0.5	54	1.6	64	−0.6
Guangzhou	17	−0.9	17	−1.5	17	−1.6	17	1.2	17	2.4
Hangzhou	28	0.1	40	1.3	38	1.3	27	−1.6	47	−0.9
Nanjing	27	0.8	29	0	29	0.3	31	0.3	39	−1.1
Shanghai	23	−1.5	34	−0.6	30	−1.0	38	0.1	71	2.4
Shenyang	20	0.5	25	0.7	27	1.5	13	−2.4	33	−0.3
Xi'an	16	0.2	19	0.1	19	0.4	21	0.5	25	−0.9

Pearson Chi-Square: 31.713 [a], $p = 0.286$.
a: 0 cells (0.0%) have expected count less than 5. The minimum expected count is 15.24.

that urban heat monitoring, prediction, and warning systems should not receive the highest priorities. The second is the efficiency of addressing urban heat challenges and reducing heat-related effects. The application of urban heat mitigation and adaptation techniques and facilities can effectively alleviate and avoid heat-related impacts,[16,19,21] whereas the development of a monitoring, prediction, and warning system can only provide information. An accurate explanation of this result should be further explored through questionnaire surveys and interviews. Nevertheless, following this result, the urban planning, design, and construction sectors should focus on implementing mitigation and adaptation techniques and strategies. Efforts such as knowledge enhancement, policy and regulatory landscape, and guides and plans can be taken to promote the transformation toward urban heat mitigation and adaptation implementation.

Compared with structural measures, non-structural measures of ''education for urban heat reduction'' and ''reduction of electricity and water prices'' were more urgent than the structural measures of urban heat monitoring, prediction, and warning. On the one hand, the reduction in electricity and water prices could alleviate the electricity and water constraints, enhancing the urban heat adaptation capacity. This can help alleviate the heat vulnerability related to economic disadvantages.[8,36] On the other hand, people's demand for the reduction of electricity and water prices suggested in such megacities and the increase in electricity and water use might already form a barrier to urban heat alleviation and reduction. Education for urban heat reduction is prioritized to improve the capacity to cope with heat challenges. This might be because awareness and knowledge are useful in supporting adaptation, which can be a heat precaution strategy. Meanwhile, existing studies have indicated people had limited awareness and knowledge of heat-related risks and vulnerabilities as well as the solutions to urban heat,[34,37–39] which might be another driver to the demand for ''education for urban heat reduction.'' Overall, non-structural measures of ''awareness and knowledge'' and ''operation and behavior'' are moderately urgent; therefore, efforts are needed to achieve them. For instance, efforts such as communication with electricity and water enterprises, policy, regulation, and incentives on electricity and water supply, and smart control of electricity and water use can be conducted to support price reduction.

Perceived urgency of heat-resilient infrastructure exhibited regional variability, indicating that the priorities for developing structural and non-structural measures diversified. Within a megacity, the priorities of the five kinds of measures were generally the same, where mitigation and adaptation were the most urgent, followed by price reduction and education, and then heat monitoring, prediction, and warning, except for a few variations in Hangzhou, Nanjing, Shenyang, and Xi'an. This indicates that actions to address extreme heat challenges should be city-specific. The perceived urgency levels varied significantly among all eight megacities. In particular, the urgency levels were the highest in Chongqing, which could be attributed to extremely hot and humid weather. Following Chongqing, Shenyang also witnessed a high level of urgency, while it had a higher latitude than many other cities. This might be related to the temperature increase in China, especially the increasingly frequent extremes, making people increasingly vulnerable to heat and having a higher demand for heat-resilient infrastructure than other cities. Subsequently,

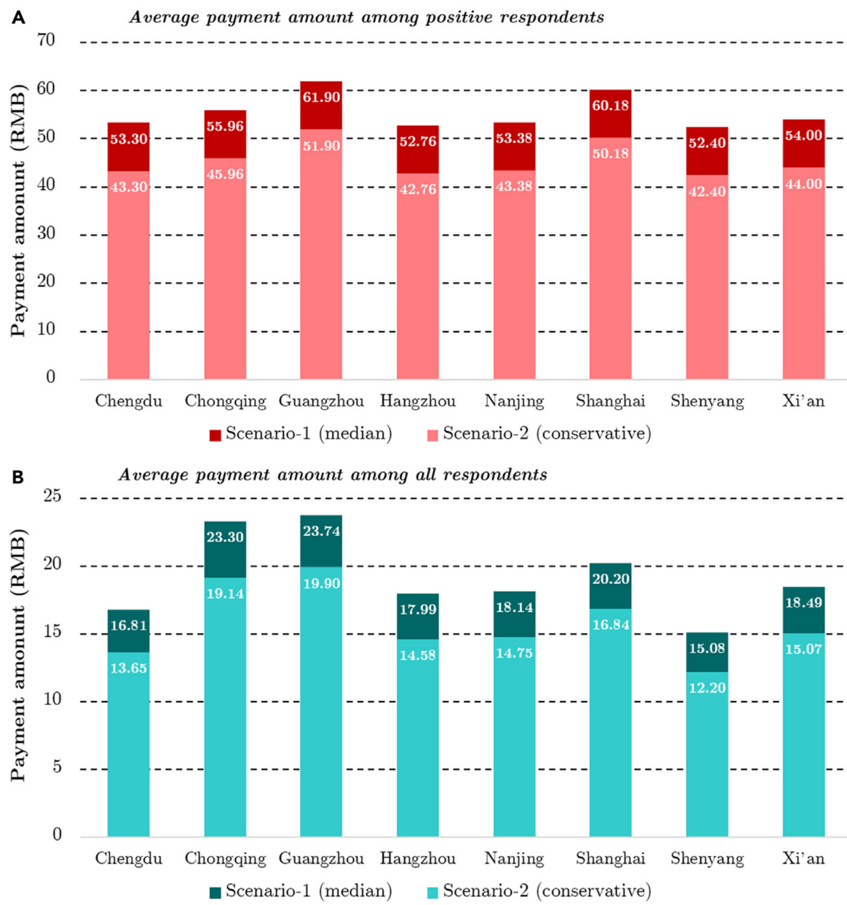

Figure 5. A comparison of the payment amount among different megacities

(A) Average payment amount among positive respondents. (B) Average payment amount among all respondents.

respondents from Shanghai, Guangzhou, and Nanjing thought that developing heat-resilient infrastructure was moderately urgent. By comparison, respondents from Chengdu suggested the least urgent situation for heat-resilient infrastructure development. Whilst Hangzhou also underwent hot-humid summers such as Shanghai and Nanjing, respondents did not think it was urgent to develop a heat-resilient infrastructure. The reasons behind this should be investigated with the consideration of adaptation strategies, awareness, and knowledge related to extreme heat and demographic characteristics (e.g., age, health, education, income, and occupation).[25,39] In addition, the different urgency levels indicated that efforts to implement heat-resilient infrastructure in different megacities can vary depending on urban contexts.

Variability of payment for heat-resilient infrastructure

Finance is an important part of non-structural measures in which public participation is significant in enabling implementation environments and fostering public and private investments. Overall, 86.4% of respondents (3758) across eight megacities indicated that the government should be involved the most in the payment. However, more than 40% of respondents suggested a cost-sharing pattern among the government, developers, and owners. Meanwhile, approximately 17.5% of the respondents suggested a sharing pattern between the government and developers. Such results showed that the respondents were rational to involve themselves in payment, but the government should play a leading role. To secure a sound economic atmosphere for heat-resilient infrastructure implementation, the government should formulate top-down financial strategies, as well as relevant policies and regulations. Thus, there could be a solid and stable environment that attracts public and private investments. Nevertheless, the requirements for governmental action and economic strategies should be tailored to each megacity. Shenyang respondents indicated that government-dependent and cost-sharing patterns were excluded. Chengdu respondents anticipated that developers who were profiters in urban development would pay for heat-resilient infrastructure. The economic burden of the Chongqing and Shanghai governments might be lower than that of other megacities because their respondents supported cost-sharing among the government, developers, and owners. This might be applicable to Nanjing, as the respondents refused the payment pattern of "fully covered by the government."

Regarding willingness to pay, only 34.6% of the respondents (3758) showed a positive attitude, while the proportion was slightly lower than that of the respondents who were reluctant to pay. Therefore, it was inappropriate to include the public in payment mandatorily. Moreover, the proportion of positive respondents (34.6%) was lower than the proportion of supporters of cost-sharing among the government, developers, and owners (41.2%). To address such a challenge, on the one hand, payment policies and regulations for heat-resilient infrastructure should be implemented in a voluntary way. On the other hand, more respondents may be interested in payment if some attractive incentives and financial strategies were implemented, since about 28.5% of the respondents were indifferent. In addition, "awareness and knowledge" and "policy and regulation" should be enhanced to inform the public of the urgency of developing heat-resilient infrastructure and the necessity of economically supporting it. However, it should be noted that the respondents' willingness to pay varied significantly across megacities. It was optimistic for Chongqing, as the respondents positively supported the payment, while it was pessimistic for Shenyang, since the respondents asserted reluctance to pay. In Nanjing, attractive incentives and financial strategies were important, as the respondents were indifferent to payment. In addition, the results indicated that Shenyang respondents ranked the development of heat-resilient infrastructure at a highly urgent level, only lower than that of Chongqing respondents. However, the Shenyang respondents did not support cost-sharing patterns, relied on government payments, and showed a strong reluctance to pay. Further investigation is needed to reveal the reasons for the conflicts between perceived urgency and payment preferences to better address this problem.

The annual payment amount among the positive respondents was analyzed. According to the conservative and median scenarios, the average payment could be 44.06 and 54.04 RMB, representing average payments of 15.22 and 18.68 RMB among all respondents. While there was no statistically significant difference in the payment composition, the payment amount was different across the eight megacities. In particular, Guangzhou respondents could pay the most for both positive respondents and all respondents, while the perceived urgency of developing heat-resilient infrastructure was not the highest (about the fourth place). This result shows a mismatch between the payment amount and the perceived urgency. Respondents from Chongqing and Shanghai, in comparison, paid the second and third most in both positive respondents and all respondents, and the perceived urgency of developing heat-resilient infrastructure in these two megacities ranked second and third. This result shows a consistent pattern between payment amount and perceived urgency. A consistent pattern was also observed in Chengdu and Shenyang. Therefore, perceived urgency could be a driver of payment, but many other factors (e.g., gender, age, income, education, and health) might also affect the payment amount.[25,40] Moreover, Hangzhou experiences hot-humid weather conditions, but the payment amount, consistent with the perceived urgency, was not high; thus, more studies are required to reveal the reasons.

Limitations of the study

Overall, this study revealed the geographic variability of the perceived urgency of constructing heat-resilient infrastructure and associated payment issues, enabling decision-makers to make scientific and proper decisions on investment. However, this study has some limitations. First, it did not investigate the associations between demographics, perceived urgency, and payment intention. The drivers and barriers behind respondents' preferences and economic decisions are still unclear, and their influence mechanisms remain an open question. Second, the survey was conducted during the COVID-19 period so that the collection of questionnaires was supported by anti-COVID-19 rules and people's reluctance to fill out the paper questionnaire. In such situations, the sample might be biased in representing the demographic structure of each megacity.

Conclusion

Urban heat challenges are increasingly severe along with climate change and urbanization. Although urban heat mitigation and adaptation techniques have been extensively studied, their application has not attracted sufficient attention. To address this gap, this study empirically investigated the perceived urgency of developing heat-resilient infrastructure and the associated payment issues in eight megacities in China. The empirical study indicated that mitigation and adaptation were the most urgent, followed by electricity and water price reduction, education for urban heat reduction, and urban heat monitoring, prediction, and warning. This original finding is important to support policymakers in formulating appropriate policies and regulations, and to guide public and private investments. Nevertheless, perceived urgency was city-specific, so relevant decisions should be tailored to each megacity. Moreover, public payments are important to enable the implementation of heat-resilient infrastructure. The payment patterns, public willingness to pay, and payment amounts were revealed, which can further support decisions on public and private investments.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106566.

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AUTHOR CONTRIBUTIONS

Bao-Jie He: conceptualization, data curation, formal analysis, funding acquisition, methodology, investigation, supervision, validation, project administration, resources, visualization, software, writing – original draft, and writing – review and editing. Mingqiang Yin: data curation, formal analysis, writing, reviewing, and editing.

DECLARATION OF INTERESTS

This article has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the article nor the study violates any of these. The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Other		
China standard map	Source: http://bzdt.ch.mnr.gov.cn/	N/A
Meteorological data	Source: rp5.ru	N/A

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Bao-Jie He (baojie.unsw@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Questionnaire design

Consistent with the framework for heat-resilient infrastructure, this study aims to understand the public demand for urban heat actions. However, a sound heat-resilient infrastructure system comprises various measures and actions, making it difficult to investigate all of these once. Five key measures to address urban heat challenges were considered to investigate the priorities and urgencies perceived by the public. The first is on urban heat monitoring, prediction, and warning that combines monitoring and warning measures in structural measures, aiming to understand the urgency of providing the public with real-time heat-related data and information through data collection, prediction, and dissemination. The second is education for urban heat reduction, corresponding to awareness and knowledge of non-structural measures, in order to understand the urgency of raising people's awareness and knowledge of heat-related risks, vulnerabilities, and solutions. The third is the reduction of electricity and water prices, corresponding to the "operation and behavior" of non-structural measures, to understand the urgency of allowing people to operate air-conditioning facilities and water-cooling strategies. The fourth is setting temporary cooling shelters, related to the adaptation of structural measures, to understand the urgency of improving the availability of immediate heat impact reduction facilities. The fifth is about urban planning and design for heat-resilient cities, related to the mitigation of structural measures, to understand the urgency of applying heat mitigation techniques and technologies in urban planning and design to address urban heat challenges fundamentally.

Finance is of importance to monetarism and enables heat-resilient infrastructure implementation in cities and communities, and it has been regarded as an important strategy in non-structural measures. Therefore, the payment issue for heat-resilient infrastructure is analyzed in three aspects. The first is to understand people's preference for cost-sharing pattern, with five possible options, including "fully covered by the government", "shared by the government and developers", "fully paid by developers", "shared by the government, developers and owners" and "others". The second is to investigate whether people are willing to pay using three options: "yes", "no", and "indifferent", if private investment or support is needed. Following a positive answer of "yes" in the second question, the third is to investigate how much they could pay each year for heat-resilient infrastructure by five levels of "<20", "20–40", "40–60", "60–80" and ">80" RMB. Furthermore, according to the contingent valuation method, the average payment among the public is estimated based on the conservative (minimum payments of 0, 20, 40, 60, and 80 RMB) and median (median payments of 10, 30, 50, 70, and 90 RMB) scenarios. Basic demographic information such as gender, age, education, monthly income, and health conditions were considered in the questionnaire. Moreover, there is a pre-question: 'Are you currently working, living, or studying in the city of ***? ' to ensure the respondents have been in the city where the questionnaire survey will be conducted. The questionnaire contents are presented in Table S2.

Questionnaire survey

The questionnaire survey was conducted in August 2020, which was the second hottest month following July (except for Chongqing). Figure S2 presents the temperature and humidity information for the eight megacities, indicating harsh urban heat challenges. In Hangzhou, Nanjing, and Shanghai, there were 30 days with a daily high temperature of 30°C, among which there were 24, 18, and 23 days with daily high temperatures of 35°C, respectively. Notably, a daily minimum temperature of 25°C is an upper threshold for people to recover from extreme daytime heat stresses. However, in these three cities, the daily minimum temperature was above 25°C for 30 days, 29 days, and 30 days. Guangzhou was also challenged by urban heat, with 29 days having a daily high temperature of 30°C and 12 days having a daily high temperature of 35°C. Moreover, the daily minimum temperatures for all 31 days in August 2020 exceeded 25°C. In comparison, the heat challenge was weaker in Chongqing and Chengdu, but there were still 17 and 16 days, respectively, with daily high temperatures of 30°C. Both cities had nine days with daily high temperatures of 35°C, and the recovery from extreme heat was compromised for eight and seven days, respectively. Shenyang and Xi'an are two cities with higher latitudes compared with all the other six cities, so urban heat challenges were the weakest among them. After 15 days, the daily high temperatures of Shenyang and Xi'an were higher than 30°C, but consistently below 35°C. In only two days, Xi'an experienced a daily minimum temperature above 25°C. In addition, the humidity in these cities was also high, making the thermal environment much worse. For instance, the monthly average relative humidity in Chengdu, Chongqing, Shenyang, and Xi'an was above 80%, and those in Shanghai and Nanjing were approximately 71% and 75%, respectively. The monthly average relative humidities in Guangzhou and Hangzhou were 69% and 68%, respectively.

The questionnaire was conducted using a combination of paper, QR codes, and an online survey, depending on the option of potential respondents, because of the COVID-19 restrictions in places. A total of 3758 valid questionnaires were collected from these eight cities, with 574, 562, 352, 528, 456, 584, 410, and 292 questionnaires from Chengdu, Chongqing, Guangzhou, Hangzhou, Nanjing, Shanghai, Shenyang, and Xi'an, respectively. Detailed demographic information on the respondents is presented in Table S3.

Statistical analysis

The original results of the perceived urgency of taking urban heat actions, preferred cost-sharing patterns, public willingness to pay, and payment amount among the 3758 respondents were first described. The Kruskal-Wallis H test is one of the main techniques used in non-parametric analysis to examine the significance of differences between continuous and categorical variables if the dataset does not follow a normal distribution. In this study, an examination of the survey samples indicated that the original data did not follow a normal distribution; therefore, the Kruskal-Wallis H test was conducted. In particular, the Kruskal-Wallis H test was performed to distinguish the perceived urgency of five aspects, including urban heat monitoring, prediction, and warning, education for urban heat reduction, reduction of electricity and water prices, setting temporary cooling shelters, and urban planning and design for heat-resilient cities among the 3758 samples. The Kruskal-Wallis H test was conducted to analyze whether there was a difference among the perceived urgencies of a specific action within the eight megacities. In a specific city, the Kruskal-Wallis H test was performed to examine the differences in perceived urgencies of the five kinds of actions. Regarding payment issues, Pearson's Chi-square tests were carried out to examine if there was a statistically significant difference among the five kinds of cost-sharing patterns, three options on willingness to pay, and five levels of payment amount. Adjusted residual (AR) was adopted as an indicator to assess whether a group was significantly outstanding, with a threshold of 1.96 at a confidence interval of 95%.