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Warm house, Cold house: a review of measures of thermal comfort used in Get Bill Smart's energy efficiency assessments

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Abstract

Managing thermal comfort, in both hot and cold climates, critically influences energy use in homes [1-4]. For low income households, who commonly live in thermally poor housing stock, maintaining thermal comfort can be costly relative to household income, leading to trade-offs between comfort, energy use and affordability. Comfort as a concept has been explored from many vantages, including as a physiological need [5,6]; a parameter for healthy housing [7]; as an energy efficiency building standard [4,8] and a cultural construct [9,10]. Yet, there is little research available that provides detailed insight into the relationship between thermal comfort and energy efficiency in existing housing stock or about the impact of support programs on these key indicators. This paper reviews measures of household thermal comfort as they relate to energy efficiency assessments in a project, Get Bill Smart (GBS), that worked with low income households in Tasmania, Australia. Thermal comfort and energy use data was collected over 15 months from 51 households, a sub-set of the 510 households participating overall. Longitudinal interviews and housing observations were also conducted. New thermal comfort and energy efficiency indicators were developed from this data. This paper demonstrates the application of these indicators by providing examples of findings in GBS. Suggestions are made for the refinement of measures discussed for use in future applications.

1. Introduction

Managing thermal comfort in homes is known to critically influence domestic energy use and energy bill affordability [1-4]. Indeed, the Australian Bureau of Statistics have repeatedly shown that thermal comfort is a primary reason Australians make energy-related changes in their homes [1,2,3]. For low income households, who commonly live in thermally poor housing stock, trade-offs often have to be made between maintaining thermal comfort and paying unaffordable energy bills, leading to negative social, physical, cost and environmental impacts [11-16]. Despite recognition of the troubling trade-offs low income

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householders make, there is little data available that provides detailed insight into the relationship between thermal comfort and energy efficiency in existing housing stock, or whether energy efficiency support programs can influence this relationship.

The Get Bill Smart (GBS) project investigated how to best support energy efficiency and thermal comfort in low-income households in Greater Hobart, Tasmania, Australia. Funded as part of the Commonwealth Government's Low Income Energy Efficiency Program (LIEEP), GBS ran from July 2013 to June 2016. The project was led by Mission Australia (a not-for-profit service provider); managed by Sustainable Living Tasmania (SLT); and monitored and evaluated by the University of Tasmania (UTAS).

Tasmania is a state with comparatively poor socio-economic indicators, cold winters and relatively old (thermally poor) housing stock, leading to it having the highest heating–degree hours in the country, and to low-income households experiencing significant energy bill stress [11,16]. Despite generally using much less energy than affluent households, Tasmanian low income householders' energy bills tend to take up far higher proportions of their incomes [17]. Among other aims, GBS therefore investigated the relationship of thermal comfort to energy use and energy efficiency and the trade-offs occupants made between them. Two approaches to energy efficiency support were trialed in GBS: a community capacity-building approach in one defined local community area; and, a conventional in-home energy efficiency upgrade approach over the whole of the Greater Hobart area. The community capacity building approach was a novel way to support household energy efficiency activity and, using a strengths-based philosophy, [18, p19] engaged locals as energy efficiency champions. The two approaches were tested in 3 groups: in-home education and upgrades only; community capacity building activities only; and, in-home education and upgrades and community capacity building combined. A fourth, representative group (who received vouchers instead of energy efficiency support) provided a comparison for the other groups.

The project collected data over 15 months in 510 different low income households and had to therefore develop practical, low interference approaches to data collection. Changes in energy use and related practices were measured with all 510 households through: surveys conducted before and after support activities were delivered; and through data from household electricity bills. Understanding thermal comfort levels and detailed energy performance in participant homes required more in-depth research and was conducted as part of the GBS Detailed Study [19]. With a participant sub-set of 51 households, the Detailed Study drew households from all four GBS approach groups in roughly equal numbers. Taking a mixed-methods (qualitative and quantitative) approach, this detailed examination augmented the research conducted with the overall participant group by exploring more complex, nuanced aspects of household energy and comfort performance [20]. The Detailed Study provided understanding of personalised dwelling experiences; dynamics and variations between households; and key influences affecting energy use and thermal comfort levels in homes.

With interest in exploring further what can be done in mixed-method, longitudinal, real world research projects like GBS and with an intention of on-going methodological improvement, this paper examines and critiques measures of thermal comfort used in the energy efficiency assessments carried out in GBS. In what follows this paper: outlines the GBS project; presents key concepts and measures relating to thermal comfort; outlines methods used in GBS to collect detailed thermal and energy data; presents selected GBS findings and discussion related to these; and makes suggestions for the refinement of the measures of thermal comfort and energy efficiency that are examined.

2. Thermal comfort and energy efficiency

Thermal comfort has been explored as a physiological need [5,6] and (related to this) as a parameter for healthy housing [7]; as a building design parameter [4] and (consequently) as an energy efficiency standard [8], and as a cultural construct [9,10]. Culturally, notions of comfort have developed and changed over time [9,10] but physiological thermal comfort has always been necessary for human health and wellbeing [6,21]. A multi-country study found that three to eight per cent of all deaths were likely attributable to thermal distress, with a higher proportion of these being from cold [22]. Interestingly, Howden-Chapman identified that temperate climates like Tasmania, rather than more extreme cold climates, may have a 'greater impact on avoidable mortality' because houses are less thermally efficient and warm clothing practices are not as systematic [12, p163]. Health gains from improved thermal conditions indoors are a significant outcome of energy efficiency upgrade programs [23, 24] and benefit householders, broader communities and governments. Recognition of the health benefits of energy efficiency programs and consequent savings for health systems in New Zealand (NZ) has led to the creation of multiple energy efficiency programs. Grimes et al. established for one program, 'Warm up New Zealand's' 'Heart Smart' program that $8 paid for energy savings activities generated $608 of health benefits (for example in reduced mortality, less hospitalisations and reduced pharmaceutical use)[25].

Indoor thermal comfort is recognized as an important technical parameter in building design, building science and consequently also in building construction standards [4]. Much current understanding about indoor thermal comfort zones stems from the study of psychrometry [26]. Modern psychrometric evaluation defines human comfort zones for varying climates using three key measures: dry bulb temperature (DBT), wet bulb temperature (WBT), and relative humidity (RH). GBS measured DBT and RH. While the relationship of RH to mould levels and indoor health is well recognized [12,27,28] and was examined in GBS, this paper focuses on DBT. In Australia energy efficiency design standards support reasonable levels of thermal comfort performance in housing through the National Construction Code (NCC) [8]. The NCC standards apply to new homes being built and substantial renovations but not to older un-renovated homes, which low income households tend to occupy.

In the NCC, energy efficiency of residential buildings is assessed under the National House Energy Rating Scheme (NatHERS). NatHERS software bases its predictions of energy consumption on an 'adaptive theory of thermal comfort'[4] which originally developed from psychrometric comfort zones. In NatHERS software a house's predicted energy consumption is calculated based on the assumption that if the temperature falls outside of identified comfort zones, then heating or cooling is activated to bring the temperature back to within these zones. Adaptive theory of thermal comfort and NatHERS assume that inhabitants of a particular location are able to acclimatize, to an extent, to that climate, and therefore thermal conditions in which physiological comfort is attained will be different in different climate zones. For example, in Tasmania NatHERS assumes the comfort zones for living rooms are 20-23°C, for bedrooms are 15-23°C overnight and 18-23°C during the morning and evenings; in Cairns NatHERS extends the top of the thermal comfort range to 26.5°C. Comfort zones in NatHERS vary for differing rooms of the house (for example bedrooms, living rooms, bathrooms) based on assumptions about activity levels and clothing levels of the occupants when in those rooms.

Relatively recently socio-technical scholars have sought to expand notions of comfort through the investigation of individual and cultural perceptions and practices related to thermal comfort. These scholars have enriched our understanding, exploring influences such as: cultural expectations about clothing and how they may effect heating and cooling; expectations about housing; habitual practices related to staying comfortable; and the effects of technical equipment 'scripts' on how we act [10,29-33]. This large body of work provides a richer, more complex perspective of thermal comfort subject that incorporates physiological, psychological and cultural phenomena.

Combined understanding from building science and social-technical studies has provided a space in which new mixed-method research approaches have developed that explore the relationship between energy use, energy efficiency, and thermal comfort. An evolved, mixed-method approach was used for the Housing, Insulation and Health (HIH) Study conducted in New Zealand in 2001-2002[34]. This study, of 1350 houses in seven communities, discussed health in interviews and recorded subjective temperature assessments. The study also conducted a sub-study with 140 houses where temperature and relative humidity were recorded in the main bedroom of each participant house every 15 minutes. Building inspectors visited the sub-study houses to assess physical building conditions, including the degree of damp and mould in each house. At 14 houses, randomly selected out of the 140, temperature and humidity were also continuously recorded outside. Budget limitations were reported as having influenced the way thermal comfort was measured in the HIH study. While one sensor per house and only 14 outside sensors all together is limited, they still provided a broad and very useful indicator of performance for thermal comfort and allowed the study to establish that added insulation had made a difference to indoor temperatures and to the health of occupants. Using mixed-methods and multiple scales of investigation the HIH study was able to record thermal comfort performance alongside other important phenomena. The GBS project built on the HIH mixed-method approach, combining building science and socio-technical approaches in order to achieve a more nuanced, complex understanding.

3. Methods

In-depth explanation of methods and ethics approvals for GBS research are provided in project reports [18,19]. Methods described here relate to the collection of, and analysis of, thermal comfort and energy efficiency data for the Detailed Study. Evaluating these methods is the key aim of this paper. Hence, we go into some depth describing the thermal comfort and energy measures and the indicators developed as part of GBS. This paper does not aim to evaluate the success of GBS support activities more generally.

Participants for GBS were recruited through SLT, who were GBS project managers. At sign-on, participants were asked to take part in the Detailed Study component of the project. GBS researchers (UTAS and RED Sustainability Consultants) visited each Detailed Study participant house three times. At initial visits (in May to July 2014) electricity and temperature logging equipment was installed, house observations were conducted and 'before' interviews were held. Interim visits (in February 2015) were held to maintain personal contact with participants; check and maintain logging equipment; and, record any relevant changes (made to appliances, the house, household occupant numbers and household practices). At the third visit (in August and September 2015) logging equipment was removed, any relevant changes were again noted and 'after' interviews were conducted. Energy efficiency support activities were conducted for relevant households over the August – Dec 2015.

Design and selection of equipment and techniques for data gathering were aimed at keeping intrusion in homes to a minimum. It was not possible or practical to set up full instrumentation in place (e.g. globe thermometer, anemometer) or to gather diarized data on daily clothing or activity patterns. Interviews, however, did cover seasonal changes in clothing and home practices.

Data logging periods generally lasted 15 months and included winter periods in 2014 and 2015. Data collected included: temperature/humidity measurements; measurements of electricity consumed by heating appliances; housing observations of physical features affecting energy use and comfort; structured survey responses; and, semi-structured interview responses. Responses, measures and observations were compared between the 2014 (before) winter and the 2015 (after) winter (when support activities had been completed). Temperature and humidity data were recorded using in-situ, stand-alone USB temperature (DBT) and humidity (RH) loggers, which recorded at 30-minute intervals over the full data collection period. Three or four temperature/humidity loggers were installed at each house: one in a main living area; one in an important bedroom; one externally in a sheltered space; and, depending on the layout of the house, one in another room. This arrangement of loggers allowed comparison of internal and external temperatures at each individual house. Wireless, plug-in electricity sensors were

placed on every heating device in the home. A current clamp sensor was also placed on each circuit in the electrical meter board. These sensors fed accumulating, minute-interval electricity consumption data to a cloud based storage service.

Observations were made of all features of the house related to thermal management and energy efficiency including heater types; orientation of living areas; the presence of curtains and blinds; and, the ability to close different zones of the house. Interviews provided understanding of participant experiences and explanations to pair with quantitative data. Interviews and surveys included questions about support activities householders had been involved with; comfort experiences; energy use; trade-offs; effects of discomfort and energy in-efficiency; home features; and key changes in the household. For the purposes of this paper interviews provided accounts of comfort experiences and discussions on trade-offs made between comfort and energy.

Internal and external temperatures were used to calculate the difference between inside and outside temperature (ΔT) during defined 'before' and 'after' winter periods. Temperature data was also used to assess time spent in thermally comfortable conditions inside the house. Change in the time spent in the 'comfort zone' was established by comparing before and after winters. Households were deemed to be in 'the comfort zone' if the temperatures sat between 18 and 24 degrees. This 'comfort zone' was defined using World Health Organisation references [5], NatHERS software assumptions for the Tasmanian climate, user experiences from prior research [16], and literature on thermal health [6].

Electricity data was used to calculate average daily winter heating power consumption (kWh/day). Combining this measure of winter heating consumption with temperature data, the GBS developed a new indicator: Household Heating Efficiency (HHE). HHE is the ratio of average ΔT (expressed in °C) to average daily heating energy consumption (kWh/day). HHE is expressed as °C/kWh/day. To the knowledge of the GBS team, HHE has not been used elsewhere. Heating efficiency was also expressed as the ratio of the percentage of time spent in the 'comfort zone' (%cz) to average daily heating power consumption (kWh/day), expressed as (%cz/kWh/day). The term used to define this ratio is Comfort Zone Efficiency (CZE).

4. Results

This results section presents four project findings that demonstrate the effectiveness of the measures of thermal comfort and energy efficiency used in GBS analysis. Note that names used in the results described below are pseudonyms that relate to specific participants and their household interview data.

The first key finding was that, in the majority of detail participants' houses, thermal comfort in winter was gained largely through the consumption of energy. Householders reported that they lived in thermally stressful environments unless there was significant input of heating energy and the quantitative data supported this. Kara (Case 43) informed us 'I can't put the heater down any more in the winter when it's cold. I can't just keep putting jumpers on and on' (after interview 1/9/15). Table 1 shows houses in the Detailed Study broken into quintiles by average living room temperature. Living rooms are often the main room heated in low income homes in Tasmania (central heating is rare in this cohort). Living rooms are often heated by one main heater which is likely to be an electric resistive heater or a heat pump (reverse cycle air conditioner). The right hand column of Table 1 shows the percentage of time household living rooms were within the defined comfort zone. In the bottom three quintiles average living room temperature was rarely comfortable. Not shown is that bedrooms are almost always maintained at a lower temperature than the living rooms. The table demonstrates that there is a close relationship between heating energy consumption and time spent in the comfort zone, but that it is not a linear relationship. There is a significant increase in energy consumption from Q2 to Q1 households, but only a small further increase in time spent in the comfort zone. Overheating due to excessive heater use was observed in several houses in the study.

Table 1: Average living room temperatures compared with heating electricity, electricity consumption and time spent in the defined comfort zone. A comparison of detailed participant households. Table from Rooney et al [19].

Before Living Temp vs Before Heating Electricity vs Before Total Electricity vs % time in CZ			
Living Temp Quintile	Before Living Temp Average (°C)	Before Heating Electricity Average (kWh/day)	Before Total Electricity Average (kWh/day)	Before % time in CZ (%)
Q1	23.00	33.50	59.76	65.6%
Q2	20.01	19.57	33.18	58.3%
Q3	18.17	13.37	28.63	29.4%
Q4	17.16	12.13	34.69	21.5%
Q5	14.62	11.76	26.29	11.1%

The second key finding was that heater efficiency had a direct impact on thermal comfort in winter. In Table 2 time spent in the comfort zone in living rooms is shown listed according to the main living heater types used. This table shows that houses with more efficient heaters (heat pumps) spent more time in the comfort zone during peak winter periods. Based on stated co-efficients of power, heat pumps are typically understood to run three to four times more efficiently than other heaters in terms of kWh of electricity consumed per kW of heat provided. What Table 2 confirms is that better heating efficiency can support longer

periods spent in the comfort zone. Interview data demonstrated that many households who had heat pumps understood this and were more at ease using the heat pump compared to other heaters because they expected they would cost less. Further, two households that moved during the study period reported choosing their next rental homes because they had heat pumps as the main heat source [19, cases 14 and 18]. Other households were not aware of the efficiency of heat pumps. For example, Teri a retired, single occupant avoided using the heat pump in her rental because she didn't understand how to make it 'blow' (hot air) comfortably [19, case 42]. Instead she used an old, inefficient electric resistive, plug-in heater. Education from family supported Teri to start using the heat pump and she consequently saw (approximately) a 30% drop in her electricity bills. Seeing better outcomes in homes where heat pumps were actively used led the GBS team to conclude that education about types of heaters, and the tariffs available was worth prioritizing and that this education had significant potential to improve energy efficiency, thermal comfort and also household expenditure on heating energy [18, 19: see example cases 14, 18 and 42].

Table 2: Main heater types compared with heating electricity and time in the comfort zone. Table from Rooney et al [19]. (Note that change in kWh/day was affected by a colder 'after' winter in 2015.)

Houses grouped by heating types	Heating electricity			% time in the comfort zone (CZ)		
	Before (kWh/day)	After (kWh/day)	Change (kWh/day (%))	Before (%)	After (%)	Change(%)
Houses with Heat Pumps	14.52	16.07	1.54 (10.6%)	41.6%	43.2%	1.6%
Houses with Hardwire resistive heaters	22.07	25.57	3.50 (15.8%)	31.8%	34.5%	2.6%
Houses with Only Heat pumps	14.55	16.01	1.46 (10.1%)	44.4%	42.7%	-1.7%
Houses with Only Resistive Heaters	23.59	28.71	5.12 (21.7%)	26.0%	29.6%	3.6%

The third key finding was that energy efficiency did not necessarily lead to comfort. Tables 3 and 4 show data from Ingrid's house [19, case 33]. Ingrid, a pensioner living on a tight budget, was extremely energy efficient and used very little energy on a daily basis (Table 3). She was 'too scared to put the heaters on…because there is too many [sic] costs involved' (after interview 1/9/15). Ingrid only used $1.50 of electricity a day and thought that was 'the lowest that anyone can' (before interview 19/5/14). In cold weather, Ingrid went to bed early (often as early as 5pm) because she could use her electric blanket. Table 4 shows that the average living, bedroom and kitchen temperatures were very low. The living room on the north (equatorial) side of the house only averaged 11.1°C during the before period and 10.5°C during the after period. The kitchen temperatures on the south side of the house were even lower.

Ingrid's indoor spaces were almost never in the thermal comfort zone during the peak winter study periods. Notably there was little difference between inside and outside temperatures, highlighting that this house had little thermal resistance in its external building shell. There was a slight increase in energy use during the after period due to it being a colder winter. Household heating generally, across the GBS study, increased in the second winter. In Ingrid's case the base level of electricity use was so low that the change was not a significant increase. Ingrid's house actually performed slightly better in the 'after' winter achieving a greater ΔT, with slightly more time in the comfort zone, even though the average temperature was lower in the second winter. Ingrid's example (and there were several others similar in the study), highlights the need for a metric that relates energy efficiency to thermal comfort. In Ingrid's case it would be almost impossible for her to be more energy efficient because she used so little energy in the first place. This energy efficiency may be beneficial financially, but it is producing a very undesirable outcome in terms of thermal comfort.

Table 3: Ingrid's average daily energy use and heating efficiency during winter conditions Case 33 from Rooney et al [19].

	Before (kWh/day)	After (kWh/day)	Change (%)
T 31 Heating (plug in heating)	0.79	0.81	2.7%
T 41 Heating (hard wired heating)	0.00	0.00	0.00
Total Heating	0.79	0.81	2.7%
Other Light and Power (T31)	2.51	3.59	43.1%
Hot Water	2.30	2.16	-6.1%
Total Household Electricity	5.61	6.57	17.1%

Table 4: Ingrid's average daily temperatures and time in comfort zone during winter conditions. Case 33 from Rooney et al [19].

	Living Temp (°C)	Bedroom Temp (°C)	Kitchen Temp (°C)	Outdoor Temp (°C)	Avg out/in temp diff (°C)	% time in comfort zone (18°C - 24°C)
Before winter	11.1	10.9	9.7	9.7	1.3	0.8%
After winter	10.5	10.1	8.8	8.8	1.5	0.9%
Difference	-0.6	-0.8	-0.9	-0.9	0.1	0.1%

The final key finding presented here is that, in low income households the relationship between energy use, thermal comfort and energy efficiency outcomes is dynamic. Table 5 below presents a summary of selected results for four households from the GBS project. These households have been chosen to demonstrate the dynamics of energy consumption and comfort measured in the GBS households and to identify possible household typologies. The data in Table 5 highlights a need for multiple measures to be used in order to understand household dynamics. The interaction between the various data points in Table 5, coupled with interview, survey and observation data allowed the GBS team to understand household thermal environments and how various key factors interacted. None of the measures on their own provide the whole picture.

Table 5: selected participant households heating efficiency compared with total heating energy and time in comfort zone during winter conditions. Case data taken from Rooney et al [19].

Household		Cassie and Partner (Case 34)	Deirdre and child (Case 13)	Troy (Case 12)	Ingrid (Case 33)
Total heating (kWh/day)	Before	10.73	53.47	12.67	0.79
	After	12.45	54.05	8.84	0.81
Household Heating Efficiency (°C hours/kWh/day)	Before	0.91	0.19	0.16	1.67
	After	0.84	0.20	0.28	1.78
% time in comfort zone (18°C-24°C)	Before	68.8	74.4	1.4	0.8
	After	72.9	83.5	0.7	0.9
Comfort Zone Efficiency (%CZ/kWh/day)	Before	6.41	1.39	0.11	1.06
	After	5.86	1.55	0.08	1.15

Cassie and her partner live in one of the newest houses in the GBS study, constructed to Australian NCC 5 star energy-rating standard (that applied at the time)[8]. Cassie's home had a reasonably small floor area 80m^2. Cassie and her partner increased heater use in the after period due to a significant illness her partner was managing. The primary source of heat was from a heat pump in the living area. Their HHE and CZE were high compared to other houses for the study indicating that there was a reasonable amount of thermal resistance in the building shell as well as an efficient source of heating. This combination allowed Cassie and her partner to spend a healthy length of time every day in the comfort zone. This situation meant that Cassie, in relation to home energy management and comfort, was one of the most relaxed householders participating. When Cassie and her partner needed to use more energy for heating, neither of them had to think too hard about it, because their heater and their home were both reasonably efficient.

Deirdre and her child lived in a suburban house that was built long before energy ratings were introduced. Their energy use was comparatively high, despite using a heat pump as one of their main heating sources. This was likely due to both mother and child needing to stay warm to help manage asthma; the building shell having little thermal resistance; large areas of un-insulated thermal mass in the house; and, the house being an open plan design. The high heating input can be seen to achieve the aim of maintaining the comfort zone indoors; however the thermally poor indoor environment is apparent in the relatively poor HHE and CZE numbers. Deirdre was clear that heating was needed for their health, so she chose to have a thermally comfortable house rather than save energy. In the before interview Deirdre reported some high bills and stress related to these high bills but also explained that she prioritised health.

Troy consumed heating energy on a level similar to Cassie and partner, yet his heating efficiency and time in comfort zone are very different to Cassie's. Troy's heating came from a mix of hard-wired and plug in resistive heating. The house was thermally poor, and the living room that he was trying to heat had three un-insulated external walls (the house design was an L shape). The terribly poor thermal resistance in his building shell can be seen by the poor HHE and CZE figures and the extremely low percentages for time spent in the comfort zone. GBS researchers observed that this house had extremely poor thermal resistance and was a very cold environment.

Ingrid's budgetary constraints lead to her minimal heater use and her house being in the comfort zone for a very small amount of time. When the temperatures at Ingrid's house were graphed, the inside temperatures generally tracked the pattern of outside temperatures with only a few degrees Celsius difference. What also stands out from Ingrid's results is the very high household heating efficiency (HHE). Rather than telling a good story about how efficient her house is, this highlights the limitations of the HHE as a measure on its own. This will be examined further in the discussion.

5. Discussion and Conclusion

From these results, conclusions can be drawn about the measures used; the indicators developed; the practicality and applicability of the GBS methods; and, the potential for using these in future applications. The specific measures described in this paper: the difference between inside and outside temperatures (ΔT); household heating efficiency; time spent in comfort zone; and comfort zone efficiency all helped to develop understanding of the relationship between thermal comfort, energy use and energy efficiency in participant homes. The measures facilitated a much more detailed understanding of building fabric performance, heating system performance, household practices and outcomes for household comfort.

There is potential for individual measures used in GBS (and combinations of these measures) to be further developed and refined for other applications. They could be used in different climates, where there may be a focus on cooling or a combination

of heating and cooling. They could also be applied to the assessment of new houses and to the task of comparing new houses to existing houses. HHE, CZE and time spent in comfort zone were all developed specifically for GBS and would benefit from further investigation as they have not been used elsewhere. Percentage time spent in comfort zone, for example, in GBS was described as a per day value averaged for the different rooms measured in the house. This value could be identified for individual rooms of a house and for shorter, more specific time periods through the day. Such refinements could align the indicator with the NatHERS comfort zones used in assessment of new houses, thereby potentially facilitating comparisons of the performance of new and existing houses. To gain a higher level of detail about householder experience, time in comfort zone could also be more systematically linked with householder responses, for example through a time of use diary being used alongside temperature logging.

While HHE and CZE are effective in assessing efficiency where heating is being used, they are not necessarily effective for comparing heated houses with houses where little or no heating is used. Comparison is problematic because HHE and CZE are ratios of electricity consumption to temperature and the temperature part of the measure factors in ambient heat in the indoor environment. Consequently these ratios became skewed when comparing houses with very high compared to very low energy consumption. Where HHE and CZE are valuable on their own is where an individual house is compared before and after an upgrade. An increase in HHE or CZE value should indicate success of the upgrade. The problem of comparing efficiency ratios highlights that while they are useful they cannot be used on their own as effective measures of overall household performance. Like all of the measures used in GBS, each individual measure helped to create understanding when analysed in combination with the other measures recorded.

In GBS, research methods were also used in combinations. The mixed-method, qualitative and quantitative research approach taken by GBS delivered a new level of understanding of the dynamics of thermal performance in low-income homes and provided enough detail to track changes that occurred due to the energy efficiency support activities GBS provided. The methods design was defined by the practicalities of capturing markers in real life situations with relatively large scale data collection needs, relatively long data collection time frames and on a relatively tight budget. Monitoring techniques used in GBS, could not be as rigorous as in building science studies (which may even be controlled lab conditions) and could not afford the expense and interference potentially caused by a more intensive building science approach, yet still needed a rich and detailed picture to develop of household performance, typologies and changes achieved. Building on mixed-method approaches used in research projects like the HIH project in NZ, GBS added another layer of detail to the thermal monitoring and, working from both understanding of building science and social-technical understanding of comfort, applied modified approaches from both these traditions to provide sound (reliable) indicators. This research approach allowed for a relatively low interference study of existing households. Improvements to the research methods for future application could include refining the integration of qualitative and quantitative data collection so their use is more streamlined leading to more integrated presentation of results.

Based on the measures and methods used the GBS study was able to achieve the level of detail of finding that will be able to inform future program and policy development. As seen in Table 5, for example, the study was able to identify within the low-income cohort, a number of household typologies, based on patterns of energy consumption and thermal comfort. Importantly for future work in the field, symptoms of healthy and unhealthy thermal environments were able to be identified. Such understanding can be used to help create more targeted assistance programs around specific aims such as health, affordability or energy savings. For broader based assistance programs it would allow the needs of individual households to be identified and assistance to them tailored to ensure support was effective.

Other future uses of the GBS data, and established indicators could include: defining benchmarks and aspirational policy goals for existing housing stock; exploring housing stress as it relates to thermal comfort; further exploration of humidity in homes and its impact on health; and comparing GBS comfort data with other LIEEP projects comfort data from other climate zones. Future applications of GBS-style research methods could include: examining thermal comfort more broadly across new and existing housing stock in Australia and across income cohorts to establish thermal performance benchmarks and national typologies; gathering data for housing quality and health policy development; and exploring the cost benefit of housing quality in relation to health savings.

This paper reviewed thermal comfort and energy efficiency measures used in the GBS project to assess whether or not these measures have value in future home energy efficiency and healthy housing programs. The measures used and the research methods within which they were applied, built on building science and socio-technical approaches to thermal comfort assessment and applied them in a mixed-method research approach. The method design that resulted allowed for a practical application of thermal comfort measures in a real life setting.

Acknowledgements

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