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Outcomes from the Victorian Healthy Homes Program: a randomised control trial of home energy upgrades

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ABSTRACT

Objectives The Victorian Healthy Homes Program investigated the impact of thermal home upgrades on energy and health outcomes in vulnerable, older individuals over winter in Victoria, Australia.
Design A staggered parallel-group randomised control trial design of 984 (764 per protocol (PP)) vulnerable households and 1313 (1015 PP) individuals. The intervention group received their upgrade prior to their winter of recruitment, and the control group received their upgrade after the winter of their recruitment.
Setting Western Melbourne (metropolitan) and the Goulburn Valley (regional) in Victoria, Australia.
Participants 1000 households were recruited: 800 from western Melbourne (metropolitan) and 200 from the Goulburn Valley (regional).
Intervention A thermal comfort and home energy efficiency upgrade of up to $AUD3500 per household.
Primary and secondary outcome measures The primary outcome was the change in indoor temperature over winter and the secondary outcomes were changes in quality of life, healthcare use and costs, self-reported health measures, energy use and costs and humidity.
Results A relatively low-cost and simple home upgrade (average cost $A2809) resulted in reduced gas consumption (−25.5 MJ/day) and increased indoor winter temperatures (average daily increase of 0.33°C), and a reduction of exposure to cold conditions (<18°C) by an average of 0.71 hours (43 min) per day. The intervention group experienced improved mental health as measured by the short-form 36 mental component summary and social care related quality of life measured by the Adult Social Care Outcomes Toolkit, less breathlessness and lower overall healthcare costs (an average of $A887 per person) over the winter period.
Conclusions The home upgrades significantly increased average winter indoor temperature, improved mental health and social care-related quality of life and made householders more comfortable while yielding reductions in overall healthcare use and costs.
Trial registration number Australian and New Zealand Clinical Trials Registry: ACTRN12618000160235.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ First randomised control trial (RCT) of its kind in Australia to study the impact of thermal home upgrades on energy and health outcomes.
⇒ The use of RCTs for such interventions is uncommon but provides a powerful approach to evaluation that can minimise the effects of confounding.
⇒ The programme was specifically designed to target vulnerable populations. These are groups with the most potential to benefit from home upgrades, either because of their socioeconomic status or because of their chronic health conditions, or both.
⇒ The retrofitted upgrade was tailored to each home based on need and delivered for a modest budget (up to $A3500). A house rating assessment was used to compare house energy efficiency before and after upgrades and across the cohorts, to avoid assessing individual intervention components.
⇒ COVID-19 impacted the power of the study because not all upgrades were able to be delivered prior to winter. This was particularly relevant for the secondary health outcome measures.

INTRODUCTION

Housing is a critical aspect of our lives and one indicator of the health and wealth of a population.[1] Despite Australia's relative wealth, the quality of its housing stock is very poor, with more than 91% of existing houses having an energy efficiency rating below code compliance.[2] Measures to improve thermal comfort and residential energy efficiency can improve household indoor temperatures which in turn reduce the risk of adverse health outcomes.[3]

There is growing recognition of the links between the home environment and health outcomes.[3–10] International evidence suggests that there is an association between residential energy efficiency and negative morbidity and mortality outcomes, particularly during winter.[11–13] For example, a study from the UK showed seasonal variation in mortality risk which differed by residential energy efficiency, with more energy-efficient homes having lower mortality risk than homes with poor energy efficiency.[12] Another UK matched-control study demonstrated reduced acute hospitalisations with a healthy housing programme.[13]

Health risks associated with cold indoor temperatures tend to have a greater impact on specific population groups including those with cardiorespiratory disease, children and older people.[8 14 15] Indoor humidity levels have the potential to affect health adversely, for example, through exacerbation of asthma and allergies. Vulnerable people, including the elderly and those with a disability or chronic illnesses are at higher risk as they are more likely to spend most of their time at home and be more exposed to health risks associated with cold homes.[14] Those with low incomes have limited means to improve the quality of their homes or afford increasing heating costs. A recent UK study found that with respect to self-reported health, energy efficiency programmes provided the greatest benefit to those on low incomes.[16] Other more recent European research has suggested that energy retrofits are a good solution for the detrimental impacts of indoor temperature on health.[17]

Randomised control trials (RCTs) in the northern hemisphere[4 6 8 18] and two in New Zealand[7 8] demonstrate that improving the thermal comfort of homes has generally positive effects on health and well-being, especially for certain populations (children, elderly) and certain health conditions (mental health, respiratory). There is a significant absence of Australian literature and related evidence on the relationship between housing conditions and health, especially using a rigorous RCT design. This study addresses this gap. Despite being in a relatively temperate region, Australia's housing stock is poor, and recent research indicates that the prevalence of cold housing (below 18°C) is grossly underestimated,[19] meaning the impact of cold housing on health could be far greater than previously thought.

The Victorian Healthy Homes Program (VHHP) delivered home thermal comfort and energy efficiency upgrades to 1000 vulnerable households in Victoria, Australia. An upgrade of up to $A3500 per home was fully paid for by the Victorian Government through Sustainability Victoria. The programme design incorporated an RCT to assess the impact of home upgrades on thermal comfort, well-being, health, energy use and costs to society.

The objectives of this paper are to report the (1) energy benefits; (2) health benefits; and (3) healthcare costs of the VHHP. The trial protocol (online supplemental file 6) was published in 2022.[20]

METHODS

Findings are reported in accordance with the Consolidated Standards of Reporting Trials guidelines (online supplemental file 3) .[21 22]

Trial design

This study was a staggered parallel group RCT design, where households were randomly assigned to one of two groups. Participants were recruited into the study over a 3-year period from 2018 to 2020, inclusive. All households received the home upgrade either prior to winter (intervention group) or after winter (control group). The trial governance structure was that the programme was funded and administered by Sustainability Victoria, it was delivered by the Australian Energy Foundation and the research component was independently conducted by the University of Technology Sydney (UTS).

Change to trial design

As a result of the COVID-19 lockdown laws in Victoria, the programme, and specifically the upgrades work in 2020, was significantly disrupted. Some intervention households did not receive their intervention prior to the winter of their recruitment year. For this reason, the following changes to the study were made: (1) the 2020 post-winter visits were conducted via telephone and (2) the cost for remaining upgrades was reduced to a target average of $A2600 from December 2020.

Participants and study setting

1000 households were recruited: 800 from western Melbourne (metropolitan) and 200 from the Goulburn Valley (regional). These areas were selected based on social or economic disadvantage and less favourable health outcomes. The average daily temperatures in these areas ranged from 3.4°C to 13.3°C.[23] The eligibility criteria for participants are reported in the protocol paper.[20]

Recruitment for the study occurred via the nine participating local government areas who disseminated promotional materials about the programme to potential eligible householders within their jurisdiction. Interested householders completed an Expression of Interest and were then contacted by telephone by Australian Energy Foundation staff to assess their eligibility and willingness to participate (convenience opt-in sample) and then to arrange a home visit with an interviewer. At this stage, the vulnerability of the primary householder was assessed, which was defined as the participant being of low income, that is, having one of the Australian Government welfare cards or receiving home care support services through local council or community organisations. This recruitment pathway resulted in predominantly older participants. During the first home visit and prior to commencing the interview, informed written consent was also sought from study participants to gain access to their energy and administrative health data. Consent forms were stored securely and separately from any other participant data to ensure confidentiality.

Public and patient involvement

Participants were mostly not able to be involved in the design and conduct of the study because it involved expertise regarding the nature of the upgrades needed and the expertise of the tradespeople. Participants were able to indicate a preference for upgrade for aesthetic purposes and/or reserve the right to say no to certain home upgrades.

Interventions

Based on a Victorian Residential Efficiency Scorecard (RES)[24] assessment of the home energy efficiency and consultation with the participant, home upgrades were selected from a suite of interventions to improve thermal comfort within the budget, considering the Australian context of often poorly insulated houses and ease of installation with the least possible disruption to occupants. The range of home upgrades could include: ceiling and underfloor insulation, draught sealing external doors, space heating (new reverse cycle air conditioning or replacement of gas heater—either with a reverse cycle air conditioner or more efficient gas heater), changed downlights to Integrated Circuit-rated Light Emitting Diodes (LED), and internal window coverings (see the study by Campbell *et al*[20] for full list and description). Each home was reassessed under the Victorian RES after the upgrades, and the change in rating (on an overall scale of 10 stars) is the change in energy cost to run the home. These ratings enabled comparisons to be made without assessing individual components of the interventions.

Outcomes

Primary

The primary outcome was the average difference in measured indoor temperature between the intervention and control groups over winter (table 1). Exposure to cold, measured by the time spent at indoor temperatures below 18°C (WHO recommended minimum), was also assessed.[25] Winter was defined as the period from 22 June to 21 September, in line with the astronomical winter in Victoria.

Due to loss of battery power in some logger devices, 78 of the 250 households in the 2019 cohort reported varying levels of missing temperature and humidity data. The data missingness levels for these 78 households averaged around 30%. An imputation method to handle incomplete temperature data in RCTs was specifically developed and used to address this issue where the analysts cannot be unblinded or refer to data from other households to improve the imputation. The spine regression model accounts for internal and external temperature, energy consumption, time of day and modelled occupancy. A more detailed outline of the methods can be found in[26].

Secondary

This study evaluated a number of secondary outcomes (table 1). Secondary outcomes were assessed for all participating members in the household. The full set of secondary outcomes is reported in the protocol paper.[20]

Quality of life

Quality of life data were collected using three established instruments, the EuroQol 5-dimension 5-level (EQ-5D-5L),[27–29] the short-form (SF)-36[30–32] and the Adult Social Care Outcomes Toolkit (ASCOT).[33] Participants completed all three questionnaires both before

Table 1 Outcome measures for the VHHP

Data	Description	Data source
Primary outcome	Average daily temperature within the home	30 min interval readings from data logger during winter
	Exposure to cold conditions (number of hours)	30 min interval readings from data logger during winter
Secondary (household level) outcome	Change in average daily humidity within the home	30 min interval readings from data logger during winter
	Household energy costs	Self-reported survey
	Total daily household energy consumption	Electricity and gas distributors
Secondary (individual level) outcomes	Health-related quality of life including health utilities	Self-reported surveys (SF-36, EQ-5D-5L and ASCOT)
	Healthcare utilisation:	
	GP visits Specialist visits Diagnostic tests	Medicare data (Services Australia)
	Medicines prescribed	Pharmaceutical Benefits Scheme (PBS) data (Services Australia)
	Hospital admissions and length of stay	Victorian Admitted Episodes Dataset (VAED)
	Emergency department presentations	Victorian Emergency Minimum Dataset (VEMD)
	Respiratory symptoms	Self-reported survey
	Absenteeism	Self-reported survey

ASCOT, Adult Social Care Outcomes Toolkit; EQ-5D-5L, EuroQol 5-dimension 5-level; GP, general practitioner; SF-36, short-form 36; VHHP, Victorian Healthy Homes Program.

and after winter. The EQ-5D-5L and SF-36 were used to measure differences in health-related quality of life and the ASCOT for differences in social care outcomes.[34]

Gas and electricity consumption

Gas and electricity consumption data obtained directly from the relevant companies were analysed for each home to determine changes in energy use and cost savings.

Health service utilisation and costs

Healthcare use and costs for individuals were identified from linked administrative health data extracts from the Medicare Benefits Schedule (MBS), Pharmaceutical Benefits Scheme (PBS), Victorian Admitted Episodes Dataset (VAED) and Victorian Emergency Minimum Dataset (VEMD). The pharmaceutical data includes all medicines listed on the PBS and dispensed to patients at a government-subsidised price. The MBS contains information on medical services that are subsidised by the Australian government including the benefits paid, the out-of-pocket costs to the patient as well as information about the nature of claim and the service provider. The VAED contains International Classification of Diseases 10th Revision and diagnosis-related groups codes on all admitted episodes from Victorian public and private acute hospitals. The VEMD contains demographic, administrative and clinical data about presentations at Victorian public hospitals with designated emergency departments (EDs). A cost was assigned to each admitted hospital episode based on diagnosis-related groups and to each non-admitted ED visit based on urgency-related group using related costs from the National Hospital Cost Data Collection.[35] All costs were in Australian dollars and adjusted to the 2020 year.

Data were extracted for the 3 years before and up to 1 year after the winter following recruitment. Data were analysed to establish the differences between the control and intervention groups in usage and cost.

Other secondary outcomes

The modified Medical Research Council (mMRC) dyspnoea scale M[36 37] was used to record respiratory symptoms as it is a simple measure of breathlessness. Absenteeism was specified in the protocol as an important secondary outcome. In the after-winter surveys, we asked about days absent from (1) work, (2) study and (3) usual activities for all adults in the household. Given the average age of the sample (76 years), there were very few participants engaged in work (99.5% indicated they had 0 days absent from work) or study (97.6% were not absent from study). The total number of days absent from usual activities over the winter period was summed and used as the measure of absenteeism.

Sample size

A total of 984 households were included in the RCT which provides sufficient power to estimate effects for primary and secondary endpoints. All households were used in the analysis of both primary and secondary outcomes (unless consent was withdrawn during the study). Sample size calculations were based on two study endpoints, one household measure (indoor temperature) and one individual measure (the SF-36 Mental Component Score (MCS)). This was because the sample size needed for the primary outcome was significantly smaller than the secondary outcomes, and we wanted to ensure we could detect significant differences in both outcomes. For the primary outcome, 125 households per group were required (power 90%, 15% loss, 5% significance level). For the secondary outcome, 475 households (950 participants) per group were required (80% power, 5% significance level, 20% loss, 2 individuals per household). For more details on these calculations, see the study by Campbell *et al*.[20]

Interim analysis and stopping guidelines

An interim blinded threshold analysis of the data occurred in October 2021 to provide feedback to Sustainability Victoria on the likely magnitude of effect needed to obtain outcomes based on current data. There were no group comparisons made at that point.

Randomisation

The randomisation sequence was a 1:1 scheme stratified by local government area using random permuted blocks and randomly varying block size of 2 and 4. It was created at UTS using the Ralloc command in Stata V.15.0.[38] The householders and the delivery partner (Australian Energy Foundation) were informed about the study arm to which a household was assigned after participant consent provision and collection of baseline data (including home assessment). After data collection was complete, the random allocation was provided to analysts in a coded form so that primary and secondary analyses were conducted blinded to group allocation.

Blinding

The trial was single-blinded; we were unable to blind the households from the timing of the home upgrade. All intention-to-treat (ITT) and per protocol (PP) analysis was conducted with group assignment in coded form only so that analysts were blinded to the household's intervention status. Unblinding occurred after all analysis of the primary and secondary outcomes was complete.

Statistical methods

A model was developed that aggregated the outcome of interest over the entire winter period from 22 June to 21 September of the relevant year of recruitment, except for quality of life which was measured at two time-points only (before and after winter). The model specification is:

$$Y_i = \alpha + \beta_0 T_i + \beta_n X_i$$

where Y is an outcome of interest for participant/household i, T denotes treatment group and X_i signifies a number of covariates including household level variables for the primary and household level secondary outcomes, and including the individual's cohort, age, gender and

Table 2 Control variables, descriptions and coding in primary outcome adjusted and unadjusted regression models

Variable name	Description	Data coding	Type of data
Intervention	Control or intervention	Group 2—intervention	Binary
Baseline	Value at baseline—pre-winter.		Continuous
Year	2018, 2019 or 2020	Dummy coded Yr2019—shows effect of being in 2019 cohort (1–2019; 0 otherwise) Yr2020—effect of being in 2020 cohort (1–2020; 0 otherwise)	Binary
Local government area	Local government areas of household	1‘Wyndham’ 2‘Hobsons Bay’ 3‘Brimbank’ 4‘Maribyrnong’ 5‘Melton’ 6‘Moira’ 7‘Campaspe’ 8‘Strathbogie’ 9‘Greater Shepparton’ (entered as dummy variables in the regressions)	Categorical
Age	Age of participants calculated from DOB		Continuous
Sex	Sex of participant	0: male 1: female	Binary
Daily gas use*	Average daily gas use over winter	MJ/day	Continuous
Daily electricity use*	Average daily electricity use over winter	kWh/day	Continuous
Floor size*	Floor area of house	Square metres	Continuous
Pre-winter star rating*	Pre-winter Residential Efficiency Scorecard (RES) star rating	Integer value between 1 and 10	Categorical
Solar Panel*	Rooftop solar panels on house	0: no 1: yes	Binary

*Variables used in adjusted analysis.
DOB, date of birth.

local government area for individual secondary outcomes. The outcomes of interest are described in table 1. Where there is a before and after winter measure, we control for the baseline values with the variable ‘baseline’ (table 2). β_0 represents the difference between the control and intervention group. In the context of an RCT β_0 can be interpreted as the impact of the VHHP. To adjust for correlations between outcomes for individuals in clusters (households), we clustered the SEs at the household level,[39] as at the household level, the over-rejection of the null hypothesis of no effect is about the same for multilevel models as for the method of correction for clustering when the number of clusters is large.[40] All analyses included adjustment for local government area (stratifying variable for randomisation) and the year of recruitment (as the severity of the winter may affect the impact of the home upgrades).

The analysis described above may not fully capture the precise impact of intervention. Unlike a typical RCT conducted in the clinical setting where the impact lies on a linear scale (effect or no effect), participants in this study can choose to take the benefit of the intervention (home upgrade) as either improving thermal comfort (indoor temperature) or a reduction in their energy consumption (gas and electricity use). This can obscure the effects if only an unadjusted model is used. We therefore conduct a regression model that captures this unique relationship between energy, indoor temperature and other factors that mediate the relationship between the two key factors. An intervention dummy variable is further added into this model to determine its marginal effect, as shown in the online supplemental material table 3. This adjusted model is used for all outcomes linked to the primary outcome.

Two types of analysis were undertaken: (1) ITT analysis, which used all households allocated to the control and intervention groups, irrespective of whether they actually received the home upgrade intervention in the correct timeframe; and (2) PP analysis, which includes only those households (individuals) who ‘completed’ the treatment as originally allocated. Our definition of ‘completed’ was that the intervention household must have received their full upgrade (all components) prior to the winter period in the year of recruitment, and control households must not have received any upgrade work prior to the end of winter (defined by 22 September) of the relevant year.

A range of modelling approaches was used for analysis. The logit model was used to analyse binary data; negative binomial models were used for count data and ordinary least squares were used for continuous data.

Table 2 presents a list of control variables; the name refers to the name seen in the output of the regression analysis. Only the key variables are included here.

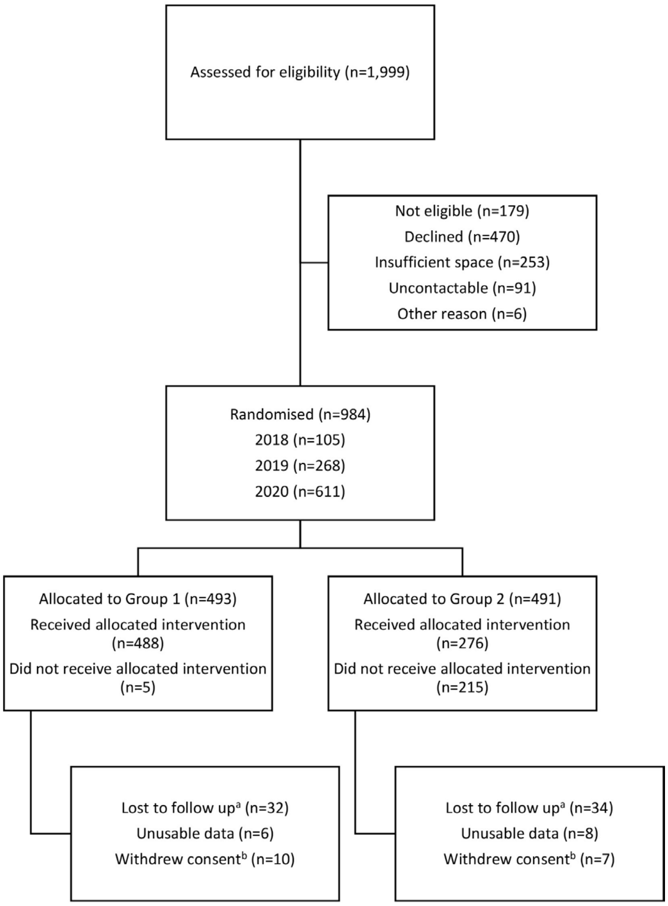

Figure 1 Consort diagram. [a]Data loggers not returned or lost. [b]Dropped out and returned data loggers early.

Variables specific to each dataset are described in the relevant results sections below.

RESULTS

Numbers randomised

Figure 1 shows the recruitment pathway for the VHHP. Of the 1999 households contacted for eligibility, 984 were included in the study and randomised, 493 to the control group and 491 to the intervention group. These households are included in the ITT analysis).

Losses and exclusions

Of the 984 households included in the trial (493 control; 491 intervention), 66 were lost to follow-up, 17 withdrew their consent and 14 had unusable data (data loggers not returned or lost). Due to the COVID-19 pandemic, 220 households did not receive their intervention during the protocol time frame. 764 households were included in the PP analysis (488 control, 276 intervention). There were 1313 individuals (649 control: 664 intervention) for the full ITT analysis. For the PP analysis, there were 1015 individuals (641 control, 374 intervention).

Recruitment

The study commenced in February 2018. Recruitment commenced in January of each year, after the previous year's after-winter interviews were completed. The programme ended in May 2022 after the final control household upgrade was completed. The final administrative data was received in May 2023. Other final data (data loggers and surveys) arrived at various points throughout the trial between January 2021 and January 2022.

Baseline data

Baseline characteristics for the control and intervention groups (ITT) are in table 3. At both the household and individual level, the control and intervention groups are not statistically different from each other on all the relevant variables, and therefore the randomisation achieved the necessary balance.

Online supplemental appendix A shows the types of upgrades that were performed across the participating households. The most common upgrade was gas heater service (45% of total households), followed by draught proofing (40%) and installation of a new reverse cycle air conditioner (39%). Carbon monoxide (CO) testing was performed before and after upgrades for households with gas heaters to ensure low CO levels. We would like to highlight that this intervention was delivered as a bundle to improve indoor warmth and thermal comfort, and it was not the aim of the paper to explore the effectiveness of individual upgrade measures.

Outcomes and estimation

Table 4 presents the mean of all the outcomes for the control and intervention group and the raw differences, and the differences from the regression analysis (ITT). The full regression tables (ITT) are presented in supplementary material. The full regression tables for PP analysis are reported in the supplementary material only when significantly different from ITT results (online supplemental material).

Primary outcome: thermal comfort

Mean indoor temperature

Using the unadjusted analysis, home upgrades did not have an impact on mean indoor temperature over winter (0.091°C; 95% CI −0.217, 0.399) for both ITT and PP analyses (online supplemental material tables 1 and 2). Under the adjusted model, home upgrades did have a statistically significant impact on mean indoor temperature over winter (0.326°C; 95% CI 0.047, 0.605) for the ITT analysis.

The intervention was also assessed by time of day, mornings (08:00–12:00), afternoons (12:00–17:00), evenings (17:00–22:00) and overnight (22:00–08:00) (online supplemental material tables 4–7). Home upgrades had the largest impact on indoor temperature in the mornings, increasing indoor temperature by 0.47°C (95% CI 0.105, 0.836) for the ITT analysis.

Exposure to cold

Home upgrades had a positive and statistically significant impact for the PP analysis, reducing exposure to cold indoor conditions analysis (−0.93 hours/day (56 mins);

Table 3 Baseline data for control and intervention groups

	Control (n)	%	Intervention	%
Households	493		491	
2018	53	11	52	11
2019	133	27	135	27
2020	307	62	304	62
Floor area (m^2 average)	115.2		115.4	
Pre-upgrade RES rating (out of 10 stars)	4.96	40 (below 5 stars)	4.96	40 (below 5 stars)
Solar photovoltaic presence (%)	130	26	133	27
Individuals	649		664	
2018	68	10	75	12
2019	176	27	181	28
2020	405	62	408	63
Males	212	33	240	37
Mean age (years)	74.85		74.82	
Local government area				
Wyndham	209	32	223	34
Hobson's Bay	71	11	62	10
Brimbank	64	10	62	10
Maribyrnong	51	8	53	8
Melton	114	18	121	19
Moira	30	5	28	4
Campaspe	35	5	34	5
Strathbogie	13	2	14	2
Greater Shepparton	61	9	64	10

RES, Residential Efficiency Scorecard.

95% CI −1.813, –0.056) for the ITT analysis. This effect was not significant for the ITT analysis (–0.71 hours/day (43 min); 95% CI −1.456, 0.029) (online supplemental material tables 8 and 9).

Assessment of differences in exposure to cold indoor conditions was not significant for mornings in ITT analysis (–0.16 hours/day (10 min); 95% CI −1.898, 0.058), however, the effect was significant for PP analysis (–0.22 hours/day (13 min); 95% CI –0.416, –0.031). This effect is equivalent to~9.6% reduction in exposure to cold during the morning, given that the entire group experiences on average 2.3 hours (138 mins) out of the 4 morning hours below 18°C. Home upgrades did not impact afternoon hours below 18°C in ITT analysis (–0.14 hours/day (9 min); 95% CI –0.346, 0.059), but were significant in PP analysis (–0.26 hours/day (16 min); 95% CI −0.504, –0.012) (online supplemental material tables 10–17).

Secondary outcomes

Perceived thermal comfort

Home upgrades were found to improve household's perceived thermal comfort, in line with findings on measured thermal comfort, where intervention households were 2.34 times (95% CI 1.83, 3.01) more likely to report an increase in self-reported thermal comfort compared with control households for the ITT analysis (online supplemental material table 18).

Humidity and hazardous conditions

Internal relative humidity levels were typically around 50%. High humidity levels, in conjunction with low indoor temperature, can lead to respiratory hazards. The WHO benchmarks a combination of relative humidity over 65% and temperatures below 16°C as hazardous to health.[41] ITT results showed that home upgrades led to nearly an hour (55 min) of reduced exposure to hazardous conditions per day (–0.925 hours/day, 95% CI −1.599, –0.250) (online supplemental material table 19).

Energy outcomes

Gas and electricity use

Home upgrades did not have an impact on average electricity use (–0.943 kWh/day, 95% CI 0.445, –2.231). This is not surprising because gas heating dominates in Victoria, with 74% of study households using gas as the main heating source. Upgrades did have a significant impact on gas use with less gas use in the upgraded homes

Table 4 Summary of energy and health regression results (ITT)

Outcome	Control group Mean	Intervention group Mean	Raw mean difference and 95% CI (t-test)	Difference from regression model (95% CI)
Energy data				
Unadjusted mean winter temperature (°C)	18.24	18.33	0.09 (–0.222, 0.390)	0.09 (–0.217, 0.399)
Mean winter temperature* (°C)	18.24	18.33	0.09 (–0.222, 0.390)	0.33 (0.05, 0.60)
Morning temperature* (°C)	17.18	17.38	0.20 (–0.172, 0.585)	0.47 (0.10, 0.84)
Hours/day below 18°C*, winter period	11.77	11.43	–0.34 (–1.16, 0.48)	–0.71 (–1.46, 0.03)
Hours/day below hazardous conditions*, winter period	2.30	1.91	–0.39 (–0.95, 0.17)	–0.925 (–1.60, 0.25)
Perceived thermal comfort (change pre–post winter)	–0.02	0.35	0.37 (0.16, 0.57)	2.34 (1.83, 3.01) (OR)
Gas use, MJ/day	222.00	202.00	–20 (–40.47, 0.93)	25.49 (–43.05, 7.92)
Gas use, entire winter, MJ	20 424.00	18 584.00	–1840 (–3722.92, 85.61)	–2345.08 (–3960.6, 728.64)
Electricity use, KWh/day	13.78	14.32	0.54 (–1.32, 2.39)	0.06 (–1.73, 2.88)
Electricity use, entire winter (KWh)	1267.76	1317.44	49.68 (–121.44, 219.88)	–86.48 (–214.36, 41.4)
Administrative health data				
MBS services	14.11	12.7	–1.041 (–0.201, 3.014)	0.906 (0.813,1.011) (IRR)
GP services	2.58	2.62	–0.045 (–0.367, 0.277)	1.016 (0.897,1.153) (IRR)
PBS services	16.17	16.53	–0.0359 (–1.518, 0.799)	1.019 (0.946,1.097) (IRR)
Hospital admissions	0.618	0.503	–0.115 (–0.477, 0.247)	1.047 (0.750, 1.463) (IRR)
Hospital length of stay	1.081	1.103	0.022 (–0.494, 0.537)	1.131 (0.716, 1.786) (IRR)
ED admissions	0.229	0.217	0.012 (–0.063, 0.087)	1.030 (0.737, 1.440) (IRR)
After winter SF-36 MCS	43.981	46.005	2.025 (0.305, 3.744)	1.730 (0.207, 3.254)
After winter EQ-5D-5L utility score	0.605	0.624	0.019 (–0.022, 0.060)	0.009 (–0.025, 0.043)
After winter ASCOT utility score	0.768	0.799	0.031 (0.010, 0.052)	0.024 (0.006, 0.042)
Survey outcomes				
Absenteeism	7.28	5.36	–1.92	0.802 (0.536, 1.20) (IRR)
Respiratory symptoms (mMRC score)	–0.0566	0.188	–0.245 (–0.388, –0.102)	–0.374 (–0.61, –0.152)

*Refers to indoor temperature.
ASCOT, Adult Social Care Outcomes Toolkit; ED, emergency department; EQ-5D-5L, EuroQol 5-dimension 5-level; GP, general practitioner; IRR, incidence rate ratio; ITT, intention-to-treat; MBS, Medicare Benefits Schedule; MCS, Mental Component Score; mMRC, modified Medical Research Council; PBS, Pharmaceutical Benefits Scheme; SF-36, short-form 36.

(–7.08 kWh/day, 95% CI –11.959, –2.201) (online supplemental material tables 20 and 21).

Energy costs

We used the average Victorian Default Offer electricity rate ($A0.29/kWh) and gas rate ($A0.107/kWh) to quantify the financial impact of gas usage savings in intervention households, which was 7.08 kWh (25.49 MJ) per day and equates to $A69.70 in savings per winter per household.

Quality of life

Two quality of life measures show significant differences between the control and intervention group (online supplemental material). The SF-36 MCS score after winter is significantly different for the intervention group compared with the control group (1.73, 95% CI: 0.21, 3.25) (online supplemental material table 22) such that they showed a significantly greater improvement in mental health. The SF36 Pysical Component Score (PCS) was not significant (online supplemental material table 23). The ASCOT scores after winter are also significantly higher for the intervention group in the ITT analysis (0.024, 95% CI: 0.006, 0.042) (online supplemental material table 24). There were no significant differences between the control and intervention groups for EQ-5D-5L or ‘health today’ scores after winter (online supplemental material tables 25 and 26).

Healthcare utilisation and cost

Overall group differences in both MBS, PBS and general practitioner service use were not statistically significant, but there was a trend that the intervention group used fewer medical services over winter (12.8 services: intervention group; 15.1 services control group).

When looking at costs, the differences between the control and intervention group in total cost for private medical and diagnostic services (called MBS charge) were significant ($A–156.57; 95% CI: −310.68,–2.47) such that the intervention group incurred significantly fewer total service costs over winter. In 2020 there was lower service use and hence overall costs compared with the 2018 and 2019, which is likely attributable to reduced use during COVID-19-related lockdowns. All regression results are shown in online supplemental material tables 27–30.

A negative binomial regression model showed no significant difference between the control and intervention groups for pharmaceutical services, gross price, net benefits or patient contributions. All regression results are shown in online supplemental material tables 31–35.

There was no significant difference between the control and intervention groups for the outcome of the number of hospitalisations, hospital costs, length of stay (days in hospital) and ED visits. An overall trend of lower hospitalisations and hospital costs was observed for the intervention group. All regression tables are shown in online supplemental material tables 36–40.

Total healthcare costs were defined as the sum of all healthcare service use costs during the 3-month winter period. These data are based on costs as reported in the MBS, PBS and hospital datasets. The regression analysis predicting total healthcare costs showed that the intervention group on average used $A886.51 (95% CI: −1879.25, −106.23) less healthcare costs than the control group (online supplemental material tables 41 and 42).

Other secondary outcomes

The control group had a higher number of days absent from usual activities (mean=7.3, SD 15.8) than the intervention group (mean=5.4, SD 13.3). This group difference was not significant in ITT analysis (coefficient=−0.22; 95% CI −0.62, 0.18; p=0.28). It was stronger in PP analysis (coefficient=−0.46; 95% CI −0.94, 0.02; p=0.058) (online supplemental material table 43).

Respiratory symptoms were measured by the self-reported changes in the mMRC dyspnoea scale.[36] Logistic regression indicated that individuals in the intervention group had a reduction (improvement) in mMRC score relative to those in the control group over winter (coefficient=−0.38; 95% CI −0.61 to −0.15; p=0.001) (online supplemental material table 44).

DISCUSSION

The VHHP is the first comprehensive evaluation of the thermal comfort, energy use and health impacts of home upgrades to be conducted alongside a randomised controlled trial in Australia. The overall results indicate that home upgrades provide important benefits in thermal comfort and quality of life, and in reduction in energy costs.

The increase in mean indoor temperatures by an average of 0.33°C and reduced exposure to unhealthy indoor conditions by an average of 43 min/day correlate to valuable energy savings and improved comfort for participants. A recent trial in Wales with more comprehensive upgrades was able to raise average indoor temperature by 3°C, but this required spending upwards of £65 000 per household.[42] Relatively speaking, our modest upgrade cost resulted in a small but significant change to indoor temperature.

These results concur with international evidence, particularly in relation to energy benefits but also for mental health improvements.[3 6–8 11 18 41 43] The finding in relation to breathlessness and mental health aligns with Osman's work on respiratory health in the elderly.[18 43] Our study demonstrates that health and energy benefits depend on baseline housing conditions, with poorer quality houses benefiting more from upgrades. This suggests careful targeting of the intervention is important to maximise benefits, similar to Thomson's work in America.[44 45]

A major factor for both the conduct and outcomes of this study was the impact of the COVID-19 pandemic. First, there was an impact on the per-protocol sample size for the 2020 cohort and consequently a loss of power to detect significant differences. There was a very large percentage of households in the intervention group that did not receive their upgrade in time. Despite this, we show significant effects in some outcomes. Consequently, we believe our effect estimates are likely a large underestimate of the true impact of home upgrades. This is even more so when we consider that we are constraining our analysis to 3 months over winter. The effects of these upgrades endure for years, and these benefits are not captured in the current analysis. This is supported by the findings in Kearns *et al* (2023) which demonstrated improved thermal comfort, reduced hospital admissions for people with respiratory conditions and improved self-reported physical health over 5 years following external wall insulation, compared with many other studies examining shorter periods. Kearns *et al* recommended follow-up periods for over a decade or more to better establish the longevity of impacts from energy efficiency works.[46]

Second, the 2020 cohort effect is significant in many of the regression models. The most obvious example of the '2020' pandemic cohort effect is evident in the administrative health data. We observe that there is a reduction in healthcare service use and cost, and our survey data reveals that individuals spent more time at home. They also are likely to use their energy differently because of these changes in behaviour. Our post-winter 2020 survey was modified to capture some of these effects. Additionally, we recognise there might have been some recall bias for the partiapitsn who were asked to recall their previous winter but this would not impact the main RCT only those from the surveys.

In this study, we did not control for the exact timing of the intervention and therefore assume that the 'length of the intervention dose' is the same for all intervention participants (3 months over winter). However, we acknowledge that households received their upgrades at differing points in time in the pre-winter period and over differing durations due to the practicalities of scheduling the various trades to undertake the works. This means that some households have had the 'dose' of the intervention longer than others.

This evaluation has yielded valuable insights into the challenges associated with undertaking population interventions of this nature. In particular, because the intervention requires modifications to the participants' homes, there are important occupational health and safety issues that require careful planning and consideration. The design of the trial also required that the modifications be conducted with time constraints, and the ability to control this proved to be challenging and beyond the control of the programme.

Despite these challenges, the programme provides rigorous, novel evidence that modest home upgrades can have important impacts on thermal comfort, energy use, healthcare costs and well-being. The strengths of this study include the randomised design, comprehensive objective and subjective thermal comfort data, objective linked health data and quality of life information for the same cohort. These findings add much-needed evidence to the research base on the co-benefits of home upgrades.

PROTOCOL

The protocol for this trial was published in BMJ Open in 2022.[20] Our response to the peer reviewers can be seen in online supplemental file 4.

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