Health and Quality of Life Outcomes

https://doi.org/10.1186/s12955-026-02521-z

Article in Press

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Received: 30 October 2025

Accepted: 14 March 2026

Published online: 06 April 2026

Cite this article as: Liao M., Rencz F., Yang Z. *et al.* Validity and responsiveness of the EQ-5D-5L, EQ-HWB and EQ-HWB-9 to measure health and wellbeing impact of heatwaves among older adults. *Health Qual Life Outcomes* (2026). https://doi.org/10.1186/s12955-026-02521-z

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Validity and responsiveness of the EQ-5D-5L, EQ-HWB and EQ-HWB-9 to measure health and wellbeing impact of heatwaves among older adults

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Abstract

Background

The health impact of heatwaves is usually assessed using mortality, morbidity and healthcare service utilization. This study explored the feasibility of using subjective measures to capture and quantify the impact of heatwaves on the health and wellbeing of older adults.

Methods

A cohort of residents aged ≥ 60 living in Fuzhou city, China, were surveyed four times: before summer in May, during heatwaves in June to July and August, and after summer in October, 2023. At all timepoints, the EQ-5D-5L, experimental EQ-HWB and self-designed questions assessing self-perceived effects of heatwaves were administered through one-on-one, face-to-face interviews. We examined the known-group validity (using Cohen's d effect sizes) and responsiveness (using standardized response mean [SRM]) of EQ-5D-5L, EQ-HWB and EQ-HWB-9 (including index values and level sum scores [LSSs]).

Results

The responses of 579, 510, 473 and 508 residents were analysed in the four waves of survey, respectively. The ceiling for EQ-5D-5L items ranged from 58.2% (*pain/discomfort*) to 94.3% (*self-care*), while for EQ-HWB items, it ranged from 32.3% (*accepted*) to 94.0% (*personal care*). The EQ-5D-5L and EQ-HWB-9 index values, and EQ-HWB LSSs demonstrated discriminative ability in distinguishing between different groups based on the self-perceived impact of heatwaves, with most of the effect sizes being small (Cohen's d: 0.04-0.31 for EQ-5D-5L; 0.16-0.34 for EQ-HWB-9; 0.28-0.45 for EQ-HWB). We found negligible responsiveness to improvements in self-perceived effects of heat (SRM: 0.07 to 0.18). Unexpectedly, improved health and

wellbeing were observed during the first heatwave compared to pre-heatwave.

Conclusion

The EQ-5D-5L, EQ-HWB and EQ-HWB-9 demonstrated satisfactory known-groups validity but limited responsiveness in measuring the health and wellbeing impact of heatwaves among Chinese older adults. Future research is recommended to further evaluate these measures as well as other outcomes measures for the purpose of quantifying the health and wellbeing impacts of heatwaves and other climate events.

Keywords

heatwave, health, wellbeing, EQ-5D-5L, EQ-HWB, EQ-HWB-9, psychometric assessment, older adult

1. Introduction

Heatwaves, or periods of excessively hot weather, are getting frequent and intense worldwide, which is considered to be related to climate change (1). In 2022, heatwaves affected millions of people in Asia, America, Europe, North Africa, and Oceania (2). In addition to threatening food production and economies, heatwaves have profound impact on people's health, particularly the health of vulnerable populations (3). For example, in 2022, there were an estimated 50,900 heatwave-related deaths in China, with 78% occurring among individuals aged 65 and above, underscoring the heightened impact of heatwave on older adults (4). Heatwaves are also associated with increased hospital admissions and emergency department visits (5) and heightened workplace injuries (6).

To date, research on the health impact of heatwaves has been focused on health outcomes that can only be objectively measured. The focal points of studies involving working populations exposed to high environment temperature have been injuries, disabilities, productivity loss, and their social and economic consequences (7).

Research on vulnerable populations such as the elderly mainly quantified the impact of high temperature in terms of mortality and morbidity. The effects of heatwave exposure on people's functioning and wellbeing, or health-related quality of life (HRQoL), have not been studied. Given that millions of people around the world are exposed to heatwaves every year, the loss in HRQoL due to heatwaves could be tremendous. Without factoring in this humanistic health burden, the true health impact of heatwaves and the effectivensss of interventions mitigating this impact could be significantly underestimated. Such underestimations could subsequently misinform policies and decision making in the fight against climate change. Therefore, there is a need to fill this knowledge gap in climate change research.

There is currently no well-established theoretical framework for conceptualising health and wellbeing in the context of heatwave research. Nevertheless, existing evidence suggests that exposure to extreme heat and heatwaves affects health and wellbeing through multiple interrelated physiological, psychological, and behavioural pathways. During heat extremes, the body's thermoregulatory capacity is challenged, increasing the risk of heat-related illness and exacerbating pre-existing conditions through mechanisms such as thermal stress, dehydration, and haemodynamic strain (8). These physiological responses may manifest as physical discomfort, fatigue, reduced appetite, difficulty breathing and reduced functional capacity (9), as well as other direct physical symptoms such as skin irritation and rashes (10) and heat- or UV-related visual disturbances (11). Heat exposure is also consistently associated with disturbances in sleep quality and duration (12, 13), which can impair cognitive performance, emotional regulation, and overall wellbeing. In addition, existing evidence indicates that elevated ambient temperatures and heatwave events are associated with poor mental health, such as increased risks of depression, mania, and

suicide (14-16). Emerging evidence further suggests that extreme heat may adversely affect cognitive functioning and social participation, as individuals adapt their daily routines and reduce outdoor or social activities to cope with heat stress (17, 18). Collectively, these pathways provide a conceptual basis for how heatwave may influence multiple dimensions of health and wellbeing.

The EQ-5D (19) is a well accepted generic preference-based HRQoL measure for quantifying the effects of health conditions and health technologies such as vaccines, drug therapy, medical devices, and clinical procedures. Although the EQ-5D is primarily used in clinical research, economic evaluations and population health surveys (20), it has also been used to measure the health impact of disasters and changed environment (14, 21-23), with some promising evidence supporting its usefulness. For example, in a longitudinal study, EQ-5D was shown to capture the health impact of armed conflicts in Colombia (23). In a retrospective study of typhoon survivors, the EQ visual analogue scale (VAS) score was higher among those assigned a volunteer worker but lower among those who lost a family member (21). These studies suggest that the EQ-5D can be useful in studying health hazards beyond diseases.

It is unknown whether EQ-5D is able to capture the adverse impact of extreme weather events, such as heatwaves, as the content of the EQ-5D descriptive system—covering mobility, self-care, usual activities, pain/discomfort, and anxiety/depression—does not provide a clear indication. On one hand, the pain/discomfort, usual activities, and anxiety/depression items may be useful since heatwaves may cause physical discomfort (8), work productivity loss (8), and mental health problems (14, 16). On the other hand, the EQ-5D lacks items that directly capture the impact of

heatwaves on other health dimensions such as sleep (12, 13), cognition (17), and social activities (18). Recent research has explored the development of a culturally relevant climate adaptation item as a supplementary item (i.e. bolt-on) for the EQ-5D-5L in the Chinese population (24, 25). The newly developed measures for health and wellbeing, EuroQol Health and Wellbeing instrument (EQ-HWB) and its shorter version, EQ-HWB-9 (26), may also be useful for assessing the diverse impacts of extreme weather events. The EQ-HWB assesses health and wellbeing across seven domains: activity, autonomy, cognition, feelings and emotions, relationships, physical sensations, and self-identity, while the EQ-HWB-9 covers six domains, excluding self-identity. The EQ-HWB and EQ-HWB-9 have been developed for the assessment of health and wellbeing in populations such as, long-term patients, social care users and carers, particularly in contexts where cross-sectorial decision making may be relevant. However, there is a lack of evidence regarding their application in heatwave research.

This study aimed to evaluate the measurement performance of the EQ-5D-5L, EQ-HWB, and EQ-HWB-9 instruments in capturing health and wellbeing issues experienced among older adults during heatwaves by examining response distributions, ceiling and floor effects, known-groups validity, and responsiveness.

2. Methods

2.1 Study design

We conducted an observational cohort study of older adults to measure their health and wellbeing. We planned four waves of data collection, each at a different time in 2023, including early summer in May before heatwaves began (pre-heatwave), the first and a subsequent heatwave in June to August (heatwave 1 and heatwave 2), and

in autumn in October (post-heatwave). We chose to study older adults because they are particularly susceptible to heat-related illness and mortality due to age-related declines in thermoregulation, higher prevalence of chronic conditions, and reduced physiological and social adaptability (4, 27, 28).

We conducted the study in Fuzhou city, the capital city of Fujian Province in southeast China, which has a humid subtropical climate characterized by hot and humid summers. As there is no internationally agreed definition of heatwave, we adopted China Meteorological Administration's definition, which states that a heatwave is a continuous occurrence of daily maximum temperatures of ≥35℃ for three days (29). According to historical meteorological data, multiple heatwaves occurred in July and August in Fuzhou in the past 23 years. We recruited a cohort of older residents from two urban communities, most of whom resided in reinforced-concrete apartments equipped with electric fans or air-conditioning. There were no city-wide closures of businesses or schools during heatwaves, but government-issued heat alerts and public health advisories were in place.

The longitudinal design aimed to assess the responsiveness of the EQ-5D-5L and EQ-HWB instruments against the hypothesis that the scores would change from pre-heatwave to heatwave and from heatwave to post-heatwave. We hypothesized that health and wellbeing would decline during heatwaves compared to pre-heatwave and post-heatwave periods. As there were no previous heatwave studies using these instruments, we conservatively assumed that the mean change in the EQ-5D-5L index value could be as small as 0.03, with a standard deviation of up to 0.20. Although small, a systematic review suggests that a change of 0.03 could be meaningful in certain contexts (30). Based on this assumption, we determined that a sample of 351 individuals was needed to ensure a statistical power of 80% at a significance level of

0.05. Assuming a drop-out rate of 10% per wave, we targeted an initial sample size of 500 individuals for the first wave of survey.

We prioritised data collection during the first heatwave, as previous studies suggested that the first heatwave has a greater health impact (e.g. higher risks of heat-related hospitalizations and mortality) than subsequent heatwaves (31, 32). Data collection from a subsequent heatwave was also planned to account for the possibility of lagged or cumulated health effects of heatwaves. Prior evidence suggests that some heatwave-related health consequences, such as exacerbation of cardiovascular and respiratory conditions, may occur one week after a heatwave (3, 33, 34).

2.2 Participants and recruitment

We recruited a study cohort from two urban residential communities. With help from community officials, we screened selected residents for their eligibility in the recreation centres of their communities. Potentially eligible residents were informed and invited to the recreation centres by their community officials via social media (WeChat), telephone, or word of mouth. Residents who passed by the recreation centres during the recruitment period were also invited for screening if they were interested. The inclusion criteria were: [1] aged 60 years or above; [2] resident of the selected communities; [3] able to communicate in Mandarin or Foochow dialect; [4] cognitively and physically capable of being interviewed by an interviewer; and [5] able to provide informed consent. Residents [1] younger than 60 years old; [2] cognitively impaired; [3] unwilling to provide contact information or give informed consent for follow-up surveys; or [4] exhibiting low cooperation or credibility based on interviewers' assessment were excluded.

2.3 Data collection

The four waves of data collection were conducted between 10th and 25th May (mean daily maximum temperature ± SD: 31.70±1.40°C), between 26th June and 7th July (mean daily maximum temperature ± SD: 35.78±0.38°C), between 3rd and 22nd August (mean daily maximum temperature ± SD: 36.61±1.57°C), and between 15th and 28th October (mean daily maximum temperature ± SD: 28.93±1.31°C). The data collection of heatwave 1 and heatwave 2 were conducted during the first and third of five heatwaves in Fuzhou in 2023 which lasted for 22 days and 9 days, respectively.

All four waves of survey were conducted face-to-face in the recreation centres of the selected communities, with the pre-heatwave surveys taking place immediately after recruitment. In addition to following up with participants from earlier waves, a few new participants were recruited during the heatwave 1 and heatwave 2 survey to achieve the desired sample size. At all timepoints, the simplified Chinese versions of EQ-5D-5L, EQ-HWB, and Brief Inventory of Thriving (BIT) questionnaires, as well as questions assessing daily activities and self-perceived effects of high temperature, were administered in a fixed order through one-on-one, face-to-face interviews. Responses were entered directly into an online electronic questionnaire (WeChat Survey Star) using iPads. All interviews were conducted in Chinese by a team of 21 trained graduate and undergraduate students from Fujian Medical University. As temperatures usually reached their highest level between 12 pm and 3 pm in Fuzhou, interviews were conducted in the afternoon.

This study was approved by the Institutional Review Board of Fujian Medical University (reference number: 2023-146).

2.4 Measures

2.4.1 EQ-5D-5L

The EQ-5D-5L is a generic preference-based measure that includes a descriptive system and a EQ VAS (35). Its descriptive system consists of five items: mobility, self-care, usual activities, pain/discomfort, and anxiety/depression, each with five response levels (no problems, slight problems, moderate problems, severe problems, extreme problems/unable to). The EQ VAS assesses an individual's self-rated health on a vertical scale ranging from 0 (the worst health you can imagine) to 100 (the best health you can imagine). Both the descriptive system and EQ VAS use a 'today' recall period (i.e. respondents rate their health on the day of completion). In this study, EQ-5D-5L index values were computed using the Chinese value set (36), which reflects the preferences of the target population. The UK crosswalk (37) and England (38) EQ-5D-5L value sets were used for sensitivity analyses to facilitate comparison with the UK-weighted EQ-HWB-9 results (see details below). It should be noted that the England EQ-5D-5L value set is not recommended by National Institute for Health and Care Excellence (NICE) and the UK crosswalk value set was intended as a temporary solution for mapping the EQ-5D-5L to EQ-5D-3L value sets (39). A new UK EQ-5D-5L value set expected to be released in the near future (40). We also calculated the level sum scores (LSSs) for the EQ-5D-5L, where higher LSSs indicate worse health status.

2.4.2 EQ-HWB and EQ-HWB-9

The EQ-HWB is a generic measure assessing health and wellbeing across seven domains: activity, autonomy, cognition, feelings and emotions, relationships, physical sensations, and self-identity (26). In this study, the experimental Simplified Chinese EQ-HWB (v1.1) was used, which includes 25 items (26, 41). A subset of these 25

items was selected to develop a shorter 9-item instrument, the EQ-HWB-9, primarily for valuation purposes (26). Each item of the EQ-HWB/EQ-HWB-9 has five levels of difficulty (no difficulty, slight, some, a lot of, unable), frequency (none of the time, only occasionally, sometimes, often, most or all the time), or severity (no, mild, moderate, severe, very severe). The recall period is 'in the last 7 days'. In this study, only the EQ-HWB was directly completed by respondents, while the EQ-HWB-9 responses were derived from the EQ-HWB. The EQ-HWB-9 index values were calculated using the UK pilot value set, which is currently the only available value set for the EQ-HWB-9 (42). There is no established method for non-preference-based scoring of the EQ-HWB and EQ-HWB-9. Following previous studies (43-46), we calculated EQ-HWB and EQ-HWB-9 scores using the LSS approach. Three EQ-HWB subscale scores were also calculated: [1] activities LSS (3 items: day-to-day activities, getting around inside and outside, and personal care), [2] pain/discomfort LSS (4 items: pain [frequency and severity] and discomfort [frequency and severity]), and [3] psychosocial wellbeing LSS (16 items: sleep, exhausted, lonely, unsupported by people, remembering, concentrating/thinking clearly, anxious, unsafe, frustrated, sad/depressed, nothing to look forward to, control over my day-to-day life, cope with my day-to-day life, accepted by others, feel good about myself, and do the things I wanted to do); and the EQ-HWB-9 with two subscales: [1] psychosocial LSS (6 items: exhausted, lonely, concentrating/thinking clearly, anxious, sad/depressed, and control over my day-to-day life), and physical LSS (3 items: getting around inside and outside, day-to-day activities, and pain [severity]) (43, 44). Higher scores on the EQ-HWB/EQ-HWB-9 LSS and their subscale LSS indicate worse health and wellbeing.

2.4.3 BIT

The BIT is a 10-item measure of psychological wellbeing (47). Each item is rated on a response scale from 1 (strongly disagree) to 5 (strongly agree). The BIT score is calculated as a single LSS, with higher scores indicating a stronger sense of psychological wellbeing. The BIT does not specify a recall period.

2. 5 Additional information

The additional information collected in the questionnaire included demographics (age, sex, education, marital status, annual income, residence, and employment), health-related variables (weight, height, smoking, drinking, and chronic diseases), and heatwave-related questions (cooling measures, daily activities, discomfort symptoms, and self-perceived adaptation to weather). These questions were pilot tested for respondent burden, clarity, and comprehensibility using a convenience sample of 20 respondents. Minor revisions were made based on respondent feedback prior to finalizing the questionnaire. Demographic and health-related questions were administered prior to the health and wellbeing questionnaires, while heatwave-related questions were presented afterward.

The temperature on the day of each interview in this study was sourced from the Reliable Prognosis weather portal (site number of Fuzhou: 558847) (48). The retrieved data comprised daily maximum temperature, daily minimum temperature, daily average temperature, and daily average relative humidity. All temperature readings were reported in degrees Celsius (°C), while relative humidity is expressed as a percentage (%).

2.6 Statistical Analysis

Descriptive statistics were used to describe respondent characteristics and scores of

EQ-5D-5L, EQ-HWB, EQ-HWB-9 and BIT across all four waves. Continuous variables were summarized as means with standard deviations (SD), while categorical variables were presented as frequencies and percentages. To assess differences between consecutive waves (i.e., pre-heatwave versus heatwave 1, heatwave 1 versus heatwave 2, and heatwave 2 versus post-heatwave), statistical tests, including the chi-squared test, Fisher's exact test, two-sample t-test, and paired t-test, were applied where appropriate. A *p*-value of less than 0.05 was considered statistically significant.

We assessed psychometric properties of the EQ-5D-5L, EQ-HWB and EQ-HWB-9, including response distributions, ceiling/floor, known-groups validity, and responsiveness. All analyses were performed using Stata 17.0 (StataCorp LLC, College Station, TX).

2.6.1 Response distributions and ceiling and floor

Response distributions across all four waves of data were examined using absolute and relative frequencies for each item level. The floor and ceiling were evaluated by examining the percentage of respondents who achieved the minimum/maximum possible scores or values for each item or each measure (49). The floor/ceiling effects were identified if over 70% of respondents score at either extremes at the item level, or over 15% do so at the instrument level (45, 46).

2.6.2 Known-groups validity

We examined the known-groups validity of EQ-5D-5L, EQ-HWB and EQ-HWB-9 scores (including index values and LSSs) and compared their sensitivity to the health and wellbeing impact of heatwaves using Cohen's d (mean difference divided by pooled standard deviations [SD] of two known groups). Known-groups were defined

in terms of [1] presence or absence of excessive sweating and [2] self-perceived adaptation to weather (yes/no) using data from the heatwave 1 and heatwave 2 survey. The effect size was interpreted as: none ($d < 0.2$), small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$), large ($0.8 \leq d < 1.4$), or very large ($d \geq 1.4$) (50). The 95% confidence intervals (CIs) for Cohen's d were calculated using the *esize* command in Stata.

2.6.3 Responsiveness

We examined the responsiveness of the EQ-5D-5L, EQ-HWB and EQ-HWB-9 by analysing the scores of residents whose life was affected by heatwaves. We compared the scores between the pre-heatwave and heatwave 1, and scores between the heatwave 2 and post-heatwave. The degree of responsiveness was assessed using the standardized response mean (SRM) (mean change divided by SD of the changed scores) which was interpreted as: none ($SRM < 0.2$), low ($0.2 \leq SRM < 0.5$), moderate ($0.5 \leq SRM < 0.8$), and high ($SRM \geq 0.80$) (50). The 95% CIs for the SRM were calculated using bootstrapping with 1000 replications and resampling with replacement in Stata.

Subgroup analyses on response distributions, ceiling/floor, known-group validity and responsiveness were performed among respondents with chronic conditions.

3. Results

Supplementary Figure 1 shows the flowchart detailing the recruitment and follow-up across the four waves of the survey. A total of 638, 559, 512 and 557 residents completed the survey of pre-heatwave, heatwave 1, heatwave 2 and post-heatwave, respectively. After excluding respondents who were younger than 60 years old or exhibited low cooperation and/or credibility, a total of 579, 510, 473 and 508 residents

were included for analysis, respectively. The mean interview duration was 24.1 minutes (range: 11.1 to 76.6 minutes).

Table 1 shows the respondents' characteristics. In the pre-heatwave survey, most of respondents were aged 60-74 years old (67.5%), female (64.6%), married (80.5%), and without employment (96.7%), and had a secondary education level or below (57.5%). While the cohort's sociodemographic characteristics remained the same over time, there are salient differences in health and heat-related characteristics across the time points. Specifically, a higher proportion of respondents took cooling measures and felt unadapted to the weather during the heatwave 1 and heatwave 2 survey compared to the pre-heatwave and post-heatwave surveys. A significantly higher proportion of respondents experienced heat-related symptoms and took measures due to feeling unwell during the heatwave 2 survey compared to pre-heatwave, heatwave 1 and post-heatwave survey (see details in Table 1).

Table 1. Respondent characteristics

		Pre-heatwave (n=579)		**Heatwave 1 (n=510)**		**Heatwave 2 (n=473)**		**Post-heatwave (n=508)**		**Pre-heatwave vs Heatwave 1**	**Heatwave 1 vs Heatwave 2**	**Heatwave 2 vs Post-heatwave**
		n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**p-value [c]**	**p-value [c]**	**p-value [c]**
Age (years)	60-74	391	67.5	348	68.2	317	67.0	348	68.5	0.804	0.684	0.619
	≥75	188	32.5	162	31.8	156	33.0	160	31.5			

		88	25.2	62	18.6	56	30.0	60	15.2			
Sex [a]	Male	205	35.4	164	36.2	157	36.8	169	37.0	0.791	0.862	0.948
	Female	374	64.6	289	63.8	270	63.2	288	63.0			
Education [a]	Secondary and below	333	57.5	255	56.3	244	57.1	257	56.2	0.694	0.799	0.786
	High school and above	246	42.5	198	43.7	183	42.9	200	43.8			
Marital status [a]	Married	466	80.5	377	83.2	347	81.3	377	82.5	0.259	0.447	0.635
	Others	113	19.5	76	16.8	80	18.7	80	17.5			
Annual income (RMB) [a]	<30000	165	28.5	127	28.0	120	28.1	127	27.8	0.947	0.952	0.986
	30000-60000	265	45.8	212	46.8	196	45.9	209	45.7			
	>60000	149	25.7	114	25.2	111	26.0	121	26.5			
Residence [a]	Living only with children	152	26.3	108	23.8	98	23.0	115	25.2	0.883	0.948	0.670
	Living only with spouse	190	32.8	157	34.7	153	35.8	157	34.4			
	Living alone	53	9.2	42	9.3	45	10.5	37	8.1			
	Living with spouse and children	167	28.8	135	29.8	122	28.6	136	29.8			
	Others	17	2.9	11	2.4	9	2.1	12	2.6			

Employment [a]	No	560	96.7	436	96.3	410	96.0	442	96.7	0.682	0.860	0.578
	Yes	19	3.3	17	3.8	17	4.0	15	3.3			
BMI [a]	Underweight (BMI<18.5 kg/m^2)	27	4.7	17	3.8	18	4.2	18	3.9	0.914	0.960	0.964
	Normal (18.5≤ BMI<25 kg/m^2)	371	64.1	292	64.5	276	64.6	290	63.5			
	Overweight (25≤ BMI<30 kg/m^2)	152	26.3	121	26.7	114	26.7	129	28.2			
	Obese (BMI ≥30kg/m²)	29	5.0	23	5.1	19	4.5	20	4.4			
Smoking [a]	No	480	82.9	381	84.1	360	84.3	379	82.9	0.606	0.934	0.581
	Yes	99	17.1	72	15.9	67	15.7	78	17.1			
Drinking [a]	No	443	76.5	352	77.7	331	77.5	349	76.4	0.651	0.947	0.685
	Yes	136	23.5	101	22.3	96	22.5	108	23.6			
Chronic diseases	No	151	26.1	160	31.4	75	15.9	76	15.0	0.054	**<0.001**	0.698
	Yes	428	73.9	350	68.6	398	84.1	432	85.0			
Taking cooling measures	No	318	54.9	12	2.4	1	0.2	402	79.1	**<0.001**	**0.003**	**<0.001**
	Yes	261	45.1	498	97.7	472	99.8	106	20.9			
Cooling measures	Electric fan	215	37.1	464	91.0	422	89.2	92	18.1	**<0.001**	0.355	**<0.001**

	Air conditioner	66	111.4	442	86.7	437	92.4	24	4.7	**<0.001**	**0.004**	**<0.001**
	Cattail leaf fan	51	8.8	200	39.2	182	38.5	5	1.0	**<0.001**	0.813	**<0.001**
	Stay in public places with air conditioner	14	2.4	22	4.3	42	8.9	2	0.4	0.081	**0.004**	**<0.001**
	Others	19	3.3	25	4.9	23	4.9	1	0.2	0.175	0.977	**<0.001**
How often use air conditioner	Not applicable	513	88.6	68	13.3	36	7.6	484	95.3	**<0.001**	**<0.001**	**<0.001**
	Always	2	0.4	61	12.0	95	20.1	3	0.6			
	Often	22	3.8	259	50.8	261	55.2	5	1.0			
	Rarely	38	6.6	115	22.6	81	17.1	15	3.0			
	Never	4	0.7	7	1.4			1	0.2			
Air conditioner temperature setting	Not applicable	513	88.6	68	13.3	36	7.6	484	95.3	**<0.001**	**0.017**	**<0.001**
	16-20℃	1	0.2	4	0.8	4	0.9					
	21-25℃	15	2.6	92	18.0	71	15.0	3	0.6			
	26-30℃	50	8.6	341	66.9	357	75.5	19	3.7			
	30℃			5	1.0	5	1.1	2	0.4			
Outdoor activities	Increased	23	4.0	25	4.9	11	2.3	60	11.8	**<0.001**	**<0.001**	**<0.001**
	Decreased	35	6.	12	24	18	39	22	4.			

			0	5	.5	5	.1		3			
	No change	487	84.1	313	61.4	252	53.3	397	78.2			
	No outdoor activity	34	5.9	47	9.2	25	5.3	29	5.7			
Outdoor duration (hours)	duration<1	114	19.7	95	18.6	85	18.0	73	14.4	0.841	0.836	0.121
	1≤duration<2	204	35.2	193	37.8	186	39.3	185	36.4			
	2≤duration<3	164	28.3	138	27.1	118	25.0	134	26.4			
	duration≥3	97	16.8	84	16.5	84	17.8	116	22.8			
Experienced discomfort symptoms in the past few days	No	285	49.2	273	53.5	112	23.7	303	59.7	0.156	**<0.001**	**<0.001**
	Yes	294	50.8	237	46.5	361	76.3	205	40.4			
Experienced discomfort symptoms in the past few days	Headache	57	9.8	17	3.3	38	8.0	35	6.9	**<0.001**	**0.001**	0.495
	Dizziness	99	17.1	36	7.1	63	13.3	54	10.6	**<0.001**	**0.001**	0.194
	Nausea	9	1.6	2	0.4	9	1.9	6	1.2	0.070	**0.032**	0.357
	Vomiting	4	0.7	3	0.6	8	1.7	2	0.4	1.000	0.132	0.056
	Thirsty	97	16.8	76	14.9	172	36.4	68	13.4	0.404	**<0.001**	**<0.001**
	Dark yellow urine	54	9.3	40	7.8	73	15.4	35	6.9	0.384	**<0.001**	**<0.001**
	Excessive sweating	52	9.0	112	22.	228	48.	28	5.5	**<0.001**	**<0.001**	**<0.001**

					0		2					
	Rash	4	0.7	3	0.6	12	2.5			1.000	**0.017**	**<0.001**
	Fatigue	52	90.0	42	82.2	88	186	32	6.3	0.662	**<0.001**	**<0.001**
	Tinnitus	47	81.1	13	26	48	10.2	38	7.5	**<0.001**	**<0.001**	0.140
	Poor appetite	47	81.1	24	47	52	111.0	23	4.5	**0.023**	**<0.001**	**<0.001**
	Polypnea	4	0.7	7	1.4	20	4.2	5	1.0	0.365	**0.006**	**0.001**
	Palpitations	18	3.1	14	2.8	26	5.5	10	2.0	0.723	**0.029**	**0.003**
	Cramp	39	6.7	44	8.6	87	18.4	76	15.0	0.240	**<0.001**	0.149
	Weakness	19	3.3	8	1.6	33	7.0	16	3.2	0.070	**<0.001**	**0.006**
	Irritable	34	5.9	36	7.1	48	10.2	11	2.2	0.426	0.083	**<0.001**
	Confusion	24	4.2	8	1.6	30	6.3	15	3.0	**0.012**	**<0.001**	**0.011**
Taking measures due to feeling unwell	No	448	777.4	337	66.1	159	333.6	360	70.9	**<0.001**	**<0.001**	**<0.001**
	Yes	131	22.6	173	33.9	314	66.4	148	29.1			
Taking measures due to feeling unwell	Reducing or stopping some daily activities	22	3.8	38	7.5	114	24.1	13	2.6	**0.008**	**<0.001**	**<0.001**
	Changing the usual routine	12	2.1	11	2.2	32	6.8	4	0.8	0.923	**<0.001**	**<0.001**
	Reducing or changing diet	6	1.0	16	3.1	46	9.7	14	2.8	**0.014**	**<0.001**	**<0.001**
	Self-medication	43	7.4	41	8.0	107	226	79	15.6	0.705	**<0.001**	**0.005**

	Self-increasing medication dosage	1	0.2			3	0.6			1.000	0.111	0.112
	Planning to see a doctor	12	2.1	7	1.4	20	4.2	7	1.4	0.379	0.006	**0.006**
	Going to a hospital or clinic for treatment	14	2.4	14	2.8	15	3.2	13	2.6	0.734	0.693	0.565
	Increasing water intake	52	90.0	133	26.1	235	49.7	80	15.8	**<0.001**	**<0.001**	**<0.001**
	Others	9	1.6	3	0.6	24.0	5.1	10	2.0	0.153	**<0.001**	**0.008**
Self-perceived adaptation to weather [b]	Not adapted to weather	47	8.1	182	35.7	169	35.7	10	2.0	**<0.001**	0.989	**<0.001**
	Adapted to weather	532	91.9	328	64.3	304	64.3	498	98.0			

BMI, Body Mass Index

[a] Data were missing for 57, 46, and 51 respondents in the second, third and fourth waves, respectively

[b] Measured using a question assessing self-perceived adaptation to weather: *Are you adapted to the current weather? The response options include: 1) very well adapted to; 2) adapted to; 3) not adapted to; 4) very poorly adapted to*

[c] Using the chi-squared test or Fisher's exact test

Table 2 shows the scores of EQ VAS, EQ-5D-5L, EQ-HWB-9, EQ-HWB, and BIT. The mean±SD EQ VAS, EQ-5D-5L and EQ-HWB-9 index values of the heatwave 1 (80.05 ± 11.65; 0.95 ± 0.11; 0.94 ± 0.10) were higher than those of the pre-heatwave (77.17 ± 14.18; 0.93 ± 0.11; 0.92 ± 0.12), heatwave 2 (78.84 ± 11.52; 0.92 ± 0.12;

0.91 ± 0.13) and post-heatwave (78.59 ± 11.58; 0.93 ± 0.11; 0.92 ± 0.12). The mean ± SD EQ-HWB LSSs of the heatwave 1 (34.07 ± 8.91) were lower than those of the pre-heatwave (37.78 ± 10.54), heatwave 2 (37.53 ± 11.30) and post-heatwave (36.39 ± 10.76). All these scores suggested that the health and wellbeing of the cohort was the best during the heatwave 1 survey.

Table 2. Scores of EQ VAS, EQ-5D-5L, EQ-HWB, , EQ-HWB-9 and BIT

	Pre-heatwave (n=579)		**Heatwave 1 (n=510)**		**Heatwave 2 (n=473)**		**Post-heatwave (n=508)**		**Pre-heatwave vs Heatwave 1**	**Heatwave 1 vs Heatwave 2**	**Heatwave 2 vs Post-heatwave**	**Pre-heatwave vs Heatwave 1 (n=453)**	**Heatwave 1 vs Heatwave 2 (n=420)**	**Heatwave 2 vs Post-heatwave (n=421)**
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean difference [a]**	**Mean difference [a]**	**Mean difference [a]**	**Mean difference [b]**	**Mean difference [b]**	**Mean difference [b]**
EQ VAS	77.17	14.18	80.05	11.65	78.84	11.52	78.59	11.58	**-2.88*****	1.21	0.25	**-2.28*****	0.54	0.12
EQ-5D-5L Index (China)	0.93	0.11	0.95	0.11	0.92	0.12	0.93	0.11	**-0.02***	**0.03*****	-0.01	**-0.01***	**0.03*****	**-0.01***

EQ-5D-5L Index (UK, crosswalk)	0.88	0.14	0.90	0.14	0.86	0.14	0.88	0.14	**-0.03****	**0.04*****	**-0.02***	**-0.02****	**0.04*****	**-0.03*****
EQ-5D-5L Index (England)	0.92	0.10	0.94	0.10	0.92	0.10	0.93	0.10	**-0.02****	**0.03*****	-0.01	**-0.02****	**0.02*****	**-0.01****
EQ-HWB-9 Index (UK)	0.92	0.12	0.94	0.10	0.91	0.13	0.92	0.12	**-0.03*****	**0.03*****	-0.01	**-0.02*****	**0.03*****	**-0.01***
BIT	38.70	5.21	38.75	4.70	39.000	5.09	38.39	5.42	-0.04	-0.26	0.61	0.24	-0.31	**0.67***
EQ-5D-5L LSS	6.27	1.77	5.94	1.56	6.48	1.91	6.33	1.91	**0.33****	**-0.54*****	0.15	**0.27*****	**-0.50*****	**0.19***
EQ-HWB LSS	37.78	10.54	34.07	8.91	37.53	11.30	36.39	10.76	**3.70*****	**-3.45*****	1.14	**3.35*****	**-3.35*****	**1.46****
EQ-HWB Activities LSS	3.41	1.05	3.30	0.98	3.66	1.49	3.56	1.40	0.11	**-0.36*****	0.10	0.09	**-0.31*****	0.12
EQ-HWB Pain/discomfort LSS	5.92	2.42	5.30	2.12	5.89	2.39	5.91	2.50	**0.62*****	**-0.59*****	-0.02	**0.51*****	**-0.58*****	0.10
EQ-HWB Psychosocial LSS	25.32	7.97	22.47	6.85	24.78	8.39	23.68	8.08	**2.85*****	**-2.32*****	**1.10***	**2.63*****	**-2.22*****	**1.24****
EQ-HW	12.	4.0	11.	3.3	12.	4.3	12.	4.2	**1.05*****	**-1.18*****	0.35	**0.91***	**-1.1**	**0.46***

B-9 LSS	28	0	22	1	40	6	05	0				**	1***	
EQ-HWB-9 Psychosocial LSS	8.39	3.16	7.64	2.70	8.35	3.36	8.06	3.34	**0.75***	**-0.71***	0.29	**0.65***	**-0.70***	**0.33***
EQ-HWB-9 Physical LSS	3.89	1.27	3.59	1.21	4.05	1.54	3.99	1.50	**0.30***	**-0.46***	0.07	**0.26***	**-0.42***	0.13

BIT, Brief Inventory of Thriving; EQ-HWB, EQ Health and Wellbeing; LSS, level sum score; SD, standard deviation; VAS, visual analogue scale

[a] Using two sample t-test

[b] Using paired t-test

* p<0.05, ** p<0.01, *** p<0.001

Figure 1 shows the distribution of EQ-5D-5L and EQ-HWB responses (also see Supplementary Table 1). Based on the data from the pre-heatwave survey, most of EQ-HWB (14 out of 25), EQ-HWB-9 (6 out of 9) and EQ-5D-5L (4 out of 5) items exhibited ceiling effects. For the EQ-5D-5L, the proportion of respondents reporting 'no problems' ranged from 58.2% (pain/discomfort) to 94.3% (self-care). For the EQ-HWB, the range was from 32.3% (accepted) to 94.0% (personal care). At the instrument level, both the EQ-5D-5L (47.0%) and EQ-HWB-9 (27.8%) exhibited ceiling effects. No floor effects were observed at either the item or instrument level for EQ-5D-5L, EQ-HWB-9 and EQ-HWB.

Figure 1. Distribution of EQ-5D-5L and EQ-HWB responses. Notes: *Part of the EQ-HWB-9. **The responses for the three positively framed items were reversed

The percentage of respondents who reported excessive sweating was 22.0% and 48.2%, in the heatwave 1 and heatwave 2 survey, respectively. The percentage of respondents who felt adapted to weather was 64.3% in both the heatwave 1 and heatwave 2 survey. As shown in Table 3, during heatwaves, respondents who did not experience excessive sweating or were adapted to weather had higher EQ VAS, EQ-5D-5L and EQ-HWB-9 index values, and lower EQ-HWB LSS compared to those who experienced excessive sweating or were not adapted to weather, respectively, with the effect sizes ranging from negligible to medium (Cohen's d: 0 to 0.52 for EQ VAS; 0.04 to 0.31 for EQ-5D-5L; 0.16 to 0.34 for EQ-HWB-9; 0.28 to 0.45 for EQ-HWB). Among the EQ-HWB and EQ-HWB-9 subscales, EQ-HWB pain/discomfort LSS, EQ-HWB psychosocial LSS, and EQ-HWB-9 psychosocial LSS demonstrated small effect sizes (Cohen's d: 0.20 to 0.45), while EQ-HWB activities LSS and EQ-HWB-9 physical LSS showed negligible effect sizes (Cohen's d: 0.04 to 0.20). Compared to these scores, BIT score exhibited smaller effect sizes (Cohen's d: 0.05 to 0.42).

Table 3. Known-groups validity for EQ-5D-5L, EQ-HWB, EQ-HWB-9 and BIT based on heatwaves related symptoms and adaptation

	Heatwave 1 (n=510)							Heatwave 2 (n=473)						
Excessive sweating	**No excessive sweating (n=398)**		**Excessive sweating (n=112)**					**No excessive sweating (n=245)**		**Excessive sweating (n=228)**				
	Mean	**SD**	**Mean**	**SD**	**Mean difference[a]**	**Cohen's d**	**Cohen's d 95% CI**	**Mean**	**SD**	**Mean**	**SD**	**Mean difference[a]**	**Cohen's d**	**Cohen's d 95%CI**
EQ VAS	80.06	11.56	80.02	12.03	0.04	0.00	(-0.21, 0.21)	80.30	10.87	77.27	12.00	**3.03****	0.27	(0.08, 0.45)
EQ-5D-5L Index (China)	0.95	0.11	0.95	0.10	0.00	0.04	(-0.17, 0.25)	0.94	0.10	0.90	0.14	**0.04****	0.31	(0.12, 0.49)
EQ-5D-5L Index (UK, crosswalk)	0.91	0.14	0.89	0.13	0.01	0.08	(-0.13, 0.29)	0.89	0.13	0.83	0.15	**0.06*****	0.40	(0.22, 0.58)
EQ-5D-5L Index (England)	0.95	0.10	0.94	0.09	0.01	0.10	(-0.11, 0.31)	0.94	0.08	0.90	0.12	**0.04*****	0.39	(0.21, 0.57)
EQ-HWB-9 Index (UK)	0.94	0.10	0.93	0.11	0.02	0.16	(-0.05, 0.37)	0.93	0.10	0.89	0.14	**0.04*****	0.34	(0.16, 0.53)
BIT	38.64	4.56	39.13	5.18	-0.48	-0.10	(-0.31, 0.11)	39.12	5.06	38.88	5.14	0.24	0.05	(-0.13, 0.23)
EQ-5D-5L LSS	5.89	1.53	6.12	1.66	-0.23	-0.15	(-0.36, 0.06)	6.17	1.66	6.81	2.10	**-0.64*****	-0.34	(-0.52, -0.16)
EQ-HWB LSS	33.53	8.65	36.00	9.57	**-2.47***	-0.28	(-0.49, -0.07)	35.49	9.79	39.71	12.37	**-4.22*****	-0.38	(-0.56, -0.20)
EQ-HWB Activities LSS	3.29	0.98	3.33	0.97	-0.04	-0.04	(-0.25, 0.16)	3.51	1.08	3.82	1.82	**-0.3***	-0.20	(-0.38, -0.02)
EQ-HWB Pain/discomfort LSS	5.20	2.07	5.64	2.28	-0.44	-0.21	(-0.42, 0)	5.44	2.12	6.37	2.57	**-0.94*****	-0.40	(-0.58, -0.22)
EQ-HWB	22	6.	23	7.	-	-	(-	23	7.	26	9.	-	-	(-0.5, -

Psychosocial LSS	.10	72	.78	17	**1.68***	0.25	0.46, -0.04)	.50	52	.17	05	**2.67****	0.32	0.14)
EQ-HWB-9 LSS	11.06	3.13	11.82	3.84	**-0.77***	-0.23	(-0.44, -0.02)	11.62	3.59	13.24	4.93	**-1.62*****	-0.38	(-0.56, -0.19)
EQ-HWB-9 Psychosocial LSS	7.49	2.56	8.14	3.11	**-0.65***	-0.24	(-0.45, -0.03)	7.78	2.85	8.95	3.74	**-1.17*****	-0.35	(-0.53, -0.17)
EQ-HWB-9 Physical LSS	3.56	1.19	3.68	1.27	-0.12	-0.10	(-0.31, 0.11)	3.84	1.28	4.29	1.76	**-0.45****	-0.29	(-0.47, -0.11)
Self-perceived adaptation to weather	**Not adapted to weather (n=182)**		**Adapted to weather (n=328)**					**Not adapted to weather (n=169)**		**Adapted to weather (n=304)**				
	Mean	**SD**	**Mean**	**SD**	**Mean difference[a]**	**Cohen's d**	**Cohen's d 95% CI**	**Mean**	**SD**	**Mean**	**SD**	**Mean difference[a]**	**Cohen's d**	**Cohen's d 95%CI**
EQ VAS	77.15	12.14	81.66	11.06	**-4.51*****	-0.39	(-0.58, -0.21)	75.08	12.36	80.9	10.5	**-5.84*****	-0.52	(-0.71, -0.33)
EQ-5D-5L Index (China)	0.94	0.11	0.95	0.10	-0.01	-0.13	(-0.32, 0.05)	0.90	0.12	0.93	0.12	**-0.03***	-0.24	(-0.43, -0.05)
EQ-5D-5L Index (UK, crosswalk)	0.88	0.14	0.91	0.14	**-0.03***	-0.21	(-0.39, -0.03)	0.83	0.14	0.87	0.14	**-0.04****	-0.27	(-0.46, -0.08)
EQ-5D-5L Index (England)	0.93	0.10	0.95	0.09	**-0.02***	-0.19	(-0.37, -0.01)	0.90	0.11	0.93	0.10	**-0.03****	-0.30	(-0.49, -0.11)
EQ-HWB-9 Index (UK)	0.92	0.12	0.95	0.09	**-0.03*****	-0.34	(-0.52, -0.15)	0.89	0.14	0.92	0.12	**-0.04****	-0.29	(-0.48, -0.10)
BIT	38.24	4.88	39.03	4.58	-0.80	-0.17	(-0.35, 0.01)	37.67	5.16	39.7	4.91	**-2.08*****	-0.42	(-0.61, -0.23)
EQ-5D-5L LSS	6.13	1.61	5.83	1.52	**0.30***	0.19	(0.01, 0.38)	6.79	1.95	6.30	1.87	**0.49****	0.26	(0.07, 0.45)
EQ-HWB LSS	36.13	10.03	32.93	8.02	**3.20*****	0.36	(0.18, 0.55)	40.69	12.75	35.8	10	**4.92*****	0.45	(0.25, 0.64)
EQ-HWB Activities LSS	3.33	0.9	3.28	1.0	0.05	0.05	(-0.13,	3.76	1.4	3.61	1.5	0.15	0.10	(-0.09, 0.29)

		3		0			0.23)		5		1			
EQ-HWB Pain/discomfort LSS	5.57	2.23	5.15	2.05	**0.42***	0.20	(0.02, 0.38)	6.38	2.73	5.62	2.14	**0.76****	0.32	(0.13, 0.51)
EQ-HWB Psychosocial LSS	24.13	7.74	21.54	6.12	**2.59*****	0.38	(0.20, 0.57)	27.18	9.555	23.45	7.336	**3.72*****	0.45	(0.26, 0.64)
EQ-HWB-9 LSS	12.06	3.888	10.76	2.885	**1.30*****	0.40	(0.22, 0.58)	13.38	4.900	11.86	3.933	**1.52*****	0.35	(0.16, 0.54)
EQ-HWB-9 Psychosocial LSS	8.36	3.211	7.23	2.288	**1.12*****	0.42	(0.24, 0.61)	9.16	3.844	7.89	2.997	**1.27*****	0.38	(0.19, 0.57)
EQ-HWB-9 Physical LSS	3.70	1.330	3.52	1.115	0.18	0.15	(-0.03, 0.33)	4.22	1.557	3.96	1.553	0.26	0.17	(-0.02, 0.36)
Cohen's d (Cohen, 2013)														
None	<0.20													
Small	0.20-0.49													
Medium	0.50-0.79													
Large	0.80-1.39													
Very large	≥ 1.40													

BIT, Brief Inventory of Thriving; CI, confidence interval; EQ-HWB, EQ Health and Wellbeing; LSS, level sum score; SD, standard deviation; VAS, visual analogue scale

[a] Using two sample t-test. * $p<0.05$, ** $p<0.01$, *** $p<0.001$

As shown in Table 4, unexpectedly, EQ-5D-5L, EQ-HWB and EQ-HWB-9 scores changed in the opposite direction to the anticipated worsening in excessive sweating and adaptation to weather due to the onset of heatwave (SRM: 0 to 0.44). Specifically, respondents who experienced a worsening in self-perceived effect of heat in the heatwave 1 survey compared to the pre-heatwave survey reported better health and wellbeing. The measures demonstrated negligible responsiveness to improvement in self-perceived effects of heat (SRM: 0.01 to 0.19). The BIT score demonstrated

negligible responsiveness to worsening in adaptation to weather due to the commence of heatwave (SRM: 0.04) and changed in the opposite direction to improvement in self-perceived effects of heat.

Table 4. Responsiveness for EQ-5D-5L, EQ-HWB, EQ-HWB-9 and BIT

Worsening	**Excessive sweating (n=86)**							**Self-perceived adaptation to weather (n=142)**						
	Pre-heatwave (no excessive sweating)		**Heatwave 1(excessive sweating)**					**Pre-heatwave (adapted to weather)**		**Heatwave 1 (not adapted to weather)**				
	Mean	**SD**	**Mean**	**SD**	**Mean difference [a]**	**SRM**	**SRM 95% CI**	**Mean**	**SD**	**Mean**	**SD**	**Mean difference [a]**	**SRM**	**SRM 95% CI**
EQ VAS	79.45	13.64	79.93	12.65	-0.48	-0.03	(-0.25, 0.18)	75.65	13.89	77.01	11.86	-1.36	-0.10	(-0.27, 0.07)
EQ-5D-5L Index (China)	0.93	0.12	0.95	0.08	-0.02	-0.20	(-0.41, 0.00)	0.92	0.12	0.94	0.10	**-0.03***	-0.19	(-0.36, -0.03)
EQ-5D-5L Index (UK, crosswalk)	0.87	0.15	0.90	0.12	-0.02	-0.19	(-0.40, 0.02)	0.86	0.15	0.89	0.14	**-0.03***	-0.21	(-0.38, -0.04)
EQ-5D-5L Index (England)	0.92	0.11	0.94	0.08	-0.02	-0.19	(-0.39, 0.02)	0.91	0.11	0.94	0.09	**-0.03****	-0.23	(-0.40, -0.07)
EQ-HWB-9 Index (UK)	0.92	0.12	0.93	0.11	-0.01	-0.12	(-0.34, 0.09)	0.89	0.13	0.92	0.11	**-0.03****	-0.24	(-0.40, -0.09)
BIT	39.00	6.50	39.22	5.41	-0.22	-0.03	(-0.25, 0.18)	38.42	5.49	38.18	5.05	0.23	0.04	(-0.12, 0.20)
EQ-5D-5L LSS	6.35	1.93	6.06	1.51	0.29	0.17	(-0.04, 0.38)	6.52	1.83	6.04	1.42	**0.49****	0.27	(0.12, 0.43)
EQ-HWB LSS	37.67	11.19	35.85	9.71	1.83	0.20	(-0.01, 0.41)	40.12	11.19	35.70	9.41	**4.42*****	0.44	(0.28, 0.61)

EQ-HWB Activities LSS	3.43	1.06	3.31	0.97	0.12	0.12	(-0.08, 0.32)	3.45	0.93	3.30	0.91	0.15	0.14	(-0.03, 0.31)
EQ-HWB Pain/discomfort LSS	5.58	2.10	5.59	2.21	-0.01	0.00	(-0.22, 0.21)	6.07	2.49	5.51	2.13	**0.56***	0.20	(0.04, 0.36)
EQ-HWB Psychosocial LSS	25.51	8.84	23.76	7.41	**1.76***	0.23	(0.02, 0.43)	27.13	8.35	23.81	7.30	**3.32*****	0.43	(0.25, 0.60)
EQ-HWB-9 LSS	12.33	4.43	11.83	4.01	0.50	0.14	(-0.07, 0.35)	13.08	4.38	11.85	3.60	**1.23*****	0.32	(0.17, 0.48)
EQ-HWB-9 Psychosocial LSS	8.47	3.45	8.19	3.37	0.28	0.09	(-0.11, 0.30)	9.05	3.50	8.18	3.04	**0.87****	0.28	(0.10, 0.45)
EQ-HWB-9 Physical LSS	3.86	1.36	3.64	1.09	0.22	0.19	(-0.01, 0.39)	4.04	1.31	3.67	1.21	**0.37****	0.26	(0.09, 0.44)
Improvement	**Excessive sweating (n=186)**							**Self-perceived adaptation to weather (n=150)**						
	Heatwave 2 (excessive sweating)		**Post-heatwave (no excessive sweating)**					**Heatwave 2 (not adapted to weather)**		**Post-heatwave (adapted to weather)**				
	Mean	**SD**	**Mean**	**SD**	**Mean difference [a]**	**SRM**	**SRM 95% CI**	**Mean**	**SD**	**Mean**	**SD**	**Mean difference [a]**	**SRM**	**SRM 95% CI**
EQ VAS	76.78	12.18	77.06	12.52	-0.28	-0.03	(-0.18, 0.12)	76.29	11.89	76.64	11.91	-0.35	-0.03	(-0.19, 0.13)
EQ-5D-5L Index (China)	0.90	0.14	0.92	0.11	**-0.02***	-0.16	(-0.29, -0.03)	0.90	0.12	0.91	0.13	-0.01	-0.07	(-0.23, 0.10)
EQ-5D-5L Index (UK, crosswalk)	0.83	0.15	0.86	0.13	**-0.04****	-0.25	(-0.38, -0.12)	0.84	0.14	0.86	0.15	-0.02	-0.15	(-0.33, 0.02)
EQ-5D-5L Index (England)	0.89	0.12	0.92	0.10	**-0.02****	-0.21	(-0.34, -0.08)	0.90	0.11	0.91	0.11	-0.01	-0.12	(-0.29, 0.06)
EQ-HWB-9 Index (UK)	0.89	0.15	0.90	0.12	-0.02	-0.14	(-0.27, 0.00)	0.89	0.14	0.90	0.13	-0.01	-0.08	(-0.24, 0.07)
BIT	38.73	5.38	37.65	6.02	**1.08****	0.19	(0.06, 0.33)	37.93	5.21	37.59	6.02	0.34	0.06	(-0.10, 0.22)
EQ-5D-5L LSS	6.88	2.20	6.54	1.88	**0.34***	0.17	(0.04, 0.31)	6.74	1.93	6.59	2.11	0.15	0.07	(-0.10, 0.24)
EQ-HWB LSS	40.17	12.76	38.31	12.20	**1.86***	0.18	(0.04, 0.32)	40.24	12.85	38.68	11.89	1.56	0.15	(-0.01, 0.31)
EQ-HWB Activities LSS	3.87	1.95	3.59	1.27	**0.28***	0.15	(0.03, 0.27)	3.72	1.41	3.68	1.55	0.04	0.02	(-0.14,

														0.19)
EQ-HWB Pain/discomfort LSS	6.40	2.60	6.32	2.68	0.08	0.03	(-0.12, 0.17)	6.32	2.79	6.28	2.64	0.04	0.01	(-0.15, 0.18)
EQ-HWB Psychosocial LSS	26.46	9.27	24.99	9.44	**1.47** **	0.19	(0.06, 0.33)	26.81	9.60	25.27	9.26	1.53	0.19	(0.04, 0.35)
EQ-HWB-9 LSS	13.41	5.10	12.83	4.76	0.58	0.13	(-0.01, 0.26)	13.21	4.90	12.91	4.77	0.30	0.07	(-0.09, 0.23)
EQ-HWB-9 Psychosocial LSS	9.09	3.84	8.73	3.95	0.36	0.10	(-0.04, 0.24)	9.03	3.83	8.75	4.00	0.29	0.08	(-0.08, 0.24)
EQ-HWB-9 Physical LSS	4.32	1.81	4.10	1.41	0.22	0.12	(-0.01, 0.26)	4.18	1.55	4.17	1.47	0.01	0.01	(-0.15, 0.17)
Degree of responsiveness (Cohen, 2013):														
None	<0.20													
Low	0.20-0.49													
Moderate	0.50-0.79													
High	≥ 0.80													

BIT, Brief Inventory of Thriving; CI, confidence interval; EQ-HWB, EQ Health and Wellbeing; LSS, level sum score; SD, standard deviation; SRM, standardized response mean (mean difference/SD of the mean difference); VAS, visual analogue scale

[a] Using paired t-test. * $p<0.05$, ** $p<0.01$, *** $p<0.001$

The results of EQ-5D-5L index values based on Chinese EQ-5D-5L value set were similar to those based on the UK crosswalk and England EQ-5D-5L value sets. The findings on response distributions, ceiling/floor, known-group validity and responsiveness were consistent between the entire sample and the subgroup with chronic conditions (Supplementary Table 2-4).

4. Discussion

In this study, we assessed the validity and responsiveness of the EQ-5D-5L, EQ-HWB, and EQ-HWB-9 instruments for measuring the health and wellbeing impacts of heatwaves among older adults. While some results were puzzling and challenging to interpret, our findings provided promising evidence for the ability of these instruments in capturing the health and wellbeing impact of heatwaves. To our knowledge, this study represents the first of its kind, and it contributes to advancing research efforts to quantify the health-related quality of life and wellbeing impacts of climate change events.

Our findings indicate that the EQ-5D-5L, EQ-HWB and EQ-HWB-9 possess satisfactory known-groups validity in distinguishing between different groups based on the self-perceived impact of heatwaves. The magnitude of the between-group differences was small to moderate most of the time, suggesting either suboptimal discriminatory power of the instruments or the small impact of the heatwaves during the study period. The latter is possible as the intensity and duration of the heatwaves in the study site were both lower compared to past years. The relatively good performance of the EQ-HWB and EQ-HWB-9 suggests that measuring both health and wellbeing aspects is relevant in the context of heatwaves. In addition, the EQ VAS demonstrated relatively larger effect sizes for some known groups, suggesting that the EQ VAS may be more sensitive to general differences in self-perceived health impact. As a unique component of the EQ-5D-5L, this finding highlights its potential usefulness in capturing overall health perception in a single question. Within the EQ-HWB, the psychosocial and pain/discomfort subscales demonstrated better known-groups validity than the activities subscale. This could be due to respondents having adjusted their activities such as reducing strenuous or outdoor activities during

heatwaves. Changing activities would not be very difficult for the respondents as most of them were retired. As a result, they might not have felt much interference in their daily activities during heatwaves. In contrast, the unpleasant discomfort and mood disturbances due to high temperature are typically not preventable. This finding suggests that psychosocial and physical discomfort might be the main health and wellbeing impacts of heatwaves, highlighting the importance of considering these aspects when assessing outcomes in the context of heatwaves.

It was opposite to our expectation that health and wellbeing improved from the pre-heatwave survey to the first during-heatwave survey. Several potential explanations could account for these unexpected findings. One possible reason is that the instruments used may not be sufficiently responsive or sensitive to change in health status and wellbeing associated with heatwaves. Another contributing factor could be the nature of the heatwave itself. The heatwaves experienced in 2023, when we conducted our surveys, may not have been intense or prolonged enough to exert a significant impact on local residents' health and wellbeing. This is particularly plausible given that 2023 was an atypical year, with summer temperatures being lower than those in previous and subsequent years (51), which may have lessened the impact on health and wellbeing. Additionally, the unexpected score changes from the pre-heatwave survey to the heatwave 1 survey might have reflected the lingering effects of the COVID-19 pandemic. Our pre-heatwave survey was conducted only a few months after the end of lockdown in China, a period during which the health of the study sample might have still been affected by COVID-19. This residual impact could have introduced variability in the health status of the study cohort, leading to unusually low and high levels of health status during the pre-heatwave and heatwave 1 survey, respectively. Because of this unexpected trend and the plausible reasons for

it, we only used small subgroups of respondents who reported change in sweating and weather adaptation to evaluate responsiveness. It is worth noting that the magnitude of the mean differences in EQ-5D-5L index values was relatively small. However, given the variability in the recommended minimally important difference (MID) for the EQ-5D-5L index across different value sets, populations and settings (30, 52), it remains unclear whether the observed changes are practically meaningful.

Overall, all instruments exhibited limited responsiveness to the health and wellbeing impacts of heatwaves in this study. Comparatively, EQ-HWB with its 25 items measuring health and wellbeing was slightly more responsive than the five-item EQ-5D-5L measuring health, and EQ-HWB psychological subscale was more responsive than the activity and pain/discomfort subscales. Appending relevant bolt-ons targeting psychosocial or climate-related HRQoL dimensions may improve the conceptual coverage of EQ-5D-5L in heatwave research (24, 25). Future studies could investigate whether appending such bolt-ons to the EQ-5D-5L enhances its sensitivity and relevance in capturing heatwave-related health impacts.

This study is subject to several limitations that should be acknowledged. First, there may be selection bias due to our centralized data collection method, which involved conducting face-to-face surveys in community centres. This approach required participants to be physically mobile, potentially excluding individuals whose health was most adversely affected by heatwaves from participation. Future research should consider using online or household surveys to ensure the inclusion of the most vulnerable populations, particularly those who may be less capable to attend centralized survey locations. Second, our study faced suboptimal follow-up rates, which could also be attributed to the data collection method. Participants who were unwell may have been more likely to drop out, particularly given the requirement to

travel to the survey venue on hot days, which could have introduced attrition bias. Third, the timing of the heatwave 1 survey may have been suboptimal. Although we hypothesized that the first heatwave of the year would have a greater impact than subsequent heatwaves, it is possible that participants made extra efforts for the very first heatwave to mitigate the effects of heatwaves, such as reducing or changing their daily activities. These adaptive behaviours could have counteracted the effects of heatwaves or even resulted in a paradoxical improvement in health and wellbeing. Future studies should carefully consider the timing of assessments during heatwaves to better capture the true health impacts of heatwaves. Fourth, only the EQ-HWB was administered directly to respondents, and EQ-HWB-9 responses were derived from the corresponding items within the EQ-HWB. As the same item wording and response options were used, any differences between embedded and standalone administration would be expected to be minimal; however, this assumption warrants empirical evaluation in future research. Fifth, this study was conducted in only one city and two communities within China, which may restrict the generalizability of the findings to other geographic areas with different climate patterns, urban layouts, and levels of access to cooling resources. Finally, this study focused on older adults, and the findings may not be applicable to younger, working-age populations who might experience different impacts from heatwaves, such as occupational exposure or different adaptive behaviours. Future research could expand to include a more diverse range of locations and age groups to better understand the broader health implications of heatwaves.

5. Conclusion

The EQ-5D-5L, EQ-HWB and EQ-HWB-9 demonstrated satisfactory known-groups validity but limited responsiveness in measuring the health and wellbeing impact of heatwaves among older adults. Further research is warranted to further evaluate these measures as well as other outcome measures for the purpose of quantifying the health and wellbeing impacts of heatwaves and other climate events.

Abbreviations

BIT	Brief Inventory of Thriving
EQ-HWB	EQ Health and Wellbeing
HRQoL	Health-related quality of life
LSSs	Level sum scores

SD	Standard deviations
SRM	Standardized response mean
VAS	Visual analogue scale

Acknowledgements

Not applicable.

Author contributions

J.X., N.L., F.R. and Z.Y. contributed to study conceptualization, methodology, and funding acquisition. Data curation, project administration, resources, and supervision were provided by J.X. and N.L.. M.L. conducted the formal analysis and, together with J.X. and N.L. drafted the manuscript. All authors reviewed and approved the final manuscript.

Funding

This study was supported by the EuroQol Research Foundation (project number: 1599-RA). The funder had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Data availability

The data supporting this study are available from the corresponding authors upon reasonable request.

Ethics approval and consent to participate

This study was approved by the Institutional Review Board of Fujian Medical University (reference number: 2023-146) and conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants.

Consent for publication

Not applicable.

Competing interests

F.R., Z.Y. and N.L. are members of the EuroQol Group. F.R. is employed by the EuroQol Research Foundation. F.R. serves as co-editor-in-chief at Health and Quality of Life Outcomes and had no involvement in the editorial or peer review process for this manuscript. The other authors have no conflicts of interest to declare. Views expressed in the article are those of the authors and are not necessarily those of the EuroQol Research Foundation.

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