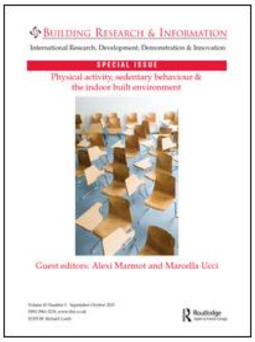

Routledge
Taylor & Francis Group

Building Research & Information

ISSN: 0961-3218 (Print) 1466-4321 (Online) Journal homepage: http://www.tandfonline.com/loi/rbri20

Impacts of energy-efficiency investments on internal conditions in low-income households

Wouter Poortinga, Shiyu Jiang, Charlotte Grey & Chris Tweed

To cite this article: Wouter Poortinga, Shiyu Jiang, Charlotte Grey & Chris Tweed (2017): Impacts of energy-efficiency investments on internal conditions in low-income households, Building Research & Information, DOI: 10.1080/09613218.2017.1314641

To link to this article: http://dx.doi.org/10.1080/09613218.2017.1314641

Published online: 27 Apr 2017.

BRI
BUILDING RESEARCH & INFORMATION
2017
https://doi.org/10.1080/09613218.2017.1314641

Routledge
Taylor & Francis Group

RESEARCH PAPER

OPEN ACCESS Check for updates

Impacts of energy-efficiency investments on internal conditions in low-income households

Wouter Poortinga [a,b], Shiyu Jiang [a], Charlotte Grey [a] and Chris Tweed [a]

[a]Welsh School of Architecture, Cardiff University, Cardiff, UK; [b]School of Psychology, Cardiff University, Cardiff, UK

ABSTRACT

Living in cold conditions poses a risk to health, in particular to low-income, fuel-poor households. Improving the energy efficiency of the housing stock may bring multiple positive health gains through improved indoor temperatures and reduced fuel consumption. This study used a multilevel interrupted time-series approach to evaluate a policy-led energy-performance investment programme. Long-term monitoring data were collected for intervention and control households at baseline ($n = 99$) and follow-up ($n = 88$), creating a dataset with 15,771 data points for a series of daily-averaged hydrothermal outcome variables. The study found that the intervention raised indoor air temperature by on average 0.84 K as compared with control households, thereby bringing the majority of indoor temperature measurements within the 'healthy' comfort zone of 18–24°C, while average daily gas usage dropped by 37%. External wall insulation was the most effective measure to increase indoor air temperature. The greatest increases were found in the evening and at night, in the bedroom, and in British steel-framed buildings. No evidence was found that the intervention substantially increased indoor relative humidity levels when accompanied by mechanical ventilation. The study concludes that the multilevel interrupted time-series approach offers a useful model for evaluating housing improvement programmes.

KEYWORDS
energy efficiency; housing; humidity measurements; monitoring; public health; public policy; retrofit; temperature measurements

Introduction

Background

It is widely acknowledged that living in cold conditions poses various health risks, in particular to low-income, fuel-poor households (Marmot Review Team, 2010, 2011). Improving the energy efficiency of the housing stock may bring multiple positive health gains through improved internal conditions and comfort, and lower financial stress from reduced fuel consumption during the heating season (Thomson & Thomas, 2015). Affordable warmth interventions have been associated with improved thermal comfort, better household finances, an expansion of living space and improved family relationships. The evidence suggests that the benefits of such energy-efficiency interventions are the greatest when targeted at those with inadequate warmth and with existing poor health (Thomson, Thomas, Sellstrom, & Petticrew, 2013). The health benefits of energy-efficiency investments are predominantly associated with improvements related to increased thermal efficiency through two interrelated pathways (Gilbertson, Grimsley, & Green, 2012; Grey et al., 2017; Liddell & Guiney, 2015; Thomson & Thomas, 2015). The first pathway is where energy-efficiency investments increase internal air temperature, leading to better *living conditions*. Warmer homes have been shown to be beneficial for respiratory and mental health through improved thermal satisfaction (Hills, 2012), expanded living space (Gilbertson, Stevens, Stiell, & Thorogood, 2006), and reduced risk of social isolation (Bonnefoy, 2007). The second pathway is where energy-efficiency investments make heating the home more *affordable* (Marmot et al., 2011). Reduced spending on heating bills alleviates financial stress and fuel poverty among low-income households (Caldwell et al., 2001; Gilbertson et al., 2006), and helps to free financial resources for better food security (Beatty, Blow, & Crossley, 2014; Bhattacharya, DeLeire, Haider, & Currie, 2003) and reduced social isolation (Ormandy & Ezratty, 2016).

More recently there have been suggestions that increasing the energy efficiency of a home could have detrimental

CONTACT Wouter Poortinga PoortingaW@cardiff.ac.uk

effects on people's health (Bone, Murray, Myers, Dengel, & Crump, 2010). The health risks of energy-efficiency investments are predominantly associated with internal hydrological conditions. Reduced ventilation through insulation and draughtproofing may increase relative humidity levels (Laverge, Van den Bossche, Heijmans, & Janssens, 2011), which may promote mould growth at higher than 60% relative humidity levels (Arundel, Sterling, Biggin, & Sterling, 1986; Baughman & Arens, 1996). Low ventilation rates and higher energy-efficient homes have been associated with asthma and allergic symptoms in children (Bornehag, Sundell, Hägerhed-Engman, & Sigsgaard, 2005; Hägerhed-Engman et al., 2009; Sharpe, Thornton, Nikolaou, & Osborne, 2015a). Modelling studies suggest that energy-efficiency retrofits with ventilation can improve occupants' health through reduced exposure to cold and pollutants, but that their benefits will be reduced if not properly implemented alongside ventilation (Hamilton et al., 2015). Evidence is emerging that higher energy efficiency is associated with increased risk of asthma (Sharpe, Thornton, Nikolaou, & Osborne, 2015b). However, it is not clear whether the increase is due to poorer internal hydrological conditions, as the same study found that energy efficiency was also associated with lower levels of mould growth. Furthermore, traditional UK housing has low thermal performance and high levels of air permeability (Bone et al., 2010). Moderate increases in energy efficiency and airtightness may therefore not lead to substantial increases in relative humidity levels (Hong, Ridley, Oreszczyn, & Group, 2004).

A relatively small number of studies have been conducted to investigate empirically the impacts of energy-efficiency investments on internal conditions. Previous research has shown that both insulation and heating measures can increase living room and bedroom temperatures (Caldwell et al., 2001; Howden-Chapman et al., 2007; Oreszczyn, Hong, Ridley, & Wilkinson, 2006). Evidence further suggests that energy-efficiency improvements can lower indoor relative humidity levels in both living rooms and bedrooms, and that these effects are greater for more extensive improvements (Oreszczyn, Ridley, Hong, & Wilkinson, 2006). This counters the suggestion that affordable warmth interventions may increase the risk of respiratory conditions through increased air tightness and relative humidity levels. However, most research in the area has been cross-sectional (Green, Ormandy, Brazier, & Gilbertson, 2000), did not include control households (Hong, Oreszczyn, & Ridley, 2006), and used spot measurements (Wilkinson et al., 2001) or short-term monitoring (Caldwell et al., 2001). As observed previously by Oreszczyn, Ridley, et al. (2006), most studies did not correct for external conditions during the monitoring periods. Evidence for increases in relative humidity levels have been anecdotal or inferred from cross-sectional studies only (Sharpe et al., 2015a). Raising indoor air temperatures through better insulation should reduce relative humidity levels, unless there is inadequate ventilation (Bone et al., 2010). Furthermore, thus far the impacts of affordable warmth investments on internal conditions have only been studied for a small number of measures, such as insulation and heating, but not for other energy-performance measures, such as new windows and doors and connection to the gas mains network.

Research in the area tends to be based on studies with relatively small sample sizes. Household monitoring studies are labour and resource intensive, and it may be difficult to recruit large numbers of households to participate in studies. Data-analysis techniques have almost exclusively relied upon averaged or standardized household temperatures to estimate model parameters (Green & Gilbertson, 2008; Howden-Chapman et al., 2007; Richardson et al., 2006; Summerfield et al., 2007). That means that the sample size is effectively limited to the number of households included in the study. Furthermore, existing approaches are restricted in their ability to examine the impacts of individual measures when there is variation in the measures delivered within energy-efficiency improvement programmes, different building and construction types, or to study the performance of energy-efficiency measures under different external conditions, as they do not have sufficient statistical power to conduct such sub-analyses.

Present study

Interrupted time-series approach

This study addresses some of these issues through detailed long-term household monitoring of intervention and control households at baseline and follow-up. Both internal and external hydrothermal conditions were measured at high interval frequency and combined into a comprehensive dataset amenable to multilevel interrupted time-series analysis (Reddy, 2011). This approach allows the impacts of the energy-efficiency interventions to be estimated with a maximum level of statistical power, while adjusting for external conditions. Interrupted time-series analysis is a valuable study design for evaluating the effectiveness of public health interventions (Lopez Bernal, Cummins, & Gasparrini, 2016). It involves the analysis of repeated observations over time, usually at equal time intervals before and after an intervention (the 'interruption') in order to detect whether the intervention has produced an effect different from underlying exogenous, secular trends. A time-series approach is particularly well suited to analyse the repeated measurements taken by household monitors. Rather than making comparisons on the basis of averaged or standardized temperatures, an interrupted time-series analysis makes use of all (daily averaged) measurements to determine model parameters. It is therefore able to provide more precise estimates than can be done using averaged or standardized temperatures. This can be done either with or without a control group that did not receive the intervention (Kontopantelis, Doran, Springate, Buchan, & Reeves, 2015). Known time-varying confounders (*e.g.* seasonality or external conditions) can be controlled for at the observation level.

The multilevel extension of the interrupted time-series approach allows the longitudinal analysis to be conducted for multiple properties at the same time (Jones & Subramanian, 2011). Multilevel modelling is an approach that explicitly models clustered or grouped data. In the multilevel version of interrupted time-series analysis, the observations (level 1) are nested within the different intervention and control households (level 2). The approach explicitly deals with the interdependence among the hydrothermal observations within the households (Goldstein, 2011).

Energy-efficiency intervention programme

The monitoring study reported in this paper was part of a comprehensive evaluation of a policy-led energy-efficiency programme (Poortinga, 2014). The programme was designed to improve the energy efficiency of existing homes in low-income areas in Wales, with the aim to reduce the number of households living in fuel poverty, create jobs and regeneration, and contribute to climate-change mitigation by reducing household energy use. The study focused on the second phase of the programme that took place from 2012 to 2015. The programme helped to improve the energy performance of more than 4800 homes located in mixed-tenure, low-income neighbourhoods that had a high number of 'hard-to-heat, hard-to-treat' homes, and where as a result people are at a high risk of living in fuel poverty. Typical energy-efficiency measures included external wall insulation (with mechanical ventilation), new windows and doors, heating system upgrades, and the connection of off-gas communities to the gas mains network. The programme was managed by two scheme managers, whose building surveyors determined the most appropriate and cost-effective measures on a scheme-by-scheme basis.

Aims

The overall aim of the study was to examine the impacts of the intervention programme on internal hydrothermal conditions and energy use in low-income households. More specifically, it set out to examine the impacts of the intervention programme on whole-house indoor air temperature and relative humidity levels in these households, as well as comparing individual energy-efficiency measures. It further determined the impact of the intervention programme on internal conditions within different rooms (*i.e.* living room, bedroom and kitchen), at different times of the day, and under different external hydrothermal conditions. In order to examine whether the intervention would decrease potential exposure to risky internal conditions, it examined changes in average daily length and cumulative substandard internal hydrothermal conditions following the energy-efficiency improvements. Finally, the study examined the impact of the intervention on household gas usage.

The research focused on low-income households. This is relevant, as the benefits of energy-efficiency interventions can be taken as energy saving or as extra warmth. The rebound effect, or lower-than-expected gains of energy-efficiency improvements due to increased demand for energy, is usually greater in lower-income groups (Gavankar & Geyer, 2010). This is because they are more likely to have an unmet demand for energy services, such as warmth, than higher-income groups. The impacts of energy-efficiency investments on internal conditions are therefore likely to be different for households with high or low incomes. The current study will provide estimates of how the energy investment programme changed indoor conditions as well as household gas usage in the areas.

Methods

Participants and procedure

The study had a quasi-experimental controlled before-and-after design consisting of long-term monitoring of the indoor environment in two subsequent heating (winter) seasons. The study was conducted in five low-income areas where the programme was scheduled to take place, and five comparable control areas where no such investments were planned during the duration of the study (Figure 1). All control areas were located geographically close to the intervention areas and identified with the help of local authorities to ensure that the communities were similar in terms of housing type and socio-economic make up, and exposed to similar climatic conditions. The intervention and control areas were located in Brynamman (Carmarthenshire), Caerau (Cardiff), Llay (Wrexham), Hollybush (Caerphilly), and Penydarren (Merthyr Tydfil), all in Wales. Households for the monitoring study were recruited from a community sample used to examine the health impacts of structural

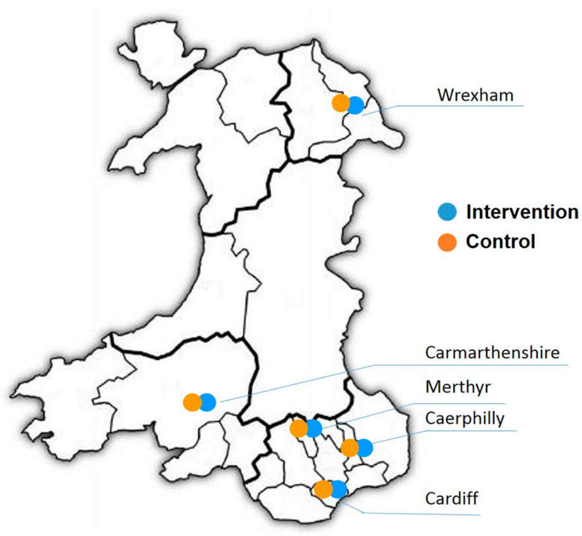

Figure 1. Locations of the intervention and control areas for the household monitoring study.

energy performance investments (Grey et al., 2017). Respondents who provided consent to be recontacted were invited to have their house monitored. The monitoring study aimed to recruit 100 households from the five intervention and five control areas, with a variety of building types, household characteristics and intervention measures.

In total, 99 households agreed to take part in the study, of which 50 were located in the intervention areas and 49 in the matched control areas. Households were visited during January and February 2014 to install the indoor data loggers for the baseline period, and again in March and April 2014 to collect them. The households that took part in the first part of the study were recontacted by letter prior to the 2014/15 heating season. The reminder letter was followed up by a telephone call to arrange an installation visit for the follow-up period. Households were visited in November 2014 to install indoor data loggers, and again in April 2015 to collect them. Eleven per cent of the households dropped out due to ill-health or relocation, resulting in a final sample of 88 households ($n = 48$ intervention, $n = 40$ control). A loss to follow-up analysis suggests that attrition did not bias the samples in a systematic way. The analysis involved a comparison of the characteristics of the households included in the final study sample and those who dropped out in between baseline and follow-up. The absence of any significant differences between the two groups reflects the low attrition rate in the study (11%). Table 1 shows the characteristics of the intervention and control households at baseline and follow-up. Local weather stations were installed in or close to the five monitoring areas to record external meteorological conditions during the baseline and follow-up periods. Gas and electricity meter readings were taken during the installation and collection visits at both the baseline and follow-up periods.

The final dataset involved 99 households that were monitored for on average of 46 days (standard deviation (SD) = 9) during the baseline period, and 88 households that were monitored for on average of 127 days (SD = 32) during the follow-up period. The dataset contained 15,771 data points for a series of daily-averaged hydrothermal outcome variables. The daily-averaged variables of all monitored households were included in the final dataset. However, only the 88 households that were monitored at both the baseline and follow-up periods were used to estimate the parameters reported in this paper.

The research received ethical approval from the School Research Ethics Committee (SREC) of Cardiff University.

Measures

The following intervention and outcome variables were included in the analyses.

Intervention measures

The intervention measures included external wall insulation (with mechanical ventilation), new windows and doors, boiler and heating system upgrades, and connection to the gas mains network. The measures were recorded for each participating household. In this study, 35 intervention households received external wall insulation, nine received new windows and doors, 48 received a new boilers or heating system, and 20 were connected to the mains gas network. Of the 48 properties, 32 received two measures and 16 received three measures. The most common combinations were external wall insulation with a new heating system ($n = 19$), and a connection to the gas mains network with a new heating system ($n = 13$). Nine properties received external wall insulation, new windows and doors, and a new heating system. Seven properties received properties received external wall insulation in combination with a new heating system, and were connected to the gas mains network. Figure 2 shows that, on average, the measures increased the standard assessment procedure (SAP) energy and environmental performance ratings of the intervention households from 52 (SD = 12) to 66 (SD = 5), which equates to rising from an energy performance certificate (EPC) band E to band C.

Indoor air temperature and relative humidity

The main outcomes of the household monitoring study were (daily averaged) indoor air temperature and relative humidity at different times of the day and in different

Table 1. Characteristics of the intervention and control households at baseline and follow-up.

		Intervention		Control	
Characteristics	**Category**	**Baseline, % (*n*)**	**Follow-up, % (*n*)**	**Baseline, % (*n*)**	**Follow-up, % (*n*)**
Building age	Before 1919	22.5 (11/49)	28.9 (13/45)	39.1 (18/46)	35.9 (45/39)
	1919–44	28.6 (14/49)	20.0 (9/45)	32.6 (15/46)	33.3 (14/39)
	1945–65	32.6 (16/49)	37.8 (17/45)	0.0 (0/46)	0.0 (0/39)
	1965–79	8.2 (4/49)	8. 9 (4/45)	26.1 (12/46)	28.2 (11/39)
	1980 or later	8.2 (4/49)	4.4 (4/45)	2.2 (1/46)	2.6 (1/39)
Building type	Detached	4.0 (2/50)	4.4 (2/46)	4.1 (2/49)	4.8 (2/42)
	Semi-detached	42.0 (21/50)	47.8 (22/46)	49.0 (24/49)	40.5 (17/42)
	Terraced	52.0 (26/50)	45.7 (21/46)	40.82 (20/49)	47.6 (20/42)
	Bungalow	0.0 (0/50)	0.0 (0/46)	2.0 (1/49)	2.4 (1/42)
	Flat	2.0 (1/50)	2.2 (1/46)	4.1 (2/49)	4.8 (2/42)
Construction type	British steel framed	30.0 (15/50)	32.6 (15/46)	38.8 (19/49)	42.9 (18/42)
	Masonry solid wall	60.0 (30/50)	58.7 (27/46)	57.1 (28/49)	54.8 (23/42)
	Masonry cavity wall	10.0 (5/50)	8.7 (4/46)	4.1 (2/49)	2.4 (1/42)
Number of bedrooms	1	2.0 (1/49)	2.2 (1/45)	4.1 (2/49)	4.8 (2/42)
	2	8.2 (4/49)	8.9 (4/45)	10.2 (5/49)	9.5 (4/42)
	3 or more	89.8 (44/49)	89.0 (40/45)	85.7 (42/49)	85.7 (36/42)
Tenure	Owner occupied	61.2 (30/50)	57.8 (26/45)	61.2 (30/49)	61.9 (26/42)
	Private rental	14.3 (7/50)	11.1 (5/45)	8.2 (4/49)	11.9 (5/42)
	Local authority rental	24.5 (12/50)	24.4 (11/45)	28.6 (14/49)	26.2 (11/42)
	Housing association rental	2.0 (1/50)	6.7 (3/45)	2.0 (1/49)	0.0 (0/42)
Household composition	Without children	68.8 (33/48)	67.4 (31/46)	81.3 (39/48)	80.5 (33/41)
	With children	31.3 (15/48)	32.6 (15/46)	18.8 (9/48)	19.5 (8/41)

rooms within the home. Tinytag Ultra 2 data loggers were placed in the living room, kitchen and main bedroom, positioned away from any direct heat source and external windows. They were placed in a location where they would cause the least disturbance to the occupants and were unlikely to get covered, typically on top of a cupboard or shelf at a height of about two metres. Due to practical issues of placing loggers in dwellings in diverse circumstances, furnishings and personal preferences, the exact locations where they were positioned within the rooms varied. Indoor air temperature and relative humidity were recorded every 15 minutes. Tinytag Ultra 2 data loggers have an air temperature reading range of –25 to 85°C, with a resolution of 0.01 K and an error range of ±0.35 K; and a relative humidity reading range of 0–95%, with a resolution of 0.3% and an error range of ±3.0% at 25°C.

The data were used to calculate the daily average indoor air temperature and relative humidity, as well as the daily average indoor air temperature and relative humidity in the morning (06.00–09.00 hours), during the day (09.00–18.00 hours), in the evening (18.00–23.00 hours), and at night (23.00–06.00 hours). The data were used for the three rooms separately and combined to calculate a whole house average.

The study further explored the impacts of the intervention on the length and cumulative substandard internal conditions. The length and cumulative substandard internal conditions were derived from duration and cumulative exposure measures commonly used in

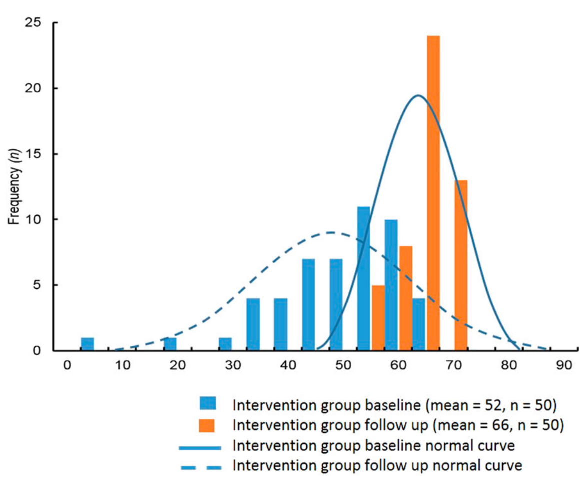

Figure 2. Standard assessment procedure (SAP) ratings of intervention households before and after installation of the energy-efficiency measures.

environmental epidemiology (de Vocht, Burstyn, & Sanguanchaiyakrit, 2015; Nieuwenhuis, 2015). These measures reflect the duration and total amount of (potential exposure to) such substandard conditions. The *length of substandard internal conditions* was determined by recording the time each day the indoor air temperature dropped below 16 or 18°C, and indoor relative humidity was above 60%. These thresholds were based on the literature showing that indoor air temperatures of at least 18°C in winter pose a minimal risk to the health of a sedentary person and to people over 65 years of age or with pre-existing medical conditions (National Institute for Health and Care Excellence, 2014). Indoor air temperatures below 18°C increase the risk of high blood pressure, with the risks being heightened with temperatures below 16°C. Indoor air temperatures below 16°C may further diminish resistance to respiratory diseases (Public Health England, 2014). Relative humidities above 60% have been linked to respiratory and allergic conditions, as well as to fungal growth and house dust mite infestations (Arundel et al., 1986; Baughman & Arens, 1996).

The *cumulative substandard internal conditions* is the time integral of the intensity of substandard conditions beyond the chosen thresholds, thus representing the daily dose of substandard internal conditions to which householders potentially get exposed. The cumulative substandard indoor air temperature reflects the amount of under-heating over the period of a day. The cumulative substandard indoor relative humidity reflects the total amount of exposure to risky humidity levels. The cumulative substandard internal conditions are expressed in °C hour and % RH hour for indoor air temperature and relative humidity, respectively.

Outdoor air temperature, relative humidity and heating demand

Outdoor air temperature and relative humidity were measured by local weather stations installed in or close to the monitoring areas, typically in a participating household's garden. Outdoor air temperature and relative humidity were recorded every 15 minutes by local Delta-T-GP1 weather stations. Delta-T-GP1 weather stations have an air temperature reading range of −20 to 70°C with a resolution of 0.05 K and an error range of ±0.3 K, and a relative humidity reading range of 0–100% with a resolution of 0.2%, and an error range of ±2% between 5% and 95% and of ±2.5% for < 5% and > 95% relative humidity.

The measurements were combined to calculate the average whole-day outdoor air temperature and relative humidity, as well as the average outdoor air temperature and relative humidity in the morning (06.00–09.00 hours), during the day (09.00–18.00 hours), in the evening (18.00–23.00 hours), and at night (23.00–06.00 hours).

The outdoor air temperature measurements were subsequently converted into daily heating degree-days (HDDs) (CIBSE, 2006). HDDs reflect the demand for the energy needed to heat buildings over a specific period, in this case a day. The heating demand is calculated by summing the differences between the outdoor air temperature and a reference temperature. As such, the HDD measure is an exposure measure reflecting the cumulative amount of degrees the temperature falls below the base temperature over a day. The reference temperature, 15.5°C in the UK, reflects the outdoor temperature at which generally no heating is needed to maintain comfortable internal conditions (Hitchin, 1983; Hong, Gilbertson, Oreszczyn, Green, & Ridley, 2009). In this study HDDs are calculated as the mean temperature difference for the 96 daily readings, analogous to the mean degree-hour method (CIBSE, 2006).

HDDs provide some advantages over other methods that use mean outdoor temperatures to calculate energy demand. They take account of fluctuations in outdoor air temperature and exclude periods when space heating is not needed, therefore capturing extreme conditions in a way that mean temperature methods cannot. This makes them more reliable in estimating energy consumption, particularly in milder conditions and in periods with fluctuating or extreme cold snaps where they capture both the magnitude and length of an event. HDDs also have a number of shortcomings (Valor, Meneu, & Caselles, 2001). They are based on assumptions about when additional energy is needed to heat a building, ignore that some buildings are only heated during specific periods, and do not reflect variations in the ability of different buildings to retain heat or to exploit solar gains.

Average daily gas usage

Average daily gas usage was calculated from meter readings taken during the installation and collection visits for both the baseline and follow-up periods. The change in average daily gas usage provides an indication of the effectiveness of the energy-performance investments, as most of the metered gas will have been used for space and water heating. It was not possible to take gas meter readings in off-gas areas.

Statistical analysis

The data were analysed by constructing a series of controlled multilevel interrupted time-series regression models, with daily internal conditions nested within households that either received an intervention or not. The nested multilevel design allows one to take account of the clustering of the observations over time using random effects. The approach also enables the handling of unbalanced data, where the number of observations differ for the different households and time periods (Goldstein, 2011). This makes the approach suitable for analysing monitoring data of multiple properties with different start and end dates.

Analyses were conducted with the MLwiN 2.36 software package (Rasbash, Charlton, Browne, Healy, & Cameron, 2016). The software is specifically designed for fitting multilevel models, in this case an 'interrupted time-series' regression analysis. The analysis involved the use of the time series of the daily-averaged hydrothermal conditions measured during the baseline and follow-up periods in the intervention and control households. The interruption occurred between baseline and follow-up sampling periods when intervention households had improvement work done to their homes. The interruption in the 'interrupted time series' therefore refers to the energy-efficiency improvements undertaken in the intervention households. This was then compared with control households who did not receive the energy-efficiency investments during that period.

The basic statistical models included three independent variables, *i.e.* the intervention group; the measurement period; and an interaction between measurement period and the intervention group. The intervention-group variable indicated whether the measurements were taken in an intervention or a control household. The measurement-period variable indicated whether the measurements were taken in the baseline or during the follow-up period. The interaction term of the measurement-period and intervention-group variables indicated that the intervention has taken place in the follow-up period for the intervention households. The regression coefficient related to this term shows the level of change in internal conditions for the intervention group relative to the control group.

The statistical models were further controlled for external condition. This was done by including the daily-averaged external measurements as independent variables. The models with indoor air temperature as the outcome variable included daily HDD values as a covariate to control for external thermal conditions. The models with indoor relative humidity as the outcome variable additionally included a measure of the average daily outdoor relative humidity to control for external hydrological conditions.

Interrupted time-series analyses typically include a time variable (indicating the time elapsed since the start of the study, as measured in days) and a time after the interruption variable (indicating the time elapsed since the intervention, as measured in days) in order to identify trends over time and changes in the trend after the intervention, respectively (*cf.* Lopez Bernal et al., 2016). However, as no obvious trend over time was observed within the baseline and follow-up periods, these terms were excluded from the regression models.

One problem with repeated measurement data is that the measurements are often not independent, which violates one of the assumptions of ordinary least squares regression. Autocorrelation within time series, when measurements close to one another are more similar than measurements that are further apart, may lead to increased type I errors. The autocorrelation function (ACF) and partial autocorrelation function (PACF) in MLwiN indicated autocorrelation with a diminishing lag. Autocorrelation reflects the internal correlation within a time series, showing the degree to which the different measurements are interdependent (*cf.* Lopez Bernal et al., 2016). An autoregressive model was constructed by adding a weight specifying that the error covariance decreases as the time distance between measurements increases in order to control for the observed dependency (Jones & Subramanian, 2011).

Results

Descriptive results

Table 1 summarizes the characteristics of the intervention and control households at baseline and follow-up. It shows that the two groups only differed in terms of building age. There were no differences for building type, construction type, number of bedrooms, tenure, and household composition. Dropout between baseline and follow-up appeared to have occurred at random, therefore not biasing the results.

Table 2 shows the average internal conditions for the 88 households that were monitored at both baseline and follow-up. It reports the descriptive results unadjusted for external conditions and suggests that indoor air temperatures increased for the intervention group but decreased for the control group between baseline and follow-up. The changes in indoor relative humidity were less pronounced. Small reductions were observed for both the intervention and control groups. The internal conditions presented in Table 2 are not adjusted for external hydrothermal conditions.

The distribution of internal conditions for the intervention and control groups at baseline and follow-up are presented in Table 3. The results presented are again unadjusted for external conditions. Figures

Table 2. Average indoor conditions at baseline and follow-up for the intervention and control groups unadjusted for outdoor conditions.

	Intervention		Control	
Outcome	**Baseline, mean (SD)**	**Follow-up, mean (SD)**	**Baseline, mean (SD)**	**Follow-up, mean (SD)**
Indoor air temperature (°C)				
Overall average (whole house)	18.09 (2.44)	18.95 (2.37)	17.50 (2.63)	17.38 (2.66)
Morning (whole house)	16.98 (2.70)	17.88 (2.56)	16.13 (2.63)	16.21 (2.48)
Day (whole house)	18.19 (2.46)	18.97 (2.31)	17.56 (2.83)	17.52 (2.69)
Evening (whole house)	18.82 (2.42)	19.77 (2.52)	18.53 (2.79)	18.22 (2.92)
Night (whole house)	17.93 (2.53)	18.81 (2.44)	17.35 (2.46)	17.12 (2.59)
Daily average (living room)	18.53 (2.59)	19.33 (2.68)	18.40 (2.36)	18.26 (2.77)
Daily average (bedroom)	18.16 (2.89)	18.86 (2.91)	17.41 (3.25)	16.64 (3.22)
Daily average (kitchen)	18.09 (2.92)	18.68 (2.69)	16.74 (3.69)	17.25 (3.39)
Indoor relative humidity (% RH)				
Overall average (whole house)	56.09 (10.63)	53.53 (9.70)	58.37 (10.88)	56.53 (10.28)
Morning (whole house)	56.80 (11.63)	53.84 (10.30)	59.32 (10.87)	57.07 (10.33)
Day (whole house)	55.48 (10.36)	53.21 (9.09)	58.13 (10.65)	55.91 (9.90)
Evening (whole house)	56.33 (10.29)	53.81 (10.05)	58.26 (11.15)	56.87 (10.65)
Night (whole house)	56.41 (11.15)	53.59 (10.14)	58.36 (10.97)	56.85 (10.63)
Daily average (living room)	53.76 (11.50)	52.27 (10.77)	55.56 (10.85)	53.25 (10.94)
Daily average (bedroom)	56.90 (12.20)	54.24 (10.69)	58.72 (11.37)	59.38 (11.24)
Daily average (kitchen)	57.61 (11.11)	54.08 (10.57)	60.84 (14.30)	56.96 (12.72)

represent the proportion of measurements falling into the different indoor air temperature and relative humidity bands. At baseline, the distribution of indoor air temperature and relatively humidity levels were largely comparable for the two groups, $\chi^2(3) = 1.761$, $p = 0.623$ and $\chi^2(3)= 2.659$, $p = 0.447$, respectively. The distribution of the indoor air temperature differed at follow-up, $\chi^2(3) = 18.231$, $p = 0.000$. The proportion of substandard indoor air temperatures measurements decreased for the intervention group, but increased for the control group. In contrast, the proportion of indoor air temperatures measurements that were within the 18 and 24°C band (the recommended comfort zone) increased for the intervention group but decreased for the control group. It is likely that the changes are the result of the energy-efficiency investments as the intervention and control households were located in areas that were geographically close to one another. Table 3 further shows that the proportion of substandard relative humidity measurements (*i.e.* > 60% RH) decreased for both the intervention and control groups. The distribution of indoor relatively humidity levels for the intervention and control groups were still comparable at follow-up, $\chi^2(3) = 3.001$, $p = 0.391$.

Table 3. Distribution of indoor conditions at baseline and follow-up for the intervention and control groups unadjusted for outdoor conditions.

	Intervention		Control	
Outcome	**Baseline (%)**	**Follow-up (%)**	**Baseline (%)**	**Follow-up (%)**
Indoor air temperature (°C)				
< 16	23.5	11.0	27.0	30.4
16–18	20.3	18.5	26.3	26.6
18–24	55.1	68.5	45.5	42.9
> 24	1.2	2.0	1.1	0.1
Indoor relative humidity (% RH)				
< 40	5.2	9.8	3.5	6.1
40–50	30.3	34.3	26.5	25.3
50–60	30.7	29.3	25.1	34.8
> 60	35.4	25.	45.0	33.8

Indoor air temperature

Table 4 shows the estimates and 95% CIs of the measurement period × intervention group interactions for indoor air temperature. These interactions indicate the levels of change in indoor air temperature observed in the intervention households as compared with the controls. The results show that the overall average whole-house temperature of intervention households increased by 0.84 K relative to the control households, and adjusted for external hydrothermal conditions. The largest changes were observed in the evening (1.17 K) and at night (1.01 K). Slightly smaller changes were observed in the morning (0.51 K) and during the day (0.62 K). Significant increase

Table 4. Relative changes in indoor air temperatures for the intervention households relative to the control households.

Outcome	Relative change (K)	95% CI (K)	*p*
Indoor air temperature (°C)			
Daily average (whole house)	0.84	0.64–1.04	< 0.001
Time of day			
Morning (whole house)	0.51	0.26–0.75	< 0.001
Day (whole house)	0.62	0.40–0.84	< 0.001
Evening (whole house)	1.17	0.94–1.04	< 0.001
Night (whole house)	1.01	0.79–1.24	< 0.001
Rooms			
Daily average (living room)	1.01	0.78–1.23	< 0.001
Daily average (bedroom)	1.28	1.04–1.52	< 0.001
Daily average (kitchen)	0.24	−0.01 to 0.48	0.060
Measures			
Daily average (external wall insulation)	1.12	0.69–1.55	< 0.001
Daily average (windows and doors)	−0.02	−0.39 to 0.35	0.924
Daily average (heating system)	−0.19	−0.69 to 0.31	0.463
Daily average (Gas network)	0.69	0.29–1.09	< 0.001
Building construction			
Daily average (cavity wall)	−0.17	−0.58 to 0.25	0.430
Daily average (solid wall)	0.74	0.51–0.96	< 0.001
Daily average (British steel framed)	1.54	1.26–1.83	< 0.001
Heating demand condition			
< 6 HDD	1.03	0.87–1.19	< 0.001
6–8 HDD	1.03	0.90–1.17	< 0.001
8–10 HDD	0.59	0.47–0.72	< 0.001
10–12 HDD	0.80	0.65–0.94	< 0.001
> 12 HDD	0.79	0.63–0.95	< 0.001

were observed in the living room (1.01 K) and bedroom (1.28 K), but not in the kitchen. The observed increase in the kitchen (0.24 K) was non-significant.

Table 4 further shows that some intervention measures were more effective than others in raising indoor air temperatures. External wall insulation produced the largest increase in indoor air temperature (1.12 K) relative to control households. Connecting a property to the gas mains network also increased the indoor air temperature significantly, on average by 0.69 K. A new boiler or heating system (−0.19 K) and new windows and doors (−0.02 K) did not change the indoor air temperatures of the intervention households as compared with the control households.

The impacts of the intervention were different for the three building construction types included in the study. Table 4 shows that the intervention increased indoor air temperatures in buildings with solid walls by 0.74 K and in British steel-framed buildings by 1.54 K as compared with similar buildings that did not receive the measures. The intervention did not significantly change indoor air temperatures in buildings with cavity walls.

The change in indoor air temperatures resulting from the intervention differed under different heating demand conditions. The increases in indoor air temperature ranged from 0.59 K to 1.03 K. The increases were the highest for the lower heating demand conditions (*i.e.* under 6 HDD and between 6 and 8 HDD) and the lowest for the 8–10 HDD band.

Indoor relative humidity

Little evidence was found that the intervention increased levels of indoor relative humidity. Table 5 shows that, on average, the intervention increased indoor humidity levels by 0.04% RH relative to the control households. It further shows the changes were consistent for different levels of outdoor relative humidity conditions. None of the changes differed significantly from the changes observed for the control households under the same conditions. The different intervention measures had differential impacts on internal hydrological conditions. Both a gas network connection (3.86% RH) and the installation of new windows and doors (5.15% RH)

Table 5. Relative changes in indoor relative humidity for the intervention households relative to the control households.

Outcome	Relative change (% RH)	95% CI (% RH)	*p*
Indoor air temperature (% RH)			
Daily average (whole house)	0.04	−0.74 to 0.83	0.915
Measures			
Daily average (external wall insulation)	−0.60	−2.26 to 1.06	0.479
Daily average (windows and doors)	5.15	3.73–6.57	< 0.001
Daily average (heating system)	−1.59	−3.52 to 0.34	0.107
Daily average (Gas network)	3.86	2.31–5.41	< 0.001
Building construction			
Daily average (cavity wall)	4.57	2.94–6.20	< 0.001
Daily average (solid wall)	−0.90	−1.76 to −0.03	0.041
Daily average (British steel framed)	−0.35	−1.49 to 0.78	0.540
Outdoor relative humidity			
50–60% RH	−0.69	−1.87 to 0.49	0.255
60–70% RH	−0.29	−1.14 to 0.56	0.504
70–80% RH	0.05	−0.83 to 0.93	0.910
80–90% RH	0.02	−0.86 to 0.91	0.961
> 90% RH	0.08	−0.83 to 1.00	0.859

increased indoor relative humidity levels. The increases were, however, small in absolute terms. External wall insulation, which included the installation of mechanical ventilation, did not increase levels of indoor relative humidity (−0.60% RH). The observed change in the intervention household was not significantly different from the change observed in the control households, Similarly, new boilers or heating systems did not significantly change indoor relative humidity levels as compared with the control households (−1.59% RH).

The effects of the intervention on indoor relative humidity levels were different for the different building construction types (Table 5). The intervention increased indoor relative humidity levels in buildings with cavity walls by 4.57% RH. Again, this increase is small in absolute terms. The intervention decreased indoor relative humidity levels in buildings with solid walls by a small −0.90% RH. The intervention did not significantly change indoor relative humidity levels in British steel-framed buildings (−0.35% RH) as compared with similar buildings that did not receive energy-efficiency improvements.

Length and cumulative substandard internal conditions

The study further explored the impact of the intervention on the average daily length and cumulative substandard internal conditions. Table 6 shows that there is no evidence that the intervention reduced the daily length of temperatures being below 18°C or below 16°C. The intervention did, however, reduce the length of indoor relative humidity levels being over 60% RH by 1.14 hours.

Table 6 further shows that the intervention had a positive effect on the three cumulative substandard internal conditions measures. The daily cumulative amount of the indoor air temperature being under 18°C was reduced by 3.62 K hour in the intervention households as compared with the control households. The daily cumulative amount of the indoor air temperature being under 16°C was reduced by 4.20 K hour. The daily cumulative amount of the indoor relative humidity levels being above 60% was reduced by 19.32% RH hour in the intervention households relative to the control households.

Table 6. Relative changes in length and cumulative substandard conditions for the intervention households relative to the control households.

Outcome	Relative change	95% CI (% RH)	*p*
Length of substandard conditions			
< 18°C (hours)	0.27	−0.49 to 1.03	0.483
< 16°C (hours)	0.20	−0.48 to 0.88	0.567
> 60% RH (hours)	−1.14	−2.00 to −0.28	0.009
Cumulative substandard conditions			
< 18°C (°C hours)	−3.62	−6.95 to −0.30	0.003
< 16°C (°C hours)	−4.20	−6.64 to −1.76	< 0.001
> 60% RH (% RH hours)	−19.32	−29.68 to −8.96	< 0.001

Average daily gas usage

Figure 3 shows the average daily gas usage for a subset of the intervention ($n = 26$) and control households ($n = 37$) at baseline and follow-up periods (no gas reading could be taken from the households in the off-gas areas). Average daily gas usage decreased from 3.88 to 2.45 m^3 for the intervention households, a reduction of 36.9%. In contrast, average daily gas usage increased from 4.60 to 4.76 m^3 for the control households. A repeated-measures analysis of variance (ANOVA) showed that the intervention group × measurement period interaction was significant, $F(1,60) = 35.985$, $p = 0.000$, $\eta^2 = 0.379$ (Cohen's $d = 1.41$) after controlling for the households' total heating demand over the monitoring period. Note that it was not possible to separate gas usage for heating or for other purposes, such as cooking. However, the results reflect the relative reduction in gas usage in the intervention households as compared with the controls. It is unlikely that systematic changes in cooking behaviour will have contributed to this result.

Discussion

This study provides new evidence of the impacts of energy-efficiency investments on internal conditions and household energy use using a multilevel interrupted time-series approach. Internal conditions were

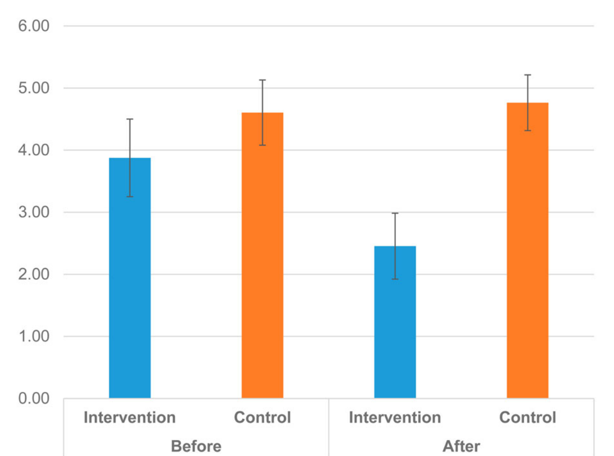

Figure 3. Daily average gas consumption (m^3) with 95% confidence interval (CI) for the intervention and the control households at baseline and follow-up.

monitored for a minimum of 28 consecutive days before and after the installation of energy-efficiency measures, and compared those with internal conditions of households that did not receive such measures. Local weather stations were installed to allow the results to be adjusted for external conditions. The study found that the intervention raised indoor air temperature on average by 0.84 K, while average daily gas usage dropped by 37% as compared with control households. The intervention reduced the cumulative amount of the indoor air temperature being substandard. Overall, the intervention did not increase indoor relative humidity levels, although small increases were found for some individual measures. The study found that the intervention reduced the average daily length and cumulative amount of indoor relative humidity levels being over 60% RH. The reductions were small in absolute terms. The finding that the greatest increases were found in the evening and at night, as well as in the living room and bedroom, suggests that the intervention makes the biggest difference when spaces are in use.

The intervention measures were not equally effective. The introduction of external wall insulation and connection to the gas mains network significantly increased indoor air temperatures; windows and doors or a new heating system did not. The increases in indoor air temperatures in British steel-framed buildings and buildings with solid walls can mainly be attributed to the external wall insulation they received. Both windows and doors and connection to the gas mains network increased indoor relative humidity, although these increases were small in absolute terms. External wall insulation most likely did not increase indoor relative humidity because of mechanical ventilation installed alongside. Increases in indoor relative humidity levels were only observed in buildings that received cavity-wall insulation (which were generally without mechanical ventilation), not in British steel-framed buildings or in buildings with solid walls receiving insulation. It shows the importance of using mechanical ventilation when making building more airtight (Bone et al., 2010).

The observed changes in indoor conditions for the insulation and heating measures were similar or somewhat smaller than those found in previous research. The Warm Front study group reported living room temperature changes of 0.58 K for insulation and 1.36 K for heating measures, and bedroom temperature changes of 1.14 K for insulation and 1.98 K for heating measures respectively (Oreszczyn, Hong, et al., 2006). Even greater changes were found for dwellings that received both heating and insulation measures. These were pre–post comparisons only, rather than temperature changes relative to control households, but were controlled for external conditions. Howden-Chapman et al. (2007) found increases in average bedroom temperatures of 0.50 K and decreases in average relative humidity levels of 2.3% RH (Howden-Chapman et al., 2007). The Glasgow Warm Homes Study (Caldwell et al., 2001) found increases in mean temperatures of more than 2 K for the living room and 3 K for the bedroom. The study found no significant change in relative humidity levels. While the changes reported by Howden-Chapman et al. (2007) and Caldwell et al. (2001) were relative to control households, both studies used averaged temperature and relative humidity estimates, thereby limiting their statistical power. Higher increases were reported by Critchley et al. (2004), although that study involved a move from poor-quality tower blocks to high-quality low-rise buildings.

The effects of connection to the gas mains network and new windows and doors have not been studied before and, therefore, cannot been compared with previous research. The current study found that connection to the gas mains network increased indoor air temperature but did not change indoor relative humidity levels. This is most likely due to gas central heating being more efficient and affordable than oil central heating (which most households had before the connection). Oil is traditionally one of the more expensive fuels used to heat homes and is subject to sudden price changes due to changes in demand. This may make occupants more reluctant to heat their home to an adequate level. The observation that new windows and doors increase indoor relative humidity levels is most likely due to reduced air infiltration. While one may expect this to be associated with increased indoor air temperatures, it is possible that the same temperature is experienced as more comfortable due to reduced air movement or draught (ASHRAE, 2013), and as a result the energy-efficiency investments may have been used to reduce the energy bill rather than to increase indoor air temperatures.

Changes in indoor conditions should always be accompanied by data on energy use in order to interpret whether and to what extent the benefits of improved energy efficiency are taken as energy saving or as extra warmth, the latter also being known as the rebound effect (Chitnis & Sorrell, 2015; Milne & Boardman, 2000). This is on the understanding that rebound effects tend to be higher in lower-income groups with unmet energy services (Gavankar & Geyer, 2010). There is evidence that in the energy-efficiency programme reported in this paper, which specifically focused on low-income areas, the benefits were taken both as energy saving and increased warmth, although, as discussed below, research would benefit from more disaggregated energy monitoring to make a more detailed assessment of the energy used for heating.

The study had a number of strengths. Most notably it used a comprehensive household monitoring dataset that was amenable to multilevel interrupted time-series analysis. To our knowledge, this approach has not been used before in the context of household monitoring, and it provides more detailed estimates than was possible with previous approaches used in built-environment research. Rather than using single average or standardized temperature estimates, thereby effectively ignoring most of the collected information and limiting the dataset to the number of monitored households, the current study used information from the whole monitoring period. While the study only included a relatively small number of households, they were observed for a minimum of four weeks before and after the intervention. The monitoring data were used to calculate the average daily indoor air temperature and relative humidity measures, resulting in a detailed dataset with more than 15,000 data points. The longitudinal study therefore allowed the model parameters to be estimated with far more precision, using multiple observations per household as opposed to just one averaged or standardized value. The multilevel approach explicitly deals with the interdependence among the hydrothermal observations within the different households (Goldstein, 2011). Other strengths of the study include the use of both local weather stations and control households which were selected to be as similar to the intervention households as possible, allowing not only for adjustments for external conditions and heating demand on a daily basis but also for the exclusion of other time-dependent variables and secular trends during the monitoring period. As such, the study has taken an approach similar to 'energy epidemiology' in that it uses well-established public health methodologies in built-environment research. The study has shown that such methodologies can be applied successfully, and may provide a useful addition to other discipline-specific methods (Hamilton et al., 2013).

While the study involved detailed long-term monitoring before and after the intervention, including a control group, and controlled for external hydrothermal conditions, it did not monitor occupancy, heating and/or occupant behaviour. Occupancy and occupant behaviour have a large impact on the energy consumption and internal conditions of buildings (Guerra Santin, Itard, & Visscher, 2009; Yohanis, Mondol, Wright, & Norton, 2008). Including these aspects would improve our understanding of adaptive behaviours resulting from the energy-efficiency investments. Information about occupancy would also help to determine with more precision the length and cumulative amount of exposure to substandard temperatures. However, it was beyond the scope of the study to incorporate internal household behavioural dynamics. Furthermore, energy use was estimated from meter readings taken during the installation and collection of the monitors. This can only provide a broad indication of the energy savings as a result of the energy-efficiency investments. Higher-resolution energy monitoring, sensors and social science research methods are needed to provide more precise and ideally disaggregated estimates for specific purposes (such as heating or cooking) to get a better understanding of occupants' behaviour, their thermal experiences and responses to changes in the built environment.

A further limitation was that the monitoring sample was self-selected. The study was conducted in low-income areas, which tend to have low response rates for research studies (Parry, Bancroft, Gnich, & Amos, 2001). There is, however, little evidence that selection and attrition have systematically biased the sample, suggesting that the results may be generalized to similar energy-performance investment programmes. The results may, however, not be directly generalizable to non-deprived communities or households with different financial circumstances who respond differently to energy-efficiency investments (Gavankar & Geyer, 2010).

Finally, the intervention involved a number of different energy-efficiency measures, depending on the type and location of the properties. This is both a strength and a weakness. While this means that the houses were non-identical and that there was not a single intervention that was evaluated, the multilevel interrupted time-series approach allowed us to estimate the effect of different energy-efficiency measures and in different types of buildings. It is important to note that all properties received multiple energy-efficiency measures. This paper only explored the effects of the individual measures using a time-series regression-based approach. The effects of the different combination on indoor conditions will be explored in future analyses. It may also be possible that the impacts of the interventions differ according to housing type. It was beyond the scope of this paper to conduct more detailed analyses. Also, here we will conduct further investigations to identify potential interactions between housing type and the different energy-efficiency measures.

Conclusions

The study suggests that the intervention has been successful in reducing energy use while improving living conditions of households in low-income areas, which were the main aims of the intervention programme. The intervention raised indoor air temperature, while average daily gas usage dropped as compared with control households. Although the overall increase in temperature was relatively small (in the order of 1.0–1.5 K), it reflects long-term average increases, reducing the potential exposure of substandard temperatures; it brought the majority of the indoor temperatures within the 'healthy' comfort zone of 18–24°C (National Institute for Health and Care Excellence, 2014; Public Health England, 2014). An above-average increase in bedroom temperature suggests that the intervention helped to expand comfortable space within the home (Gilbertson et al., 2006). The study found no support for the suggestion that insulation and draughtproofing increase indoor relative humidity levels when accompanied by mechanical ventilation. This suggests that energy-efficiency investment programmes will primarily be beneficial by providing improved living conditions that are conducive to good physical and mental health (Thomson & Thomas, 2015), although the relative effectiveness of the different measures were found to be different. Insulation remains the most effective measure to improve living conditions, together with the replacement of expensive oil heating systems with gas central heating. However, the indoor air temperature of buildings with cavity wall construction did not increase over and above the impacts of the measures themselves. A continued focus on these measures and building types is likely to bring the biggest gains to reduce energy use and fuel poverty.

Methodologically, the study proposed a (multilevel) interrupted time-series approach to examine the impacts of energy-efficiency investments on internal conditions and energy use in low-income households. The approach can be used with a sample size as small as one (with a standard interrupted time series), as well as with multiple households using the multilevel version as described in this paper. The multilevel interrupted time-series approach, therefore, offers a useful model for further evaluations of housing improvement programmes, even when there are limited resources available to conduct such evaluations.

Acknowledgements

The views and opinions expressed in this paper are those of the authors and do not necessarily reflect those of the Public Health Research (PHR) programme, the National Institute for Health Research (NIHR), the National Health Service (NHS) or the Department of Health. The authors thank: the Welsh government and two Arbed scheme managers (Melin Homes and Willmott Dixon) for their support, the local authorities involved in the selection of Arbed schemes for their valuable input, and the Communities First groups in south Wales for their advice. Last but not least, they thank the households for taking part in this research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This project is funded by the National Institute for Health Research PHR programme (project number 11/3020/05).

ORCID

Wouter Poortinga http://orcid.org/0000-0002-6926-8545
Shiyu Jiang http://orcid.org/0000-0002-6387-6638
Charlotte Grey http://orcid.org/0000-0002-4072-8851
Chris Tweed http://orcid.org/0000-0002-7656-6460

References

Arundel, A. V., Sterling, E. M., Biggin, J. H., & Sterling, T. D. (1986). Indirect health effects of relative humidity in indoor environments. *Environmental Health Perspectives*, *65*(3), 351–361. doi:10.1289/ehp.8665351

ASHRAE. (2013). *ANSI/ASHRAE standard 55–2013: Thermal environmental conditions for human occupancy*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Baughman, A. V., & Arens, E. A. (1996). Indoor humidity and human health – Part I: Literature review of health effects of humidity – influences indoor pollutants. *ASHRAE Transactions*, *102*(1), 192–211.

Beatty, T. K. M., Blow, L., & Crossley, T. F. (2014). Is there a 'heat-or-eat' trade-off in the UK? *Journal of the Royal Statistical Society. Series A. Statistics in Society*, *177*(1), 281–294. doi:10.1111/rssa.12013

Bhattacharya, J., DeLeire, T., Haider, S., & Currie, J. (2003). Heat or eat? Cold-weather shocks and nutrition in poor American families. *American Journal of Public Health*, *93* (7), 1149–1154. doi:10.2105/AJPH.93.7.1149

Bone, A., Murray, V., Myers, I., Dengel, A., & Crump, D. (2010). Will drivers for home energy efficiency harm occupant health? *Perspectives in Public Health*, *130*(5), 233–238. doi:10.1177/1757913910369092

Bonnefoy, X. (2007). Inadequate housing and health: An overview. *International Journal of Environment and Pollution*, *30*, 411–429. doi:10.1504/IJEP.2007.014819

Bornehag, C. G., Sundell, J., Hägerhed-Engman, L., & Sigsgaard, T. (2005). Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor Air*, *15*(4), 275–280. doi:10.1111/j.1600-0668.2005.00372.x

Caldwell, J., McGowan, S., McPhail, J., McRae, C., Morris, G., Murray, K., … Young, D. (2001). *Glasgow warm homes study: Final report*. Glasgow: Glasgow City Council Housing Services.

Chitnis, M., & Sorrell, S. (2015). Living up to expectations: Estimating direct and indirect rebound effects for UK households. *Energy Economics*, *52*, S100–S116. doi:10.1016/j.eneco.2015.08.026

CIBSE. (2006). *Degree-days: Theory and application. TM41*. London: The Chartered Institution of Building Services Engineers.

Critchley, R., Gilberston, J., Green, G., & Grimsley, M. (2004). *Housing investment and health in Liverpool*. Sheffield: Centre for Regional Economic and Social Research, Sheffield Hallam University.

Gavankar, S., & Geyer, R. (2010). *The rebound effect: State of the debate and implications for energy efficiency research*. Santa Barbara, CA: Bren School of Environmental Science and Management.

Gilbertson, J., Grimsley, M., & Green, G. (2012). Psychosocial routes from housing investment to health: Evidence from England's home energy efficiency scheme. *Energy Policy*, *49*, 122–133. doi:10.1016/j.enpol.2012.01.053

Gilbertson, J., Stevens, M., Stiell, B., & Thorogood, N. (2006). Home is where the hearth is: Grant recipients' views of England's home energy efficiency scheme (warm front). *Social Science and Medicine*, *63*(4), 946–956. doi:10.1016/j.socscimed.2006.02.021

Goldstein, H. (2011). *Multilevel statistical models*. London: John Wiley & Sons.

Green, G., & Gilbertson, J. (2008). *Warm front better health – health impact evaluation of the warm front scheme*. Sheffield: Sheffield Hallam University. Retrieved from http://www.shu.ac.uk/research/cresr/sites/shu.ac.uk/files/warm-front-health-impact-eval.pdf.

Green, G., Ormandy, D., Brazier, J., & Gilbertson, J. (2000). Tolerant buildings: The impact of energy efficiency measures on living conditions and health status. In F. Nicol & J. Rudge (Eds.), *Cutting the cost of cold: Affordable warmth for healthier homes* (pp. 87–103). London: E & FN Spon.

Grey, C. N., Jiang, S., Nascimento, C., Rodgers, S. E., Johnson, R., Lyons, R. A., & Poortinga, W. (2017). The short-term health and psychosocial impacts of domestic energy efficiency investments in low-income areas: a controlled before and after study. *BMC Public Health*, 17(1), 140. doi:10.1186/s12889-017-4075-4

Guerra Santin, O., Itard, L., & Visscher, H. (2009). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings*, *41*(11), 1223–1232. doi:10.1016/j.enbuild.2009.07.002

Hägerhed-Engman, L., Sigsgaard, T., Samuelson, I., Sundell, J., Janson, S., & Bornehag, C.-G. (2009). Low home ventilation rate in combination with moldy odor from the building structure increase the risk for allergic symptoms in children. *Indoor Air*, *19*(3), 184–192. doi:10.1111/j.1600-0668.2008.00573.x

Hamilton, I. G., Milner, J., Chalabi, Z., Das, P., Jones, B., Shrubsole, C., … Wilkinson, P. (2015). Health effects of home energy efficiency interventions in England: A modelling study. *BMJ Open*, *5*(4), e007298. doi:10.1136/bmjopen-2014-007298

Hamilton, I. G., Summerfield, A. J., Lowe, R., Ruyssevelt, P., Elwell, C. A., & Oreszczyn, T. (2013). Energy epidemiology: A new approach to end-use energy demand research. *Building Research and Information*, *41*(4), 482–497. doi:10.1080/09613218.2013.798142

Hills, J. (2012). *Getting the measure of fuel poverty*. London: Department of Energy and Climate Change.

Hitchin, E. R. (1983). Estimating monthly degree-days. *Building Services Engineering Research and Technology*, *4* (4), 159–162. doi:10.1186/s12889-017-4075-4

Hong, S. H., Gilbertson, J., Oreszczyn, T., Green, G., & Ridley, I. (2009). A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Building and Environment*, *44*(6), 1228–1236. doi:10.1016/j.buildenv.2008.09.003

Hong, S. H., Oreszczyn, T., & Ridley, I. (2006). The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. *Energy and Buildings*, *38*(10), 1171–1181. doi:10.1016/j.enbuild.2006.01.007

Hong, S. H., Ridley, I., Oreszczyn, T., & Group, S. (2004). The impact of energy efficient refurbishment on the airtightness in English dwellings. *25th AVIC Conference*, *221*, 7–12. doi:10.1016/j.enbuild.2006.01.007

Howden-Chapman, P., Matheson, A., Crane, J., Viggers, H., Cunningham, M., Blakely, T., … Davie, G. (2007). Effect of insulating existing houses on health inequality: Cluster randomised study in the community. *BMJ*, *334*(7591), 460. doi:10.1136/bmj.39070.573032.80

Jones, K., & Subramanian, S. V. (2011). *Developing multilevel models for analysing contextuality, heterogeneity and change using MLwiN, volume 2*. Bristol: Centre for Multilevel Modeling, University of Bristol.

Kontopantelis, E., Doran, T., Springate, D. A., Buchan, I., & Reeves, D. (2015). Regression based quasi-experimental approach when randomisation is not an option: Interrupted time series analysis. *BMJ*, *350*. doi:10.1136/bmj.h2750

Laverge, J., Van den Bossche, N., Heijmans, N., & Janssens, A. (2011). Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. *Building and Environment*, *46*(7), 1497–1503. doi:10.1016/j.buildenv.2011.01.023

Liddell, C., & Guiney, C. (2015). Living in a cold and damp home: Frameworks for understanding impacts on mental well-being. *Public Health*, *129*(3), 191–199. doi:10.1016/j.puhe.2014.11.007

Lopez Bernal, J., Cummins, S., & Gasparrini, A. (2016). Interrupted time series regression for the evaluation of public health interventions: A tutorial. *International Journal of Epidemiology*, *dyw098*, 1–8. doi:10.1093/ije/dyw098

Marmot, M., Geddes, I., Bloomer, E., Allen, J., Goldblatt, P., & Marmot Review, T. (2011). *The health impacts of cold homes and fuel poverty*. London: Friends of the Earth & the Marmot Review Team.

Marmot Review Team. (2010). *Fair society, healthy lives*. London: UCL Institute of Health Equity.

Marmot Review Team. (2011). *The health impacts of cold homes and fuel poverty*. London: Friends of the Earth & the Marmot Review Team.

Milne, G., & Boardman, B. (2000). Making cold homes warmer: The effect of energy efficiency improvements in low-income homes A report to the energy action grants agency charitable trust. *Energy Policy*, *28*(6–7), 411–424. doi:10.1016/S0301-4215(00)00019-7

National Institute for Health and Care Excellence. (2014). *Evidence review and economic analysis of excess winter deaths. Review 3: Delivery and implementation of approaches for the prevention of excess winter deaths and morbidity*. London: National Institute for Health and Care Excellence.

Nieuwenhuis, M. (2015). *Exposure assessment in environmental epidemiology* (2nd ed.). Oxford: Oxford University Press.

Oreszczyn, T., Hong, S. H., Ridley, I., & Wilkinson, P. (2006). Determinants of winter indoor temperatures in low income households in England. *Energy and Buildings*, *38*(3), 245–252. doi:10.1016/j.enbuild.2005.06.006

Oreszczyn, T., Ridley, I., Hong, S., & Wilkinson, P. (2006). Mould and winter indoor relative humidity in low income households in England. *Indoor and Built Environment*, *15* (2), 125–135. doi:10.1177/1420326X06063051

Ormandy, D., & Ezratty, V. (2016). Thermal discomfort and health: Protecting the susceptible from excess cold and excess heat in housing. *Advances in Building Energy Research*, *10*(1), 84–98. doi:10.1080/17512549.2015.1014845

Parry, O., Bancroft, A., Gnich, W., & Amos, A. (2001). Nobody home? Issues of respondent recruitment in areas of deprivation. *Critical Public Health*, *11*(4), 305–317. doi:10.1186/s12889-017-4075-40.1080/09581590110094585

Poortinga, W. (2014). Health impact of structural energy performance investments in Wales: An evaluation of the Arbed programme. PHR Protocol project 11/3020/05 (version 3, April 2014). Retrieved 13 April 2017 from https://njl-admin.nihr.ac.uk/document/download/2007541.

Public Health England. (2014). *Minimum home temperature thresholds for health in winter: A systematic literature review*. London: Public Health England.

Rasbash, J., Charlton, C., Browne, W. J., Healy, M., & Cameron, B. (2016). *MLwin version 2.36*. Bristol: Centre for Multilevel Modelling, University of Bristol.

Reddy, T. A. (2011). Analysis of time series data. In *Applied data analysis and modeling for energy engineers and scientists* (pp. 253–288). Boston, MA: Springer US. doi:10.1007/978-1-4419-9613-8_9

Richardson, G., Barton, A., Basham, M., Foy, C., Ann Eick, S., & Somerville, M. (2006). The Watcombe housing study: The short-term effect of improving housing conditions on the indoor environment. *Science of the Total Environment*, *361*, 73–80. doi:10.1016/j.scitotenv.2005.05.007

Sharpe, R. A., Thornton, C. R., Nikolaou, V., & Osborne, N. J. (2015a). Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties. *Environment International*, *79*, 115–129. doi:10.1016/j.envint.2015.03.009

Sharpe, R. A., Thornton, C. R., Nikolaou, V., & Osborne, N. J. (2015b). Higher energy efficient homes are associated with increased risk of doctor diagnosed asthma in a UK subpopulation. *Environment International*, *75*, 234–244. doi:10.1016/j.envint.2014.11.017

Summerfield, A. J., Bruhns, H. R., Cairo, J. A., Lowe, R. J., Steadman, J. P., & Oreszczyn, T. (2007). Milton Keynes energy park revisited: Changes in internal temperatures. *Energy and Buildings*, *39*, 783–791.

Thomson, H., & Thomas, S. (2015). Developing empirically supported theories of change for housing investment and health. *Social Science and Medicine*, *124*, 205–214. doi:10.1016/j.socscimed.2014.11.043

Thomson, H., Thomas, S., Sellstrom, E., & Petticrew, M. (2013). Housing improvements for health and associated socio-economic outcomes. *The Cochrane Database of Systematic Reviews*, *2*(3), CD008657. doi:10.1002/14651858.CD008657.pub2

Valor, E., Meneu, V., & Caselles, V. (2001). Daily air temperature and electricity load in Spain. *Journal of Applied Meteorology*, *40*(8), 1413–1421. doi:10.1175/1520-0450(2001)040<1413:DATAEL>2.0.CO;2

de Vocht, F., Burstyn, I., & Sanguanchaiyakrit, N. (2015). Rethinking cumulative exposure in epidemiology, again. *Journal of Exposure Science and Environmental Epidemiology*, *25*(5), 467–473. doi:10.1038/jes.2014.58

Wilkinson, P., Landon, M., Armstrong, B., Stevenson, S., Pattenden, S., Mckee, M., & Fletcher, T. (2001). *Cold comfort. The social and environmental determinants of excess winter deaths in England, 1986–96*. Bristol: The Policy Press and the Joseph Rowntree Foundation.

Yohanis, Y. G., Mondol, J. D., Wright, A., & Norton, B. (2008). Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use. *Energy and Buildings*, *40*(6), 1053–1059. doi:10.1016/j.enbuild.2007.09.001