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# Drivers and barriers to heat stress resilience

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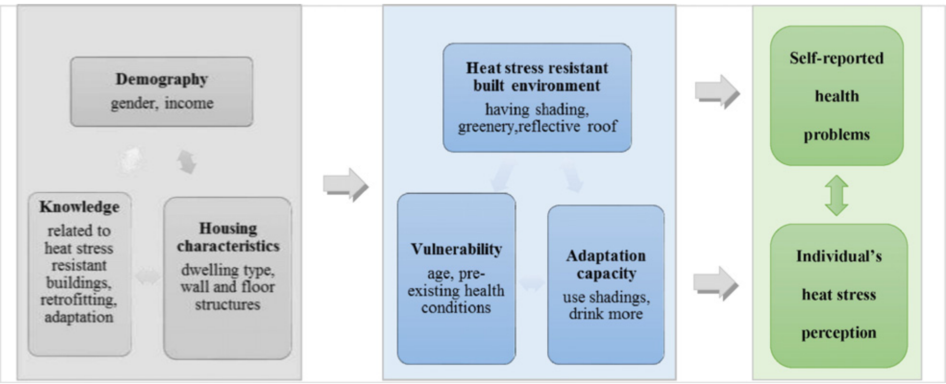
## HIGHLIGHTS

- Population heat stress resilience was surveyed in Adelaide
- The empirical benefit of heat stress resistant buildings to health was confirmed
- Air-conditioning decreases passive adaptation but not necessarily health problems
- Introducing a Building Energy Performance Certificate was recommended
- Pre-existing health conditions and tenancy predict higher vulnerability

## GRAPHICAL ABSTRACT



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## ABSTRACT

Heatwaves are the most dangerous natural hazard to health in Australia. The frequency and intensity of heatwaves will increase due to climate change and urban heat island effects in cities, aggravating the negative impacts of heatwaves. Two approaches exist to develop population heat stress resilience. Firstly, the most vulnerable social groups can be identified and public health services can prepare for the increased morbidity. Secondly, the population level of adaptation and the heat stress resistance of the built environment can be increased. The evaluation of these measures and their efficiencies has been fragmented across research disciplines. This study explored the relationships between the elements of heat stress resilience and their potential demographic and housing drivers and barriers.

The responses of a representative online survey ($N = 393$) about heat stress resilience at home and work from Adelaide, South Australia were analysed. The empirical findings demonstrate that heat stress resistant buildings increased adaptation capacity and decreased the number of health problems. Air-conditioning increased dependence upon it, limited passive adaptation and only people living in homes with whole-house air-conditioning had less health problems during heatwaves. Tenants and respondents with pre-existing health conditions were the most vulnerable, particularly as those with health conditions were not aware of their vulnerability. The introduction of an Energy Performance Certificate is proposed and discussed as an effective incentive to increase the heat stress resistance of and the general knowledge about the built environment.

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## 1. The risk factors of heatwaves

Both the intensity and frequency of heatwaves have been increasing globally (Intergovernmental Panel on Climate Change, 2014). Urban heat island effects due to urbanisation will exacerbate heatwaves and consequently raise heat-related morbidity and mortality (Hajat et al., 2010; Sheridan and Allen, 2015). Simultaneously, population vulnerability to heatwaves is increasing because of ageing populations and increasing chronic health diseases (Bambrick et al., 2011; Dengel and Swainson, 2012). Developing heat stress resilience in the community is, therefore, essential to minimise the impact of future heatwaves.

It can be argued that heat stress resilience is comprised of three elements (Hatvani-Kovacs et al., 2016): vulnerability (Li et al., 2015), the heat stress resistance of the built environment (Miller, 2015) and population adaptation (Hajat et al., 2010). A wide body of literature on health vulnerability has identified various demographic and medical risk factors to heat-related mortality and morbidity recorded by health services (Bi et al., 2011; Coates et al., 2014; Kovats and Hajat, 2008; Li et al., 2015; Martiello and Giacchi, 2010; Williams et al., 2012; Zhang et al., 2013). Only a few studies have used self-reported, heat-related health problems, even though self-reported health problems have been well-established in research (Bélanger et al., 2014) and can better capture population wellbeing.

The second element of heat stress resilience is the heat stress resistance of the built environment. Note that heat stress resistance and energy efficiency are not identical. A heat stress resistant building minimises the peak cooling demand and annual cooling energy consumption in contrast to an energy efficient building that minimises the annual energy use. Although increasing energy efficiency, especially in very inefficient homes, can decrease overheating risk (Alam et al., 2016), in other cases the desire for energy efficiency can interfere with heat stress resistance. Highly insulated building envelopes with high air-tightness can foster overheating in summer and increase the cooling demand and thermal discomfort (Dengel and Swainson, 2012; Ren et al., 2014; Sameni et al., 2015). Studies have showed that climate change will decrease heating and increase cooling consumption with the risk of overheating (Dodoo and Gustavsson, 2016; Jenkins et al., 2013; Karimpour et al., 2015; Mavrogianni et al., 2015; McLeod et al., 2013; Peacock et al., 2010; Wang et al., 2010).

Heat stress resistant buildings are imperative to minimise overheating and heat-related health problems (Quinn et al., 2014). Although air-conditioning (AC) is acknowledged as an efficient, preventive measure during heatwaves (Hajat et al., 2010) it also has several negative impacts. AC creates a feedback loop with the waste heat generated increasing local ambient temperatures (Salamanca et al., 2014), contributes to energy poverty (Kolokotsa and Santamouris, 2015; Santamouris and Kolokotsa, 2014), might cause addiction (Cândido et al., 2010) and potentially decreases other means of adaptation (Bélanger et al., 2015a).

Passive design features that do not require energy use can increase heat stress resistance and decrease cooling demand. Such heat stress resistant features include shading (Dodoo and Gustavsson, 2016; Porritt et al., 2013), solar-reflective roof colour (Cotana et al., 2014; Santamouris et al., 2007), reflective foil in the roof cavity (Saman et al., 2013), slab-on ground compared to elevated structures in warmer climates (Lapisa et al., 2013) and ceramic floor covering (Karimpour et al., 2015). Further building characteristics that can also influence heat stress resistance include orientation (Porritt et al., 2013), heavy-weight walls (Peacock et al., 2010) and garden vegetation (Cameron et al., 2012). For example, increased thermal mass of walls was associated with lower overheating risk in the UK (Peacock et al., 2010), especially when coupled with insulation and nocturnal ventilation (Demanuele et al., 2011). An Australian building simulation study found thermal mass as an effective tool to maintain a comfortable indoor temperature around the year (Gregory et al., 2008), while McLeod et al. (2013) indicated that thermal mass might be detrimental in bedrooms and during prolonged heatwaves in the UK. Further empirical studies should be undertaken in the Australian climatic context, concentrating on heatwave periods. Furthermore, efficient cooling techniques that increase heat stress resistance include ground cooling systems, solar chimneys, hybrid systems using both natural and mechanical systems and ceiling fans (Santamouris et al., 2007).

Nevertheless, empirical research on the impact of heat stress resistant building design on health is limited (Barnett et al., 2014). Only a few studies have evaluated housing characteristics, such as dwelling types and the availability of AC (Bélanger et al., 2015b; Jenerette et al., 2015; Tran et al., 2013), insulation or bedroom location on the upper floor (Salagnac, 2007; Vandentorren et al., 2006).

Adaptation, the third element of heatwave resilience, refers to behaviour changes made to minimise exposure to heat. Only a few studies have investigated the efficacy of different adaptation techniques in relation to health (Bélanger et al., 2015a; Jenerette et al., 2015; Nitschke et al., 2013; Tran et al., 2013). The majority of these studies focused on the most vulnerable social groups, such as older or underprivileged ones, instead of the general population.

Research suggests that an association exists between the built environment and the acceptable range of indoor temperatures as a consequence of adaptation (Baker and Standeven, 1996; Brager and de Dear, 1998; de Dear and Brager, 2002), which should be explored and utilised by building designers (Cândido et al., 2010). This aspect has not yet been examined in relation to heatwave vulnerability. Consequently, to our knowledge, no study has examined the relationship between the heat stress resistance of the built environment, adaptation and vulnerability and their impacts on heat-related, self-reported health problems considering a broad range of social groups.

The main aims of the study were to (1) identify the demographic and housing predictors of the heat stress resistant built environment, adaptation and vulnerability, and (2) explore the relationships between the heat stress resistant built environment, adaptation and heat-related, self-reported health problems. An exploratory survey research was undertaken. Specifically, we examined the relationships between heat stress resistance of the built environment, including retrofitting (undertaken and intended), adaptation at home and work, vulnerability, and wellbeing (self-reported health problems and perception of heatwaves) (Fig. 1). It is anticipated that the findings can be used to inform and evaluate policy changes, government subsidies and community education campaigns to achieve improvements in heat stress resistance.

## 2. Survey data and analysis methods

The survey data were collected from the metropolitan region of Adelaide, the capital of South Australia with a population of near 1.3 million people. Heatwaves have been frequent, long and severe in South Australia (Nairn and Fawcett, 2013) causing the highest number of heat-related deaths from among all Australian States (Coates et al., 2014).

The sample population, representative for age and gender of the population in the Adelaide metropolitan region (Australian Bureau of Statistics, 2011), ($N = 393$) was furnished by a survey panel provider. Respondents were recruited from among people above the age of 18 living and/or working in the Adelaide metropolitan region. The target sample size of minimum 384 was determined considering a ± 5 margin of error with a 95% confidence interval (Gomm, 2008) for the Adelaide metropolitan population of 1.3 million (Australian Bureau of Statistics, 2015). When the main demographic characteristics of the respondents were compared with the census data (Australian Bureau of Statistics, 2011), the unemployment rate was considerably higher (8.9% compared to 3%, considering population over 18). Low-income earners were, furthermore, over-represented in the lowest income category, however, the over-representation of higher-income-earners counterbalanced this impact to some extent.

The survey was approved by the ethics committee of the University of South Australia (Appendix 1). The questionnaire was presented in 5 parts, addressing demographics, adaptation, characteristics of the built

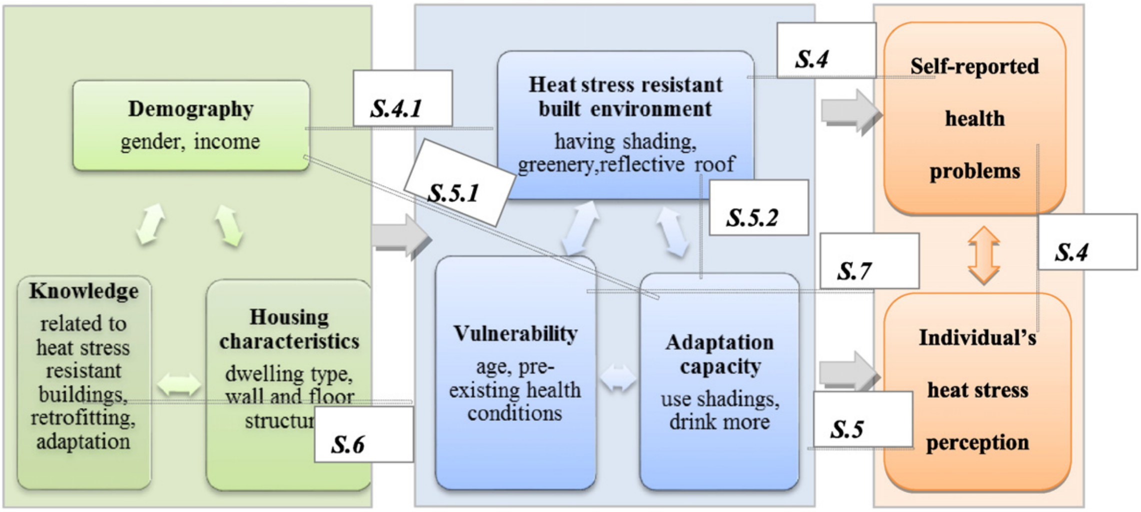

**Fig. 1.** Investigated variables of the survey analysis. The relevant result & discussion sections under each connection investigated listed in bold, italics.

environment, retrofitting activity, population relevant knowledge and wellbeing during heatwaves. The first part corresponded to basic demography. In the second part, information was collected at workplaces about the ages of buildings and AC, including its availability and adjustability. In the third part, housing characteristics were surveyed such as house types (single house, semi-detached house and apartment), types of AC (window-unit, split or ducted system and etc.) and levels of AC (one, two or more rooms, whole-house) and heat stress resistant features (e.g. insulation, garden vegetation). Questions were also raised about behavioural adaptation (e.g. wearing a sun hat) and adaptive mitigation techniques (e.g. nocturnal, natural ventilation) at home and at work. The fourth part corresponded to past and future residential retrofitting activities, including types, drivers and barriers to retrofitting. Tenancy was questioned only indirectly as reason for retrofitting or not. The resulting 20.4% tenancy, nevertheless, relates well to the 19.6% reported in the Census 2011 for Adelaide metropolitan region (Australian Bureau of Statistics, 2011). In the fifth part, the perceptions of two subsequent heatwaves that occurred in February 2015 were assessed by the respondents. The survey was available online in early March 2015, following the selected two heatwaves to ensure that heatwave experience was salient in the respondents' minds. The strengths of both heatwaves and the health symptoms during the most recent heatwave were reported. Questions about the population knowledge of heat stress resistance, adaptation and retrofitting techniques were integrated under the relevant sections.

Earlier research surveys were reviewed and some of the questions were reused (Akompab et al., 2013, 2012; Loughnan et al., 2014; National Centre for Social Research, 2010; Saman et al., 2013). The heat-related problems and severity classifications were adopted from an information sheet by the South Australia Health Department (SA Health, 2011) and a medical study (Waters, 2001). The survey design, distribution and question coding were managed with the Qualtrics online survey software program (2005). The software enabled that only relevant questions were raised depending on answers given to preceding questions. All questions had to be answered, unless ethical concerns were in place, such as age and income of the respondents. Consequently, most of the missing data were recorded under household income, where 38 respondents preferred not to answer and 17 could not answer. The descriptive and inferential statistical analyses were conducted with SPSS (IBM Corp., 2013).

The aim of the analysis was to explore the effect of adaptation, the heat stress resistance of the built environment and vulnerability on wellbeing during heatwaves, instead of building a predictive model for wellbeing. In trying to identify the significant variables influencing wellbeing, these variables can be better evaluated with univariate than multivariate analysis. In the univariate analysis, three significance threshold values were recorded ($p < 0.05$, 0.01 or 0.001).

Non-parametric tests were performed as the data were not normally distributed. The analyses utilised included Spearman's rho, Chi-square tests, Fisher's exact test and Fisher-Freeman-Halton Exact test when the assumption of minimum expected cell values was violated for the Chi-square test (Cohen et al., 2007; Pallant, 2011). Interval variables with several values, such as respondents' age and household income, and scale variables, such as the age of buildings, were regrouped. The degrees of freedom (df) was reported in the Chi-square tests to indicate the number of groups used. Df is equal to $(r - 1) * (c - 1)$ where r is number of rows and c is number of columns. The typical groups used in the analysis are listed in Table 1. For more information about the variables, please see the questionnaire (Appendix 1).

To test the validity of heatwave strengths reported by the survey respondents, the dataset of daily minimum and maximum temperatures, recorded in February 2015 at the Kent Town station, in Adelaide, South Australia was obtained from the Australian Bureau of Meteorology (BOM). The selected station has been widely used in recent studies relevant to local microclimate investigations in Adelaide (Nairn and Fawcett, 2015; Nitschke et al., 2011). Daily excess heat factors (EHFs) were calculated to assess the intensity of heatwaves. The EHF was found to better predict heatwave-related morbidity than daily temperatures in Adelaide (Hatvani-Kovacs et al., 2015). The factor is used by the BOM for heatwave forecast (Bureau of Meteorology, 2015). The EHF is calculated from the deviation of the daily mean temperatures of the recent three days ($T_i$, $T_{i-1}$, $T_{i-2}$) from the recent thirty days ($T_{i-1} \ldots T_{i-30}$), (EHIsig) and the 95th percentile of the recent thirty years ($T_{95}$), (EHIaccl) (Eq. (1)). The unit of the EHF is $°C^2$. The daily

**Table 1**
Regrouping of values of scale and interval variables.

| Variables | Groups of values |
|---|---|
| Household income | ≤$599, $600–$999, $1000–$1499, $1500–$2499, $2500–$3499, $3500–$4999, ≥$5000 or<br>≤$799, $800–$1499, $1500–$2999, ≥$3000 or<br>≤$1299, $1500–$2999, ≥$3000 or<br><$1499, ≥$1500 |
| Respondents' age | ≤24, 24–64, ≥65 |
| Qualification | Tertiary certificate level and below, advanced level diploma and above |
| Age of dwelling | Built before 1980, between 1980 and 2010, after 2010 |
| Number of heatwave resistant Design features | ≤2, 3–4, ≥5 |
| Wall types | Double brick or brick veneer (other types neglected) |
| Employment | Unemployed or employed |

mean temperatures were calculated from the average of the minimum temperature recorded in the preceding 24 h up to 9 a.m. and the maximum temperature recorded in the following 24 h from 9 a.m. of the designated day, since this adjusted EHF predicted morbidity the best (Hatvani-Kovacs et al., 2015).

Excess Heat Factor:

$$\begin{aligned}
&EHF = EHIsig * \max(1, EHIaccl)\\
&EHIsig = (T_i + T_{i-1} + T_{i-2})/3 - T_{95}\\
&EHIaccl = (T_i + T_{i-1} + T_{i-2})/3 - (T_{i-1} + \ldots + T_{i-30})/30
\end{aligned} \quad (1)$$

The results are presented according to the logic of Fig. 1. The number of corresponding sections are listed in the figure.

## 3. Heat stress resistant features of the existing residential stock

Three periods emerged from the prevalent construction types of the homes surveyed, pre-1980, 1980–2010 and since 2010. The most common wall structure type shifted from double brick (also called cavity brick walls) to brick veneer walls (Table 2, Fig. 2) in the late 1970s, causing the loss of thermal mass. Pullen (2007) has similarly defined 1978 as a transition year in Adelaide.

The loss of thermal mass in walls was, nevertheless, compensated to some extent by the longitudinally rising popularity of slab-on-ground structures used in brick veneer homes (Table 2). Newer homes were more insulated on average due to the longitudinal spread of brick veneer homes (Table 2). Unfortunately, energy efficiency measures were not introduced in the Australian Building Codes until 2003 (Australian Building Codes Board, 2013) and that resulted in uninsulated light wall structure in one out of three homes until 2010 (Fig. 2). The minimum energy-efficiency requirements for new buildings were raised gradually in 2006 and 2010, as reflected in the increased number of insulated walls reported to be built, particularly after 2010 (Fig. 2).

Newer homes had more heat stress resistant features (Spearman's $r = 0.19$, $N = 390$, $p < 0.01$), especially solar panels, which mitigate heat flow into the roof space as well as provide electricity (Table 3).

Insulated roofs and walls were more common in single and attached houses than in apartments. Furthermore, the highest (42.5%) and lowest (13.9%) external shading coverages were found among single and attached homes, respectively.

These findings confirm an increased heat stress resistance in newer homes due to the gradual increase of energy efficiency requirements for new buildings in the Australian Building Code (Australian Building Codes Board, 2016) and solar panel subsidies in South Australia. The longitudinal changes in construction types and energy efficiency encountered in the survey substantiate that the homes surveyed are mostly representative of the existing building stock. An unexpected finding is that single houses had more heat stress resistant features than attached houses and blocks of apartments. Note that the potentially advantageous lower ratio of building surface per volume in attached homes and apartments can counterbalance the lack of heat stress resistant features.

**Table 2**
Connections of housing characteristics (age and wall materials) and construction types.

| Housing characteristics | Construction types | $\chi^2$ | df | $N$ | $p$ |
|---|---|---|---|---|---|
| Age of dwelling | Slab-on-ground structure | 71.41 | 2 | 290 | <0.001 |
| | Wall material | 50.31 | 2 | 316 | <0.001 |
| | Insulated walls | 54.93 | 2 | 390 | <0.001 |
| Wall material | Slab-on-ground structure | 27.17 | 1 | 252 | <0.001 |
| | Insulated walls | Fisher's exact test | | 339 | <0.001 |

## 4. The built environment and wellbeing during heatwaves

The heat stress resistance of the built environment was assessed in two ways. Firstly, respondents were asked about whether existing satisfactory coping capacities of their homes were a reason for not retrofitting. This parameter gave a subjective assessment. Secondly, respondents were asked to identify potentially heat stress resistant features of their homes; such as insulation, shadings, double-glazing, wall materials, floor structures and AC ownership, and also of their workplaces such as the availability and adjustability of AC. The coping capacities reported were positively associated with the number of heat stress resistant features at home ($\chi^2 = 18.83$, df = 2, $N = 392$, $p < 0.01$) and the availability of AC ($\chi^2 = 4.49$, df = 1, $N = 392$, $p < 0.05$), indicating that respondents evaluated their homes in a reasonable manner.

Respondents' wellbeing was surveyed during two subsequent heatwaves in February 2015, occurring a few weeks before the survey. Their wellbeing during heatwaves was assessed in two ways, such as the perceived strengths of two subsequent heatwaves and the self-reported, heat-related health symptoms of the latest heatwave. The strengths of both heatwaves, calculated by the EHF, were in the average range, considering heatwaves since 1970s in Adelaide (Nairn and Fawcett, 2013). Calculating the EHF load, which is the sum of the daily EHFs of each consecutive heatwave day (Nairn and Fawcett, 2013), the first heatwave was slightly stronger (72.59 °C$^2$ compared to 60.29 °C$^2$). Nevertheless, the second lasted longer (Table 4). No statistical difference was found between the average perceived heatwave strengths of the two heatwaves and that can be explained by the small difference in EHF loads.

A clear positive connection was found between heat-related health problems and heat stress perceptions. Those respondents who had health problems during the heatwave in question rated the heatwave stronger ($\chi^2 = 4.60$, df = 1, $N = 390$, $p < 0.05$).

Investigating the association between the built environment and wellbeing, respondents living in homes with poor coping capacities perceived the examined heatwave stronger ($\chi^2 = 9.68$, df = 4, $N = 389$, $p < 0.05$) and reported more health problems ($\chi^2 = 15.53$, df = 1, $N = 389$, $p < 0.01$). Less health problems were reported in homes with double glazing, insulated walls and roofs and with a high number of heat stress resistant features than in homes without any of these (Table 5). Note, that all of the listed characteristics of the built environment were in association with household incomes, covered in paragraph 4.1.

The availability of AC was positively associated with both the decreased number of health problems (Table 5) and reduced heat stress perceptions (Fisher's exact test, $N = 172$, $p < 0.01$) at work but not at home. Note that the availability of AC was 91.9% and 91.1% in commercial and residential buildings, respectively. The lack of association between the availability of AC and health at home challenges whether AC can be preventive to heat-related health problems as indicated by earlier studies (Bouchama et al., 2007; Davis et al., 2003; Ostro et al., 2010) and acknowledged widely in the literature (Hajat et al., 2010). This issue was discussed by Bélanger et al. (2015a), who reported the lack of preventive power of AC and its detrimental impact on the use of other adaptation techniques at home. They have, however, not considered the level of AC. Significantly less health problems were reported in homes with whole-house than with room-unit AC (Table 5), while it can be assumed that most of the commercial buildings had whole-building AC. This result coincides with a study from the US, which found only central AC as a preventive measure to heatwave at home (O'Neill et al., 2005). Centrally ducted homes were also reported to cope better with heatwaves and their occupants perceived lower number of heatwave days annually in Australia than homes with other types of AC (Saman et al., 2013).

The insignificant impact of room-unit AC on health can also be attributed to the rare use of cool retreats, when only one room is cooled and used during heatwaves. Although the wide implication of cool

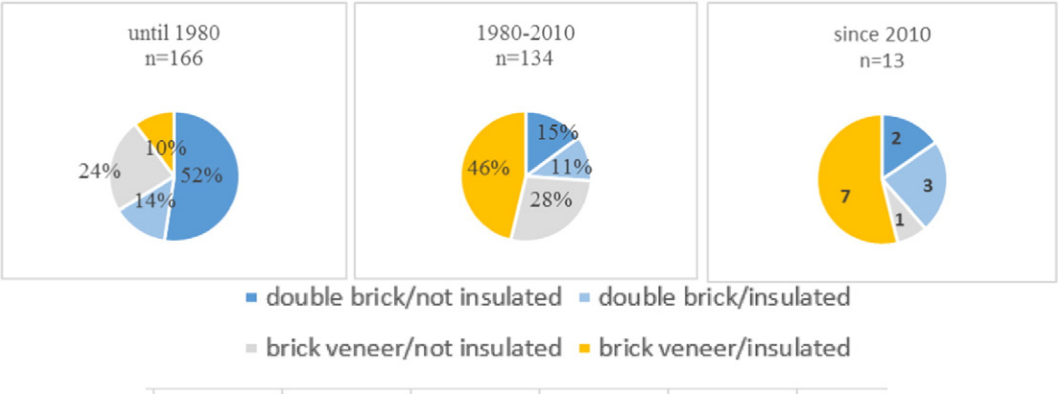

**Fig. 2.** Longitudinal changes in wall types and wall insulation based on the survey.

retreats in the built environment could result in significant energy savings (Saman et al., 2014), the findings indicate a behaviour barrier.

Surprisingly, the least severe cases were recorded among respondents, living in homes built before 1980, followed by homes built after 2010 (Fisher's exact test, $N = 77$, $p < 0.05$). This curious result might be explainable with the fundamental changes in prevalent construction types in the 1970s (Section 3). This finding shows that the loss of thermal mass and lack of substantial wall insulation in homes built between around 1980 and 2010 might be traceable in reduced heat stress resistance.

Those who had negative health issues during heatwaves were more willing to retrofit in the future ($\chi^2 = 9.73$, df $= 1$, $N = 389$, $p < 0.01$), suggesting that the experience of missing thermal comfort can be a driver to future retrofitting.

The connection presented between the heat stress resistant built environment and decreased number of self-reported health issues indicates that the built environment has a pivotal role in both the perception of heatwaves and more importantly in heat-related health problems. The changes in building construction methods led by regulations were traceable, along with their impact on wellbeing during heatwaves. Hence regulation towards more heat stress resistant homes could notably increase the population resilience against heatwaves. Future research should further investigate the preventive value of AC use in real world environment.

### *4.1. The built environment and demography*

Following Section 4 that showed the connections found between the heat stress resistant built environment and heat-related health problems, this section discusses the predictors of the heat stress resistant built environment.

The number of heat stress resistant features increased with respondents' age (Spearman's $r = 0.29$, $p < 0.01$) and income (Spearman's $r = 0.21$, $p < 0.00$). Note that income increased with age. Consequently, all respondents above 65 had at least one feature at home and they were the most likely to have insulated roofs (86.1%), internal (75.7%) and external shadings (50.0%) but unexpectedly the least likely to have green gardens (4.2%), (Table 6).

Although increasing income was not affiliated significantly with air-conditioner ownership, presumably due to the already very high coverage, (91.1%), higher income was associated with a higher level of AC. Families earning more than AU$1500 per week were more likely to have their roofs insulated than financially less affluent ones. High income earners (weekly income above AU$4000) and those with tertiary qualifications had windows with double glazing the most frequently. External shading devices, such as external blinds and shutters, were also more popular among respondents with higher qualifications.

Being a tenant had a significant negative connection with the coping capacities of homes ($\chi2 = 14.91$, df $= 1$, $N = 392$, $p < 0.01$). It can be attributed to the poor housing characteristics of tenancies. Rented homes had fewer heat stress resistant features and only 81.3% of tenants owned air-conditioners compared to 93.6% of non-tenant (Table 6).

To conclude, higher age, income, qualification and home ownership were associated with having more heat stress resistant homes. Tenants lived in less heat stress resistant homes than homeowners. Respondents above 65 lived in more heat stress resistant homes than the average. Interestingly, only external shading and double-glazing were associated with higher qualification.

Seeking the barriers to retrofitting, income was positively associated only with the size of the retrofitting budget (Spearman's $r = 0.55$, $N = 69$, $p < 0.00$), but not with the willingness to retrofit. Nevertheless, low income earners cited the expenses of retrofitting as a barrier more ($\chi2 = 10.86$, df $= 3$, $N = 194$, $p < 0.05$). The likeliness of future retrofitting was lower among respondents above 65 ($\chi2 = 8.09$, df $= 1$, $N = 392$, $p < 0.01$), the unemployed ($\chi2 = 5.84$, df $= 1$, $N = 392$, $p < 0.05$) and tenants ($\chi2 = 28.621$, df $= 1$, $N = 392$, $p < 0.01$).

The concept of an EPC (European Parliament, Council of the European Union, 2003; Szalay, 2008), already in use in the European Union (EU), might address the problems identified. Certification is compulsory for newly constructed buildings and for longer tenancies. The

**Table 3**
Connections between housing characteristics (types, age and wall types) and heat stress resistant features.

| Housing characteristics | Heat stress resistant features and relevant characteristics | $\chi^2$ | df | N | $p$ |
|---|---|---|---|---|---|
| Age of dwelling | Solar panel | 8.98 | 2 | 390 | <0.05 |
| Type of dwelling (single home, semi-detached home, apartment) | Insulated wall | 10.56 | 2 | 389 | <0.01 |
| | Insulated roofs | 21.95 | 2 | 389 | <0.001 |
| | External shadings | 11.37 | 2 | 389 | <0.01 |

**Table 4**
The meteorological parameters and the perceived strengths of the two heatwaves in question, in February 2015.

| Date | Daily maximum temperature | Daily mean temperature | Excess heat factor | Perceived heatwave strength ($N = 390$) (from neutral (1) to extreme strong (5)) |
|---|---|---|---|---|
| 13/02/2015 | 34.60 | 28.05 | −1.36 | Mean = 3.15 |
| 14/02/2015 | 41.60 | 34.05 | 17.63 | Min = 1 |
| 15/02/2015 | 38.60 | 33.70 | 37.63 | Max = 5<br>St. deviation = 1.07 |
| 16/02/2015 | 28.30 | 23.10 | 17.33 | |
| 19/02/2015 | 36.90 | 27.45 | −3.88 | Mean = 3.34 |
| 20/02/2015 | 38.80 | 31.35 | −2.51 | Min = 1 |
| 21/02/2015 | 39.50 | 32.65 | 18.35 | Max = 5 |
| 22/02/2015 | 40.00 | 31.70 | 32.59 | St. deviation = 1.05 |
| 23/02/2015 | 28.10 | 24.35 | 9.35 | |

**Table 5**
Connections between heat stress resistant features of the built environment and self-reported health problems.

| Heat stress resistant features at home | Wellbeing | $\chi^2$ | df | N | p |
|---|---|---|---|---|---|
| AC at work (yes/no) | Health problems | Fisher's exact test | | 172 | <0.05 |
| Level of AC at home | | 12.06 | 2 | 354 | <0.05 |
| Double-glazed windows | | 4.92 | 1 | 389 | <0.05 |
| Insulated walls | | 6.01 | 1 | 389 | <0.05 |
| Insulated roofs | | 5.81 | 1 | 389 | <0.05 |
| Number of heat stress resistant features | | Fisher's exact test | | 389 | <0.05 |

EPC provides a description of the main energy-efficient features of the building, assesses the energy performance and includes a list of recommended retrofitting techniques.

In the Australian Capital Territory, the energy efficiency calculation method from the National Construction Code has been adopted as a compulsory element for home acquisition since 1999. The introduction of such an EPC in the residential property market has increased the market values of more efficient homes (Australian Government Department of the Environment Water Heritage and the Arts, 2008). Such an increase in market value could be an effective incentive for landlords to retrofit in the hope of higher rents. Given that any energy-efficient retrofitting profits the tenants and only indirectly the landlords, the incentive is currently small for the decision-making landlords (Dowson et al., 2012). Furthermore, a recent national telephone survey in Australia showed that 92% of the population would like to learn information about building energy efficiency before acquisition or leasing (White et al., 2015). Although the mandatory EPC at the time of sale or release was proposed to be introduced nationwide (Belusko and O'Leary, 2010), it has not yet happened.

Based on the review of EPC in Europe, the certification could be completed with the financial implication of future retrofitting (Amecke, 2012). The survey results raise the question that government subsidies might not be the most efficient incentives for retrofitting, apart from for the most underprivileged social groups. Consequently, information dissemination about the expenses of retrofitting integrated in the EPC could better stimulate retrofitting. In case of Australia, requirements about heat stress resistance should be integrated in both the National Construction Code (Miller, 2015; Saman et al., 2013; Zuo et al., 2014) and a potential EPC.

To summarise, as Sections 4 and 4.1 described, people are aware of the heat stress resistance of their homes. They would be likely to develop their homes to enhance their wellbeing during heatwaves and they would like to know more about the energy efficiency of their homes. Therefore, an enhanced EPC tailored to the Australian conditions could be effective. The introduction of the EPC could trigger energy efficiency and heat stress resistance, increase their importance in property market value and raise the population awareness about their built environment leading to further community improvements.

**Table 6**
Associations between demography and heat stress resistant features.

| Demography | Heat stress resistant features at home | $\chi^2$ | df | N | p |
|---|---|---|---|---|---|
| Age | Insulated roof | 39.06 | 2 | 392 | <0.001 |
| | Internal shading | 19.67 | 2 | 392 | <0.001 |
| | External shading | 13.24 | 2 | 392 | <0.001 |
| | Green gardens | 6.49 | 2 | 392 | <0.05 |
| Income | Insulated roof | 5.69 | 1 | 337 | <0.05 |
| | Insulated walls | 9.94 | 2 | 337 | <0.01 |
| | Level of AC | 18.54 | 6 | 306 | <0.01 |
| | Double-glazing | 10.38 | Fisher's exact test | 337 | <0.05 |
| Qualification | External shading | 7.96 | 1 | 392 | <0.01 |
| | Double-glazing | 7.96 | 1 | 392 | <0.01 |
| Tenancy | Number of heat stress resistant features | 12.66 | 2 | 392 | <0.01 |
| | AC availability | 11.92 | 1 | 392 | <0.001 |
| Employment | Double-glazing | 3.85 | 1 | 392 | <0.05 |

## 5. Adaptation capacity and wellbeing during heatwaves

Adaptation capacities were investigated related to both self-reported health problems and heat stress perceptions. Although respondents who rated the heatwave in question as a stronger one adapted more at work ($\chi2 = 6.48$, df = 2, $N = 203$, $p < 0.05$), those who assessed the heatwave either stronger or weaker than the average adapted more at home ($\chi2 = 16.33$, df = 2, $N = 389$, $p < 0.05$). Although this result sounds contradictory at first, the bidirectional impact of adaptation and heat stress perception gives an explanation. Namely, more adaptive respondents efficiently reduced their exposures and consequently their perceptions of the heatwave, while a stronger heat stress perception triggered higher adaptation.

Respondents who had any heat stress related health problems adapted more at home ($\chi^2 = 5.88$, df = 1, $N = 389$, $p < 0.01$) (100% compared to 91.3%). Those who had more health problems during heatwaves used particular adaptation techniques more, such as planning the day, checking the weather forecast ahead, applying closed windows rules (keeping the windows closed when it is warmer outdoors than indoors) and nocturnal ventilation, having a cooling shower, moving to a cooler room, wearing light-coloured, loose-fitting clothes at home, and avoiding strenuous activities and checking the weather forecast at work (Table 7). These findings suggest that negative heat-related health problems could raise alertness and adaptation, which is consistent with an earlier study (Bélanger et al., 2015a).

Meanwhile, the lack of adaptation at work was associated with the most severe health symptoms (Fisher's exact test, $N = 37$, $p < 0.05$), indicating that the lack of adaptation can have a negative impact on health. These findings highlight that a bidirectional relationship exists between wellbeing during heatwaves and adaptation that cannot be fully explored with a one-off survey.

### 5.1. Demography and adaptation

After the association between adaptation and wellbeing was explored, the demographic drivers of adaptation were investigated. Table 8 and Table 9 present the demographic variables found in association with adaptation types. At home, adaptation increased with age. Of the respondents under 24, only 44.7% adapted compared to the 95.1% of those over 65. The result of high adaptation among people above 65 is consistent with Nitschke et al. (2013) but contradicts Bélanger et al. (2015a). Note that Nitschke et al. (2013) surveyed population over 65, in Adelaide, while Bélanger et al. (2015a) focused on a less affluent population in Canada. The highest adaptation among the oldest respondents might be attributed to their preferences for cooler temperatures reported in a recent study from Adelaide (Bills and Soebarto, 2015). Current knowledge about older people's heat stress perception is, nevertheless, incomplete (Sumavalee et al., 2016).

Older respondents, however, acted in a comfort driven way, which refers to ‘adapting by not acting’ reported in earlier studies (Bélanger et al., 2015a; White-Newsome et al., 2011). They were not just less likely to leave their homes to go to a nearby air-conditioned building, a swimming pool, the beach or hills, but they were also more reluctant to move to a cooler room within their homes (Table 8). In contrast, increasing age was associated with increased garden watering (where garden vegetation was available), use of closed windows rules, a sun hat, or an AC (with 100% usage among people over 65). The higher adaptation capacity of older people can be attributed to their cultural context to a certain extent, developed from the frugal pre and post war period in Australia. Older people accustomed to heatwaves in their early ages without AC, relying solely on natural adaptation techniques.

**Table 7**
Associations between wellbeing and adaptation types.

| Self-reported, heat-related health problems | Adaptations | $\chi^2$ | df | N | p |
|---|---|---|---|---|---|
| | Adaptation at home | | | | |
| Health problems | Planning the day | 7.86 | 1 | 389 | <0.01 |
| | Check the weather forecast | 8.34 | 1 | 389 | <0.01 |
| | Closed windows rules | 7.88 | 1 | 389 | <0.01 |
| | Nocturnal ventilation | 4.03 | 1 | 389 | <0.05 |
| | Having a cooling shower | 9.29 | 1 | 389 | <0.01 |
| | Move to a cooler room | 13.99 | 1 | 389 | <0.001 |
| | Adjust clothing | 4.86 | 1 | 389 | <0.05 |
| | Adaptation at work | | | | |
| | Avoid strenuous activities | 4.56 | 1 | 204 | <0.01 |
| | Check the weather forecast | 4.31 | 1 | 204 | <0.01 |

Therefore, they still have a higher willingness to use these traditional adaptation techniques than the younger population.

Respondents with fewer daily commitments, such as the oldest and youngest respondents, and those out of the labour force, checked the weather forecast, planned the day ahead and avoided strenuous activities more (Table 8 and Table 9). In contrast, families with two or more kids were the least able to check the weather forecast and plan the day ahead. The same pattern was found regarding the closed windows rule, which was used much less in larger families. These patterns show that inconvenience and time might be a barrier to adaptation for middle-aged working class, especially with families.

Respondents with tertiary qualifications moved to a cooler room, adopted cool retreats in their homes, used shading and stayed at work longer to take advantage of the AC more. The use of clothing-related adaptation techniques were, however, limited among people with higher qualifications and respondents between 24 and 65, presumably due to cultural and workplace expectations.

Sunscreen was used more by females and families with two or more kids. Families visited swimming pools more. Swimming pools were, albeit, less preferred by low-income earners and unemployed people, suggesting that admission price can be a deterrent factor.

Overall, significantly fewer respondents adapted at work (87.2%) than at home (93.1%) ($\chi^2 = 4.41$, df = 1, $N = 203$, $p < 0.05$) and the proportion of adaptation techniques applied was different. Techniques requiring flexibility, such as wearing light-coloured clothes ($\chi^2 = 19.31$, df = 1, $N = 365$, $p < 0.01$), moving to a cooler room ($\chi^2 = 68.27$, df = 1, $N = 365$, $p < 0.01$), or keeping the shading closed ($\chi^2 = 73.31$, df = 1, $N = 365$, $p < 0.01$) were significantly more popular at home than at work. In contrast, water drinking was used significantly more at work than at home ($\chi^2 = 6.14$, df = 1, $N = 365$, $p < 0.05$). These differences can be explained by the workplace expectations and restrictions. The limited use of shading at work might be attributed to the lack of shading devices at work, or its side-effect on reduced natural light. Respondents who adapted at work were more likely to adapt at home (Fisher's exact test, $N = 202$, $p < 0.01$), showing that individuals' customs are important.

**Table 8**
Associations between age and adaptation types.

| Demographical characteristics | Adaptation | $\chi^2$ | df | N | p |
|---|---|---|---|---|---|
| Age | Adaptation (yes/no) | 8.33 | 2 | 392 | <0.05 |
| | Go to an air-conditioned building | 7.19 | 2 | 365 | <0.05 |
| | Go to a swimming pool | 18.28 | 2 | 365 | <0.001 |
| | Go to beach or hills | 9.41 | 2 | 365 | <0.01 |
| | Move to a cooler room | 7.63 | 2 | 365 | <0.05 |
| | Water the garden | 11.62 | 2 | 335 | <0.01 |
| | Check the weather forecast | 16.62 | 2 | 365 | <0.001 |
| | Plan the day ahead | 20.72 | 2 | 365 | <0.001 |
| | Avoid strenuous activities | 14.20 | 2 | 365 | <0.001 |
| | Wear a sunhat | 28.92 | 2 | 365 | <0.001 |
| | Closed windows rule | 12.29 | 2 | 365 | <0.01 |
| | AC | | Fisher's exact test | 334 | <0.01 |

To conclude, different adaptation techniques were preferred by different social groups. Although older people adapted the most, they were more comfort driven. Meanwhile, middle-aged people and those with family were more time and commitment driven. Some particular adaptation techniques, such as cool retreat and shading, were used more by respondents with tertiary qualifications. These findings could be utilised in heatwave messages and education targeting specific social groups. For example, the limited usage even of weather forecast raises concerns about efficient heat-health message dissemination in the middle-aged population with families. Besides, it would be important to minimise external deterrents and maximise opportunities for adaptation at work. For example, relaxing dress codes during heatwaves would be beneficial.

### *5.2. The built environment and adaptation*

The adaptation techniques used at work were grouped according to the availability of AC (Table 10). Surprisingly, respondents avoided strenuous activities less at non-air-conditioned workplaces (Fisher's exact test, $N = 148$, $p < 0.05$), which might be attributed to more labour intensive work done at non-air-conditioned workplaces. Unfortunately, the availability of thermostat setting discouraged workers from passive adaptation techniques, such as shading ($\chi^2 = 5.9$, df = 1, $N = 137$, $p < 0.01$) and water drinking (Fisher's exact test, $N = 137$, $p < 0.05$) (Table 10). A similar pattern was found at home. Respondents with AC at home used natural ventilation during the night less (47.9% compared to 71%) than those living in non-air-conditioned homes ($\chi^2 = 5.15$, df = 1, $N = 365$, $p < 0.05$). Nevertheless the actual use of the installed air-conditioners did not further influence nocturnal ventilation. The detrimental impact of AC on other passive adaptations has been highlighted in an earlier study (Bélanger et al., 2015a). The decreased passive adaptation provides an explanation for the narrower range of acceptable temperatures for occupants in air-conditioned buildings compared to naturally-ventilated ones, reported in earlier studies (Baker and Standeven, 1996; Brager and de Dear, 1998; Cândido et al., 2010; de Dear and Brager, 2002).

The prevalence of the use of AC during heatwaves varied with the levels and types of AC. The higher the level of AC the more it was used (Fisher's exact test, $N = 334$, $p < 0.01$), resulting in 99.5% use in households with whole-house AC compared to 90.9% in households with one room-unit AC. The same pattern was detectable among AC types, where the use of AC was significantly lower for window/wall units (90.7%) than split systems (96.3%) or ducted system (100%) (Fisher's exact test, $N = 326$, $p < 0.05$). These results imply that AC is used more when available in more rooms of the house. The increased reliance on AC was also concluded by Cândido et al. (2010) calling AC addictive. High reliance on AC can be especially detrimental in countries, such as Australia, where overcooling of the indoor environment in commercial buildings during summer is widely practised (de Dear, 2012). In contrast, practices encouraging the mix of natural and mechanical ventilation, such as the adoption of adaptive comfort model in residential buildings, could provide a sustainable solution (Saman et al., 2013). Note that energy poverty could also be a reason for the limited use of AC in low income households (Chester, 2013), with potentially more obsolete and inefficient window/wall units. However, income did not predict the use of AC in the survey.

In summary, both the availability and adjustability of AC at home and work, respectively were associated with the decreased use of other available adaptation techniques. Having AC at home, although increased significantly the perceived home coping capacity, did not have impact on the overall heat stress perception or the heatwave-related

**Table 9**
Associations between demography and adaptation types.

| Demographical characteristics | Adaptation | $\chi^2$ | df | N | $p$ |
|---|---|---|---|---|---|
| Being out of the labour force | Check the weather forecast | 9.55 | 1 | 365 | <0.01 |
| | Plan the day ahead | 8.64 | 1 | 365 | <0.01 |
| | Avoid strenuous activities | 4.16 | 1 | 365 | <0.05 |
| | Go to a swimming pool | 13.85 | 1 | 365 | <0.001 |
| Families with less than two kids and families with two or more kids | Check the weather forecast | 7.53 | 1 | 365 | <0.01 |
| | Plan the day ahead | 4.83 | 1 | 365 | <0.05 |
| | Sunscreen | 6.01 | 1 | 365 | <0.05 |
| | Go to a swimming pool | 12.51 | 1 | 365 | <0.001 |
| Singles, families with maximum three members and families with more than three members | Closed windows rule | 8.20 | 2 | 365 | <0.05 |
| Income | Go to a swimming pool | 17.65 | 3 | 312 | <0.001 |
| Gender | Sunscreen | 8.98 | 1 | 365 | <0.01 |
| Qualification | Move to a cooler room | 4.63 | 1 | 334 | <0.05 |
| | Cool retreat | 5.40 | 1 | 334 | <0.05 |
| | Adjust clothing | 6.47 | 1 | 365 | <0.05 |
| | Take advantage of AC at work | 10.57 | 1 | 187 | <0.001 |
| | Shading | 8.11 | 2 | 148 | <0.05 |

health outcomes (Section 4). Only whole-house compared to room-unit AC was correlated significantly with the decrease of the number of health issues. To conclude, AC can decrease the use of other adaptation techniques, increase dependence on it, and perhaps whole-house AC works only as an effective prevention for heatwave-related health issues presumably due to the lack of adoption of cool retreats.

Compared to the detrimental impact of AC on passive adaptation, the higher the number of heat stress resistant features at home were available the more adaptation techniques were applied (Spearman's $r = 0.17$, $N = 362$, $p < 0.01$). Although no significant connection was found between the level of adaptation at home and the home coping capacity, those who found the coping capacities of their homes sufficient applied shadings more ($\chi^2 = 4.87$, df = 1, $N = 283$, $p < 0.05$).

Considering the excess negative impact of central AC on energy consumption and the positive impact on heatwave related health outcomes a challenging trade-off is faced. In contrast, the number of passive heatwave features at home increased the number of adaptations applied and decreased the number of heatwave-related health issues (Section 4). These results indicate that the development of a better built environment has a triple positive impact, including a direct effect on decreased energy consumption, an indirect effect through the increased adaptation, and the decreased number of health issues.

## 6. Demography, the built environment, adaptation and relevant knowledge

More confidence about heat stress resistant features at home was reported by respondents who were males, older, homeowners and, unexpectedly, those who had lower educational qualifications (Table 11). Increasing age was associated also with more knowledge about adaptation (Spearman's $r = -0.14$, $N = 392$, $p < 0.00$). It might be explained by the fact, discussed in Section 5.1, that older people in their early ages could not rely on AC and learnt the usage of other adaptation techniques. More confident in answering questions about heat stress resistant features were those who had at least one heat stress resistant feature at home, their homes could cope well with heatwaves or lived in single houses. Nevertheless, the number of self-reported, heat stress resistant features should be taken with reservations, because of the limitation of the survey tool used.

The lack of knowledge about retrofitting ($\chi^2 = 9.49$, df = 3, $N = 194$, $p < 0.05$) as obstacles to retrofit was cited by the most by low-income earners, and in general decreased with age ($\chi^2 = 7.15$, df = 2, $N = 229$, $p < 0.05$). Respondents who had more confident knowledge about different heat stress resistant features in their homes, furthermore, applied more adaptation techniques ($\chi^2 = 7.26$, df = 2, $N = 365$, $p < 0.05$). In conclusion, respondents who were more confident about the heat stress resistant features of their homes were more likely to live in homes with more heat stress resistant features, planned to retrofit in the future and adapted more. Although causality cannot be deduced from the connections found, the findings imply that a broader education about the built environment, adaptation to and retrofitting against heatwaves could foster the enhancement of both the built environment and the adaptation capacity. Currently, the relative lack of confident knowledge about the heat stress resistant characteristics of the built environment (34.9%), and specific adaptation (up to 50%) and retrofitting techniques (19%) is subject to concern, especially in the younger population. The EPC discussed in Section 4 could increase the population knowledge about the built environment.

## 7. Vulnerability and wellbeing

Vulnerability variables that have been found associated with heat-related morbidity in the literature, were assessed in relation to both self-reported health problems and heat stress perceptions. More females reported health problems ($\chi^2 = 12.83$, df = 1, $N = 390$, $p < 0.01$) than males, especially females under the age of 24 compared to older females ($\chi^2 = 4.03$, df = 1, $N = 210$, $p < 0.05$). No significant difference was found in the severity of the symptoms between genders so the higher susceptibility among females was not explainable by milder symptoms. Bélanger et al. (2014) found a similar pattern in

**Table 10**
Associations between adaptation types and AC types.

| Adaptation types | AC types among indoor workers | | | | |
|---|---|---|---|---|---|
| | Individually adjustable AC ($N = 63$) | Centrally controlled AC ($N = 74$) | No mechanical AC ($N = 11$) | Indoor workers ($N = 148$) | Outdoor workers ($N = 29$) |
| Drink plenty of water | 92.1% | 100.0% | 100.0% | 96.6% | 100.0% |
| Use AC | 92.1% | NA | NA | 89.2% | NA |
| Keep shadings (curtains, awnings etc.) closed | 41.3% | 63.5% | 63.6% | 54.1% | NA |

**Table 11**
Associations between demography, the built environment, adaptation and knowledge about the heat stress resistant features at home.

| Demography, characteristics of the built environment and adaptation | Knowledge | $\chi^2$ | df | $N$ | $p$ |
|---|---|---|---|---|---|
| Gender | | 15.36 | 1 | 392 | <0.001 |
| Age | | 42.49 | 2 | 392 | <0.001 |
| | | 79.68 | 6 | 392 | <0.001 |
| Qualification | Knowledge about the heat stress resistant features at home | 6.23 | 1 | 392 | <0.05 |
| Type of homes | | 15.75 | 2 | 389 | <0.001 |
| One or more heat stress resistant features at home | | 46.98 | 1 | 392 | <0.01 |
| Home has sufficient coping capacity | | 18.24 | 1 | 392 | <0.01 |
| Tenants | | 21.26 | 1 | 392 | <0.001 |

Canada, where females had more complaints than males, though only under 65. Females were also found more at risk in terms of self-reported health symptoms in an earlier survey undertaken with a representative population over 65 in Adelaide (Nitschke et al., 2013) and in a recent study about health symptoms surveyed in public spaces in the Mediterranean (Pantavou et al., 2015). Overall, there is an uncertainty in the literature, whether gender influences the vulnerability to heatwaves or not (Hajat et al., 2007; Li et al., 2015; Ye et al., 2012).

Females also perceived heatwaves stronger than males, during both the first ($\chi2 = 11.46$, df $= 2$, $N = 390$, $p < 0.05$) and the second heatwaves ($\chi^2 = 12.96$, df $= 2$, $N = 390$, $p < 0.05$). Females have been repeatedly found to be more susceptible to heat stress in earlier studies, even though in slightly different contexts, such as heatwave risk perception (Akompab et al., 2013) and the annual number of days with heat stress (Saman et al., 2013). To conclude, the results support that heat perception is higher among females than males.

Fortunately, females (93.4%) were more willing to adapt ($\chi^2 = 9.34$, df $= 1$, $N = 203$, $p < 0.01$) than males (77.8%), albeit only at work. Bélanger et al. (2015a), investigating underprivileged households in Canada, also found higher levels of adaptation among females under the age of 64. It might explain, why females have been associated with higher morbidity in only some of the studies (Ye et al., 2012).

Having any pre-existing health conditions was significantly associated with health problems during heatwaves ($\chi^2 = 16.71$, df $= 1$, $N = 390$, $p < 0.01$), and a greater number of health conditions triggered further health problems ($\chi^2 = 26.8$, df $= 2$, $N = 390$, $p < 0.01$). However, no particular condition was affiliated with a higher number of issues during heatwaves. Having pre-existing health conditions has been a widely reported predictor in the literature (Li et al., 2015). Although the number of people with pre-existing health condition(s) was increasing with age ($\chi^2 = 7.84$, df $= 2$, $N = 390$, $p < 0.05$) and independent of income, an unexpected result was that heat-related health problems were not influenced by age.

Even though the majority of the literature found age as an important predictor of vulnerability to heat in Australia (Li et al., 2015), in a previous study in Adelaide, age was found as a risk factor in univariate but not in multivariate analysis of heat-related hospitalisation (Zhang et al., 2013). A recent study about outdoor thermal comfort from Athens has also found pre-existing health conditions predictive of self-reported health symptoms but not age (Pantavou et al., 2015). Consequently, pre-existing health conditions might be a stronger predictor of heat-related health problems than age, also identified as a preponderant risk factor by Bélanger et al. (2014). It can be attributed to the pattern encountered that older people lived in more heat stress resistant homes (Section 4.1) and adapted more (Section 5.1). These results suggest, in line with an earlier study from Adelaide (Nitschke et al., 2013), that the population over 65 has already received heatwave health messages and behaved accordingly. In contrast, people with health conditions still do not see themselves more vulnerable. Respondents with pre-existing health conditions did not perceive the heatwave stronger, adapt more at home, have more heat stress resistant features, or plan to retrofit in the future more.

Being a tenant had a significant negative association with both heat stress perceptions ($\chi2 = 6.85$, df $= 2$, $N = 392$, $p < 0.05$) and health problems ($\chi2 = 10.34$, df $= 1$, $N = 392$, $p < 0.01$). This association reflects the conclusion of Baker et al. (2014), that rental tenure predicts poorer health status, in general, than owner-occupation. The high heat-related health problems among tenants can be attributed to their poor housing characteristics. Rented homes had fewer heat stress resistant features and only 81.3% of tenants owned air-conditioners compared to 93.6% of non-tenants (Section 4.1). Investigating the demographic variables related to renting, tenancy is not income- but age-related ($\chi2 = 19.07$, df $= 2$, $N = 392$, $p < 0.01$), with increasing housing ownership with age. Surprisingly, families with two or more children were more likely to rent their homes ($\chi2 = 4.23$, df $= 2$, $N = 392$, $p < 0.05$).

Respondents with higher household income rated the second heatwave significantly weaker, similar to the findings of Saman et al. (Saman et al., 2013) about the less number of heatwave days perceived annually by higher income earners ($\chi^2 = 13.15$, df $= 6$, $N = 335$, $p < 0.05$). The perception of the first heatwave was, nevertheless, not weaker by higher income earners and that might be caused by the limitation of human retrospective review.

In conclusion, future heatwave prevention measures should target the population with pre-existing health conditions, females and those renting their homes, who were at high risk. People with pre-existing health conditions were often oblivious to their higher vulnerability, while tenants had poorer than average heat stress resistant homes. Patients with pre-existing health conditions should be encouraged to: apply the full range of adaptation techniques, retrofit their homes, learn more about and seek diagnosis and treatment in case of heat-related symptoms. The poor housing quality of tenancies could be addressed by the introduction of the EPC (described in Section 4).

## 8. Conclusions

The study used a survey to identify the drivers and barriers to a heat stress resilient urban population. Significant connections were found between the elements of heat stress resilience, including the heat stress resistance of the built environment, the level of adaptation and vulnerability to heat-related negative health issues.

A novelty of this research is that the real-world impacts of a wide variety of heat stress resistant building features were analysed according to wellbeing during heatwaves. Increased heat stress resistance has the potential to foster the population's adaptation capacity and wellbeing during heatwaves, and decrease energy consumption. The introduction of an EPC could encourage the development of heat stress resistance, minimise cooling demand and the role of AC. Compared to passive heat stress resistant building features, the availability of AC increased the reliance on AC and decreased the use of other passive adaptation techniques. Its preventive power against heat-related health problems was limited to whole-house AC at home.

Tenancy was identified as a predictor of health problems during heatwaves due to poor housing quality. The EPC could serve as an incentive for landlords to retrofit their tenancies with the advantage of increasing property value and tenant fees. The introduction of this certificate would be particularly beneficial, if tenancy is primarily age and not income driven.

Targeted education of the population about their built environment, adaptation and retrofitting techniques would be essential. Knowledge development could foster both adaptation and retrofitting. The introduction of an EPC would broaden the knowledge of the general population about heat stress resistance. Knowledge dissemination through the EPC could trigger higher retrofitting activity, since willingness to retrofit is not income-related. Further studies should evaluate the benefits and learnings from the EPC system in Europe and in the Australian Capital Territory, and its potential further implications in Australia.

Adaptation techniques adopted during heatwaves varied with social groups. Older people were more comfort driven, while employed, middle-aged people living in families were more time and commitment driven. Consequently, tailored health messages would be essential for different social groups.

People with pre-existing health conditions and females were found as high risk groups during heatwaves. While higher perception and adaptation were found at work among females, people with poor health were oblivious of their vulnerability. In contrast, older people were not more vulnerable presumably due to the higher level of adaptation and heat stress resistance in their homes. Heatwave messages seem to have been received by the older population, while future preventive measures should focus more on people with pre-existing health conditions.

The findings of the study are useful for policymakers working in the realms of housing and urban planning to create guidelines and regulations for heat stress resistant building design and retrofitting. Such policies could decrease the negative health outcomes of heatwaves and populations' overdependence on AC. There is a missing knowledge about heat stress resistant design in the Australian climate and future research should explore the real-world impact of AC on heat stress resilience. The new knowledge gained about the differences in adaptation types adopted by different social groups should be integrated in heatwave messages. The high level of vulnerability of population with pre-existing health conditions identified will be useful to pay more attention to this social group by health services and in heatwave management plans.

A limitation of the study was that the sample was representative only for but not across age groups and genders. Younger females were over-represented while older females were under-represented. This limitation was addressed by identifying the gender and age discrepancies. The results were reported only if the correlation was significant also within age or gender subgroups. Another limitation was the size of the sample size in terms of the selection of the analysis method. Multilevel analytical approach (Merlo, 2003) might be an alternative approach to analyse such a complex model, presented in Fig. 1. However, that would have required a much larger sample size, presumably with several thousand responses, since multilevel analysis required minimum sample sizes for each level of analysis, categorized by the variables. The characteristics of the online survey caused a further limitation, namely that only people with at least minimal computer literacy could access the questionnaire.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.07.028.

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