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Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties

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Abstract

Introduction

Fuel poverty affects 2.4 million UK homes leading to poor hygrothermal conditions and risk of mould and house dust mite contaminations, which in turn increases risk of asthma exacerbation. For the first time we assess how fuel poverty, occupants' risk perception and use of mechanical ventilation mediates the risk of mould contamination in social housing.

Methods

Postal questionnaires were sent to 3,867 social housing properties to collect adult risk perception, demographic and environmental information on occupants. Participant details were linked to data pertaining to the individual properties. Multiple logistic regression was used to calculate odds ratios and confidence intervals while allowing for clustering of individuals coming from the same housing estate. We used Structured Equation Modelling and Goodness of Fit analysis in mediation analyses to examine the role of fuel poverty, risk perception, use of ventilation and energy efficiency.

Results

Cost prevented the heating of homes in one third of participants, and average risk perception scores ranged from 0 to 10, with a mean ranging between 5 to 7 for the eight risk perception questions. Increased risk perception was associated with a 60-80% reduction in self-reported visible mould contamination. The combination of fuel poverty behaviours was associated with a two-fold increased risk of visible mould contamination, which included inadequate heating (OR 3.4 95%;CI 2.0-5.8) and not heating the home due to cost (OR 2.2 95%;CI 3.2). Increased risk perception and use of extractor fans did not mediate the association between fuel poverty behaviours and increased risk of mould contamination.

Discussion

Fuel poverty behaviours increased the risk of mould contamination, which corresponds with existing literature. For the first time we assessed how this association maybe modified by occupant behaviours. Increased risk perception and use of extractor fans did not modify the association between fuel poverty and mould contamination. This suggests that fuel poor populations may not benefit from energy efficiency interventions due to ineffective heating and ventilation strategies. Future work should consider the interaction between occupant behaviours, awareness and the built environment, and the resultant impact on indoor microbial exposures.

Conclusion

Fuel poverty behaviours affected around a third of participating households and represents a risk factor for increased exposures to damp and mouldy conditions, regardless of adult risk perception, heating and ventilation strategies. A multidisciplinary approach is required to assess the complex interaction between occupant behaviours, risk perception, the built environment and the effective use of heating and ventilation strategies.

Study implications

Our findings have implications for housing policies and future housing interventions. Effective communication strategies focusing on awareness and perception of risk may help address indoor air quality issues. This must be supported by improved household energy efficiency with the provision of more effective heating and ventilation strategies, specifically to help alleviate those suffering from fuel poverty.

Highlights

- Increased adult risk perception reduced the risk of visible mould contamination
- Fuel poverty behaviours increased visible mould contamination and odour
- Fuel poverty remained a risk regardless of risk perception & ventilation
- Increased household energy efficiency reduced the risk of mould contamination

Key words

Risk, fuel poverty, mould, asthma, ventilation, health

Abbreviations:

ACH: Air exchange rate
IAQ: Indoor air quality
IMD: Index of Multiple Deprivation
LARES: The Large Analysis and Review of European housing and health status
MSqPCR: Mold specific quantitative polymerase chain reaction
OR: Odds ratio
SEM: Structured equation modelling
SES: Social economic status

1.0 Introduction

Tailored housing improvements aimed at improving ventilation and heating offers a cost-effective approach for delivering healthcare to individuals suffering from moderate to severe asthma (Edwards and others 2011). There is also compelling evidence supporting energy efficiency interventions aimed at vulnerable populations (Gibson and others 2011), though the success of housing interventions can be impacted by occupant behaviours and fuel poverty. Fuel poverty affects around 2.4 million UK households (Department of Energy & Climate Change 2014a) and up to 34% of homes in some European countries (Liddell and Morris 2010). Inadequate heating leads to poor hygrothermal conditions and increases risk of damp and mould contamination (Sharpe and others 2014b), and the exacerbation of symptoms in asthmatic individuals (Sharpe and others 2014a).

The best available evidence to date suggests that homes must be of an appropriate size for the household and affordable to heat (Thomson and others 2013). Addressing occupant behavioural and build environment risk factors using multidisciplinary interventions involving home-based education, cleaning and mould abatement can decrease asthma triggers and improve quality of life (Sweet and others 2014; Wu and Takaro 2007), although not all educational programs are successful (Wu and Takaro 2007) and mould growth can return following its removal (Burr and others 2007) or within 12 months of energy efficiency upgrades (Richardson G and others 2005). This may be because few intervention studies identify the dynamics of how people perceive and use the environment (Berke and Vernez-Moudon 2014), or how occupant awareness contributes to the provision of adequate heating and ventilation (Dimitroulopoulou 2012).

Occupant awareness of the potential health effects of air pollution may have a direct and indirect impact on people’s awareness (Hunter and others 2003) and mental health (Shenassa and others 2007). Perceptions of risk may be modified by variations in occupant awareness and the adoption of different coping strategies to minimise exposures thought to be a health risk (Crosland and others 2009). This is likely to be complicated by fuel poverty behaviours when occupants make financial trade-offs (Anderson and others 2012; O'Sullivan and others 2011), ration heating (Lomax and Wedderburn 2009) and ventilation to save heat and energy. The impact of occupant awareness and resultant impact on indoor dampness, mould and indoor air quality (IAQ) will be regulated by a complex interaction between behavioural factors and the build environment (Sharpe and others 2014b).

Addressing occupant behaviours resulting from low risk perception offers an opportunity for health interventions to help alleviate dampness and mould contamination, and associated risk of asthma symptoms (Hunter and others 2003). It is also important to consider recent trends in increased household energy efficiency, consequent of a policy to reduce the UK carbon footprint and alleviate fuel poverty. Increasing household energy efficiency is achieved by upgrading heating systems, insulation and reducing ventilation rates to prevent heat loss. Reduced ventilation rate increases risk of damp and mould contamination (Sharpe and others 2014b), and has been shown to be a risk factor for asthma and allergic diseases (Bornehag CG and others 2005) when air exchange rates per hour (ach) fall below the European standard of 0.5 ACH (Dimitroulopoulou 2012). Assessing occupant behaviours and ventilation strategies are needed to understand variations in the indoor microbial profile and how it interacts with the built environment (Meadow and others 2013) and asthma outcomes (Sharpe and others 2014a).

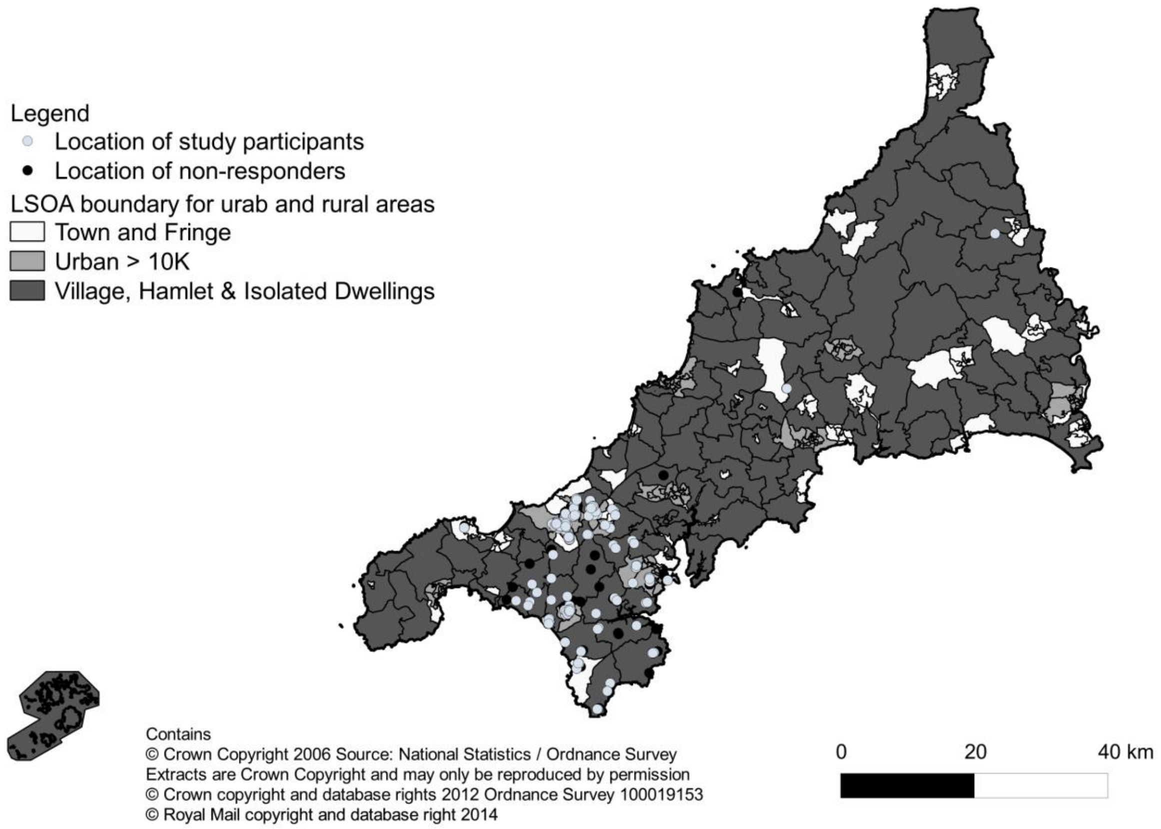
To our knowledge, no study has assessed how fuel poverty and energy efficiency interact to modify the risk of mould contamination, and how the association is mediated by risk perception and use of mechanical ventilation. In the following paper, we focus on housing managed by a UK social housing association, a not-for-profit organisation responsible for the provision of affordable housing (Government 2013). Social housing associations are responsible for managing 17% of the UK housing stock (Government 2013). This provides an opportunity for area-level interventions targeting populations living in lower socio- economic status in order to help reduce indoor exposures to physical, chemical and biological agents and disease initiation and/or exacerbation. Our aims are to determine whether 1) risk perception and fuel poverty behaviour modifies the risk of visible mould growth, 2) fuel poverty behaviour and mould contamination is mediated by occupant's risk perception, 3) fuel poverty behaviours and mould contamination is mediated by occupant's use of extractor fans, and 4) household energy efficiency and risk of mould contamination is mediated by fuel poverty behaviours.

2.0 Methods

2.1 Postal Questionnaire

Ethical approval for this cross sectional study was granted by the University of Exeter Medical School, application number 13/02/013. We sent out 3,867 postal questionnaires to tenancy holders residing in social housing in the South West of England, UK (Figure A.1), during the months of August 2012, October 2013, November 2013 and January 2014. Questionnaires were designed using a closed questioning technique to collect demographic and behavioural data on all occupants in each household. Written consent was obtained using a form containing a series of scripted questions concerning participant involvement in various elements of the study.

Figure A.1 Location of households managed by the Social Housing Association, Cornwall, England



The questionnaire collected information about all of the household occupants and indoor behaviours thought to modify the risk of indoor mould contamination. Behavioural questions were designed to obtain demographic characteristics such as smoking status, the amount of time participants spent indoors on an average day, employment, frequency of vacuuming, presence of pets, extent of carpeting, clothes drying methods, heating and ventilation patterns. We asked participants about their current awareness of the potential health risks resulting from exposure to damp and mould, efforts to alleviate dampness related exposures, and fuel poverty behaviours. We asked participants about their perception of risk associated with the presence of mould (a score of 0-10) and considered a low risk perception when participants scored between 0 and 4, and then a high risk perception for scores between 8 and 10. Our risk perception and fuel poverty exposures were defined by asking participants the following questions;

1. Perception of risk was assessed by asking “on a scale of 1 to 10 (10 being the highest risk), What do you perceive the risk to adults and children’s health if” (Latent variable L1 – excluding inadequate heating and ventilation):
    - Adult living with mould greater >postcard in your lounge?
    - Adult living with mould greater >postcard in your bathroom?
    - Adult living with mould greater >postcard in your bedroom?
    - Child living with mould greater >postcard in your lounge?
    - Child living with mould greater >postcard in your bathroom?
    - Child living with mould greater >postcard in your bedroom?
    - You have inadequate heating in your home?
    - You have inadequate ventilation in your home?
2. Fuel poverty behaviours were assessed by asking three dichotomous questions (Latent variable L2);
    - Do you not ventilate your home to save heat / energy?
    - Do you think your home is adequately heated?
    - Do you not heat your home because of cost?
3. We asked participants about the use of mechanical ventilation to reduce indoor dampness, which were defined by (Latent variable L3);
    - Do you use the extractor fan when cooking?

- Do you use the extractor fan when having a bath/shower?

Our dichotomous outcome variables were defined by asking participants about the presence of visible mould growth anywhere in the home, and then the presence of a mouldy/musty odour in the home within the last 12 months. We use mould contamination in the following sections to describe both the presence of visible mould growth and/or a mouldy/musty odour in subsequent analyses.

2.2 Housing characteristics

Questionnaire data was merged with property records from the Social Housing Association's asset management and stock condition data (February 2014) using a household identifier. Energy efficiency ratings were calculated according to the Government's Standard Assessment Procedure (SAP). SAP 2009 was used for compliance with building regulations in England & Wales (BRE 2013) for new builds (Part L1A) and existing buildings (Part L1B). It is the chosen methodology for delivering the EU performance of building directive (EPBD) and is used in the calculation and creation of Energy Performance Certificates (Kelly and others 2012). SAP ratings were provided by the social housing provider and were auto assessed using RDsap 9.91 (BRE 2014) and taken from new build energy assessments (Department of Energy & Climate Change 2014b).

2.3 Socio-economic status (SES)

The Index of Multiple Deprivation (IMD) score has been shown to have a strong relation with health in both rural and urban areas(Jordan and others 2004). We obtained the IMD scores for 32,482 (Large Super Output Areas) LSOAs in England and Wales, which contain a mean population of between 1,000 and 1,500 people (ONS 2014). The score uses the English Indices of Deprivation 2010 to identify areas of England experiencing multiple aspects of deprivation. There are scores for seven domains including income, employment, health and disability, education skills and training, barriers to housing and services, living environment, and crime, which were merged with our data using property full postcodes. We use the road distance to services sub-domain, which constitutes part of the Barriers to Housing and Services domain, to assess differences between urban and rural areas such that increased distance to healthcare, food shops, schools and post office represents more rural and isolated areas (Department for Communities and Local Government 2014). IMD data "Contains public sector information licensed under the Open Government Licence v2.0" found online at http://www.nationalarchives.gov.uk/doc/open-government-licence/version/2/.

2.4 Literature search

We searched eight online databases to identify relevant studies utilising a similar methodology to ours. Databases included Medline, AMED, Web of Science, Scopus, Environment Complete, GreenFile, Pubmed and the Applied Social Sciences Index and Abstracts. We used a structured literature search using terms "risk perception" and damp or mould or mold or "fuel poverty".

2.5 Statistical analysis

We adopted a convenience sampling frame to collect information about adults residing in the same household and social housing estate, defining each estate as the highest order cluster level. We used multiple logistic regression to calculate odds ratios and confidence intervals, allowing for clustering(Institute for Digital Research and Education 2014; Stata 2013) of individuals in houses located on the same housing estate. This was done using the option *cluster* in Stata version 13.0 (Stata Corp., College Station, US) to adjust standard errors for intragroup correlation. We used descriptive statistics to describe participant and household demographics (Table A.1) to assess the representativeness of our sample (Appendix A), and to compare demographic differences of those with low versus high risk perception, and those with and without fuel poverty behaviours (Appendix B). Ordinal perception of risk scores (0-10) and dichotomous fuel poverty behaviours were used to assess the risk of visible mould growth in our unadjusted model. We used our *a priori* including adult sex, month of survey, employment status, date of tenancy, and the date of any glazing, loft insulation and heating system upgrades in adjusted models (Table A.2). We also assessed other demographic risk factors (Table A.3) and housing characteristics (Table A.4) thought to modify the risk of visible mould contamination.

We then used Structured Equation Modelling (SEM) to define our exposure latent variables and outcome measures were defined by the presence of any visible mould growth and the presence of a mouldy/musty odour in our mediation analyses. The latent variables were not measured directly but derived by combining multiple measures, which summarized different facets of occupant's perception of risk; fuel poverty behaviours and use of mechanical ventilation (Figure A.2). We used the Lavaan (latent variable analysis) library (Rosseel 2012) version 0.5-16, which is a package for running SEM in R (http://www.r-project.org/). The diagonally weighted least squares (DWLS) estimator with the probit link function were used to calculate z-scores and robust standard errors (Rosseel 2014). We used z-scores to estimate the risk of mould contamination, and a positive or negative z-score represents how many standard deviations above or below of the mean respectively, and the associated risk of mould contamination. We used the "pnorm" function in R to calculate the probability (%) from the z-scores, which is proportion of participants that have the same corresponding z-score. In order to compare our results to the previous analyses, we converted probit to logit values for each score by using the following equation:

$$\text{Logit} = \text{z-score} \times (\pi/\sqrt{3})$$ (Collett 2003)

We chose to use the probit link function to model the association between our binary outcomes and the predictors instead of logit because although the probit distribution is very similar to logit, it has better convergence properties. We then calculated odds ratios by taking the exponential of each estimate.

In mediation analysis we calculate the direct effect (c) between our exposure and outcome variables and then how this is mediated by the latent variable (indirect effect ab). The total effect (c+ab) measures how the direct effect is mediated by the indirect effect, and where the association remains unchanged this means that the mediator has no effect on our outcomes i.e. visible mould and mouldy/musty odour. Goodness of Fit (GOF) estimates were then calculated for each model, which includes the root mean squared error of approximation (RMSEA), the comparative fit index (CFI) and the standardised root mean squared residual (SRMR). We considered a model to be a good fit if the lower bound 90% confidence interval was <0.05, the CFI value was close to 1 and SRMR was between 0 and 0.08 (Stata 2013).

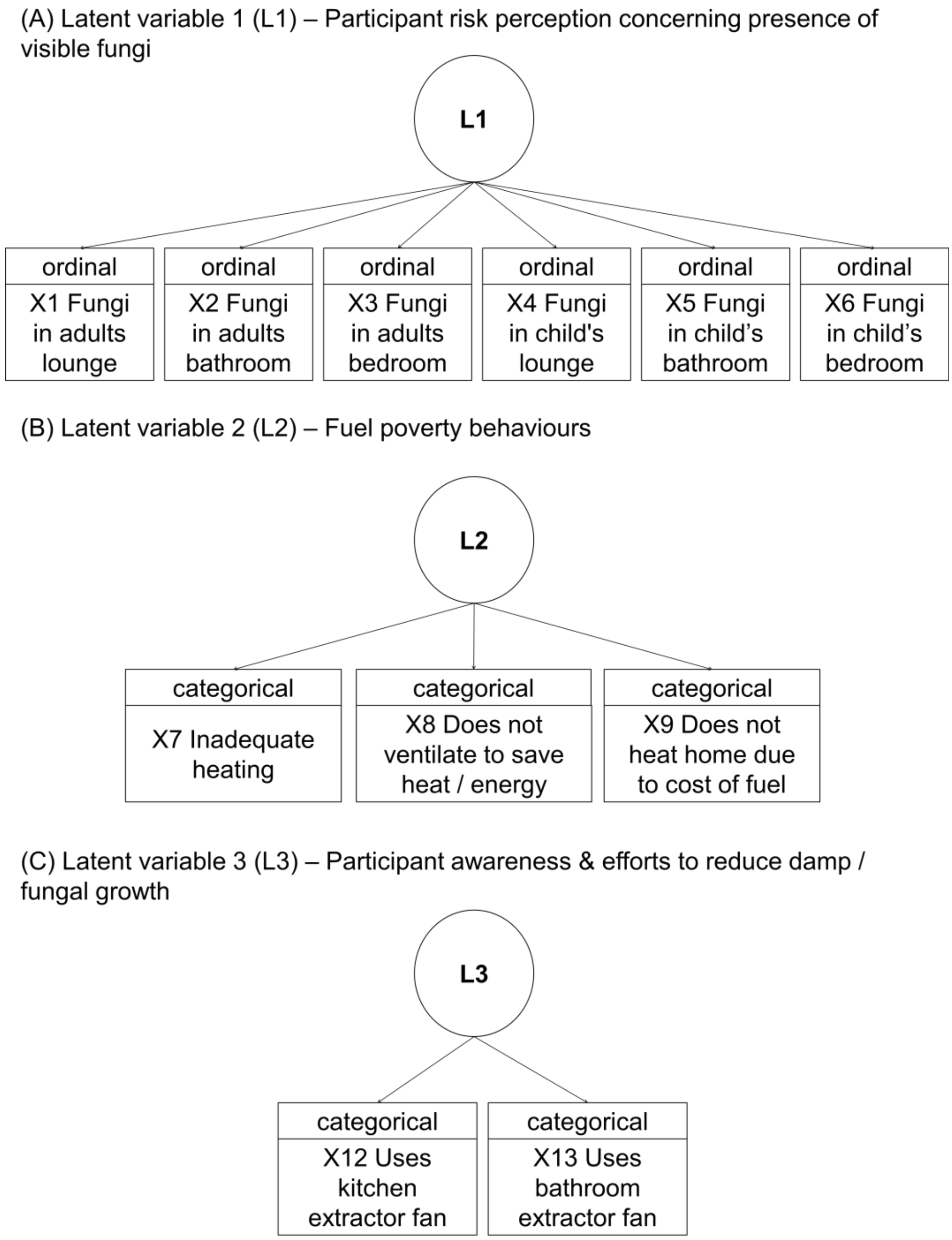


Figure A.2 SEM measurement models

3.0 Results

The results presented here are based on 18% (n=671) of the households we originally targeted during the Cornish Health Project (Table A.1). The data provided has been collected from the single named adult completing the questionnaire on behalf of the household. Study participants completing the questionnaire form had a mean age of 60 years (SD ±17.1), over half lived alone (57.9%) and 20% of participating adults had seen a doctor in the last 12 months for asthma symptoms. All but sixty participants had lived in their current home for more than one year, with a mean occupancy period of 12.3 years (SD ±11.8). Mean risk perception scores for the eight questions ranged from 5-7 out of 10 with standard deviations ranging from ± 3.3 to 3.8. Searching online databases did not reveal any comparable studies to validate the risk perception findings.

Twenty-one percent of participants said they believed damp and mould impacted their family's health, and fuel poverty behaviours affected 23% and 30% of households where participants said they don't ventilate or heat the home, respectively due to cost. Participants resided in homes that were representative of the whole housing stock in terms of geographic location covering urban and rural environments (Figure A.1), build age, architectural type, construction, heating, glazing and energy efficiency (Appendix A). Nearly half of the properties had some fungal growth ranging from a few spots up to and over an arm's length in size. A total of 84% participants stated they ventilate to minimise damp/fungi, with 70% using mechanical ventilation in the kitchen and bathroom when cooking and having a bath or shower. The following presents our findings for fuel poverty behaviours, risk perception, use of ventilation, energy efficiency and risk of mould contamination.

Table A.1 Participant & household Characteristics (N=671)

Variable	Study Participants				
	n	(%)	mean	range	SD
Summary of participant characteristics					
Proportion of male participants	663	37.4			
Mean household occupancy	670		1.7	1-10	1.1
Household occupancy; single occupancy		57.9			
2		27.5			
3		7.6			
4+		7.0			
Participants in employment or self-employed	645	20.1			
Participant in receipt of benefits; Child tax credits	658	11.3			
Working tax credits		6.9			
Smoking status: current smoker	657	24.5			
Participant smokes indoors	208	52.4			
Presence of any pet;	639	47.1			
Cat		27.7			
Dog		20.7			
Participants dries washing indoors, all methods	635	71.2			
Excluding the use of a vented tumble dryer		54.9			
Summary of built environment risk factors					
Indices of Multiple Deprivation 2010	670		34.2	9.4-60.9	16.6
Mean build age	668		1968	1880-2013	21.3
Number of houses	668	41.0			
Number of semidetached / detached properties	660	38.6			
External wall constructed from block or brick	576	83.9			
Gas used as primary heating	655	54.9			
Average SAP rating	616		65.7	24-88	
Loft insulation depth >250mm	617	87.8			
Cavity wall insulation	636	83.7			
Windows double glazed	639	99.8			
No visible mould growth anywhere in the home	365	57			
One or two spots	35	5			
Several small patches (postage stamp)	51	8			
Bigger than a postcard	81	13			
Up to an arm's length (1m)	55	8			
Greater than an arm's length	58	9			
Presence of a mouldy/musty odour in last 12 months	545	27.9			

3.1 Risk perception, fuel poverty behaviours and risk of visible mould growth

High adult risk perception (a score between 8 to 10) of the potential health effects resulting from exposure to mould growth >postcard size in the bedroom, lounge and bathroom was associated with an 80% reduced risk of visible mould growth (Table A.2). A 60% reduced risk of mould growth was associated with the high risk perception score and living with inadequate heating and ventilation. High risk perception concerning children being exposed to visible mould growth was associated with a reduced risk of 60% to 90%. When assessing fuel poverty behaviours, we found no association between participants not ventilating to save heat and energy and risk of visible mould growth. However, not heating the home due to cost or inadequate heating was associated with a 2-3 fold increased risk of visible mould growth.

Table A.2 Risk perception of risk, ventilation & fuel poverty behaviours & risk of visible mould growth

Risk factor	Percent (n/d)	unadjusted		adjusted	
		OR	95% (CI)	OR	95% (CI)
Perception of risk of adults living with fungal contamination >postcard in the following rooms					
Bedroom score; 0-4	77 (17/22)	Ref		Ref	
5-7	59 (37/63)	0.4	0.1-1.3	0.3	0.1-1.0
8-10	53 (107/202)	0.2	0.1-0.5**	0.1	0.0-0.4**
Lounge score; 0-4	76 (42/55)	Ref		Ref	
5-7	60 (48/80)	0.5	0.2-0.9	0.3	0.1-0.7**
8-10	44 (67/152)	0.2	0.1-0.3***	0.1	0.1-0.3***
Bathroom score; 0-4	74 (57/77)	Ref		Ref	
5-7	52 (45/86)	0.4	0.2-0.8**	0.3	0.11-0.7**
8-10	45 (23/64)	0.2	0.1-0.3***	0.2	0.1-0.3***
Perception of risk of adults living with inadequate heating and ventilation					
Inadequate heating score; 0-4	58 (14/24)	Ref		Ref	
5-7	59 (39/66)	1.0	0.4-2.5	1.0	0.4-2.4
8-10	49 (96/195)	0.4	0.2-0.9*	0.5	0.2-1.1
Inadequate ventilation score; 0-4	63 (22/35)	Ref		Ref	
5-7	57 (31/54)	0.8	0.3-2.0	1.0	0.4-2.7
8-10	48 (94/197)	0.4	0.2-0.7**	0.4	0.2-1.0*
Perception of risk of children living with fungal contamination >postcard in the following rooms					
Bedroom score; 0-4	64 (7/11)	Ref		Ref	
5-7	61 (27/44)	0.9	0.2-3.5	0.9	0.22-4.3
8-10	50 (98/197)	0.4	0.1-1.4	0.4	0.11-1.5
Lounge score; 0-4	81 (13/16)	Ref		Ref	
5-7	57 (35/61)	0.3	0.1-1.2	0.3	0.1-1.7
8-10	46 (35/83)	0.1	0.0-0.5**	0.2	0.0-0.8*
Bathroom score; 0-4	66 (19/29)	Ref		Ref	
5-7	59 (41/70)	0.7	0.3-1.9	0.9	0.3-2.7
8-10	40 (52/129)	0.3	0.1-0.7**	0.4	0.1-1.0*
Fuel poverty					
Does not ventilate to save heat and energy; no	46 (200/435)	Ref		Ref	
yes	46 (59/127)	1.0	0.7-1.5	1.1	0.7-1.7
Participant stated home is inadequately heated; no	40 (199/502)	Ref		Ref	
yes	67 (78/116)	3.1	1.9-5.0***	3.4	2.0-5.8***
Does not heat the home due to cost; no	40 (164/407)	Ref		Ref	
yes	59 (101/170)	2.2	1.5-3.1***	2.2	1.5-3.2***

- adjusted model for adult sex, month of survey, employment status, date of tenancy, date of glazing, loft insulation and heating systems upgraded

* $0.01 \le p < 0.05$, ** $0.001 \le p < 0.01$ & *** $p < 0.001$

We further investigated the potential of bias by including participants believing that damp and mould impacted their family's health into our adjusted models for fuel poverty behaviours. Increased risk of visible mould growth was consistently seen in participants stating their home is inadequately heated (OR 2.1 95%;CI 1.1-3.9) and that they do not heat the home due to cost (OR 1.6 95%;CI 0.9-2.6). Not heating the home due to cost was not statistically significant, though the direction of the effect estimates remained consistent, and this is likely to be due to a lack of power.

3.2 Fuel poverty behaviours mediated by adult risk perception

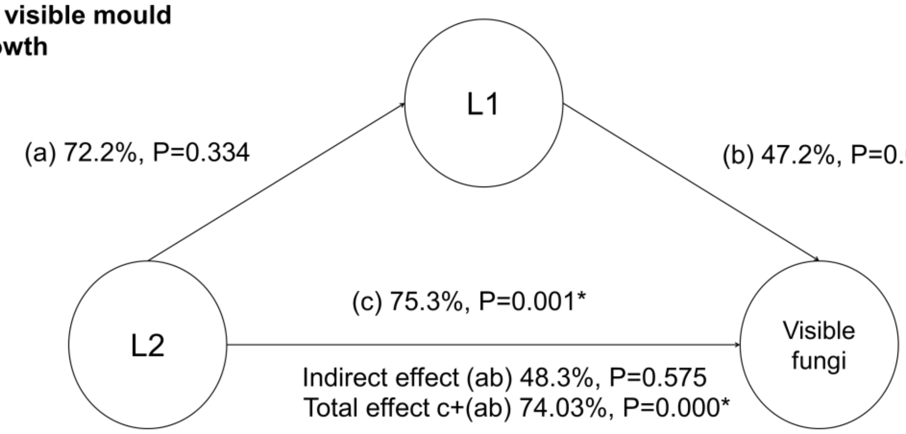
We used structured equation modelling to assess the direct effect pathway (c) between latent variable for fuel poverty behaviours (L2) and risk of A) visible mould growth and B) the presence of a mouldy/musty odour (Figure A.3). The results of our mediation analyses show that fuel poverty behaviours increased the probability of homes having visible mould growth (75.3%) and the presence of a mouldy/musty odour (81.9%). The models assessing both outcomes were considered a good fit when assessing RMSEA, CFI and srmr.

There was no association between fuel poverty behaviours and a per unit increase in adult risk perception in mediation pathway (a) in either model. When assessing the association between a unit increase in risk perception (L2) and A) risk of visible mould growth in pathway (b) we observed a 47% reduction in probability. No association was observed with the presence of a mouldy/musty odour. The indirect effect (the effect of ab) was not associated with the presence of A) visible mould growth or B) a mouldy/musty odour. The lack of association regarding the indirect effect pathway (ab) means that increased risk perception did not mediate the association between fuel poverty and mould contamination. For this reason the total effect estimates (c+(ab)) remained unchanged and ranged from an increased probability of 74% and 81% for A) visible mould growth and B) a mouldy/musty odour, respectively.

To assess the odds of exposure among cases and controls we converted the z-scores (Figure A.3) into odds ratios (Appendix C). Fuel poverty behaviours (L2) were shown to be associated with around a 3-fold increased risk for A) the presence of visible mould growth and B) a mouldy/musty odour in direct effect pathway (c) and total effect estimates (c+(ab)). The estimated odds ratios are similar in effect size to our multiple logistic regression results (Table A.2).

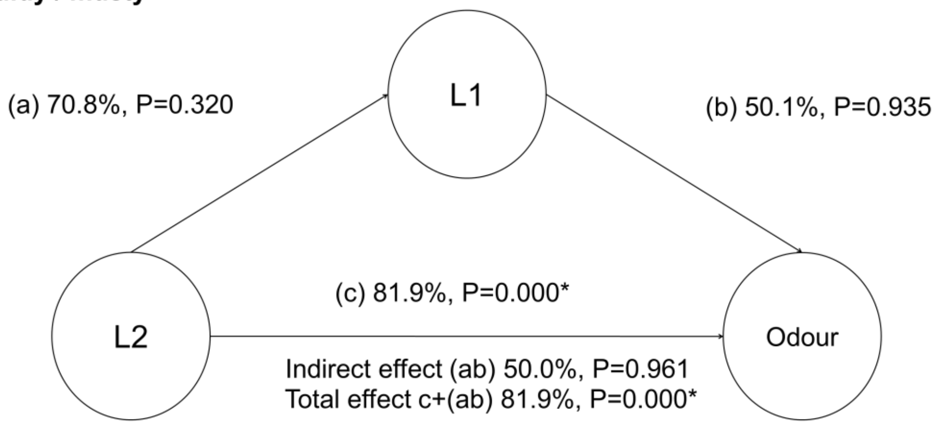
Figure A.3 Fuel poverty behaviours (L2) increases the risk of visible mould and mouldy odour, and is not mediated by risk perception (L1)

(A) visible mould growth



Pathway	z-score	Probability %	SE	P value	Lower CI	Upper CI	Direction of association
c	0.683	75.3	0.202	0.001*	0.329	1.030	↑
a	0.590	72.2	0.610	0.334	-0.437	1.614	-
b	-0.069	47.2	0.028	0.015*	-0.128	-0.016	↓
ab	-0.041	48.3	0.072	0.575	-0.155	0.022	-
c+(ab)	0.642	74.0	0.176	0.000*	0.295	0.976	↑
Goodness of fit; RMSEA 0.000, CFI 1.000, srmr 0.064							

(B) Mouldy / musty odour



Pathway	z-score	Probability %	SE	P value	Lower CI	Upper CI	Direction of association
c	0.912	81.9	0.218	0.000*	0.548	1.395	↑
a	0.548	70.8	0.552	0.320	-0.521	1.572	-
b	0.002	50.1	0.027	0.935	-0.050	0.057	-
ab	0.001	50.0	0.025	0.961	-0.046	0.051	-
c+(ab)	0.913	81.9	0.215	0.000*	0.550	1.397	↑
Goodness of fit; RMSEA 0.00, CFI 1.00, srmr 0.06							

3.3 Fuel poverty behaviours mediated by use of mechanical ventilation

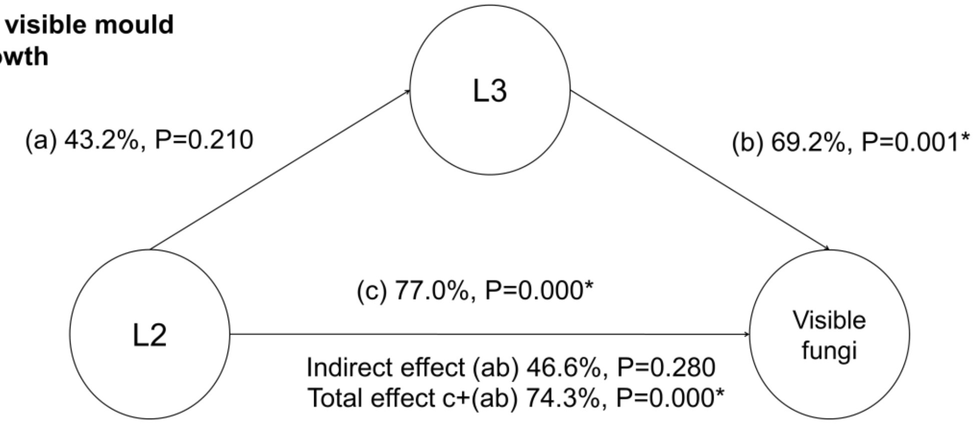
In this model, we replaced risk perception latent variable (L2) with the use of ventilation (L3), which includes participants stating that they use the extractor fans in the kitchen and bathroom when cooking and having a bath or a shower (Figure A.4). Both models were considered a good fit (RMSEA, CFI and srmr) in mediation analyses between L2, L3 and risk of A) visible mould growth and B) a mouldy/musty odour.

Direct effects pathway (c) between fuel poverty behaviours (L2) and risk of A) visible mould growth and B) a mouldy/musty odour corresponded to our previous model (Figure A.3) with an increased probability of 77% and 61%, respectively. No association was observed between mediation analysis pathway (a) between fuel poverty behaviours (L2) and the reported use of extractor fans in the kitchen and bathroom. The use of extractor fans (L3) was associated with an increased probability of having A) visible mould growth (69.2%) and B) a mouldy/must odour (57.1%) in effect pathway (b). There was no association in the indirect effect estimates (ab) between L2 and risk of A) visible mould growth and B) a mouldy/musty odour. Thus, no change was observed in the total effect estimates (c+(ab)).

The total effects (c+(ab)) remained statistically significant when we converted into odds ratios with effect sizes ranging from OR 3.3 and OR 1.6 for the risk of A) visible mould growth and B) a mouldy/musty odour, respectively (Appendix C). Mediation analyses suggest that the use of extractor fans did not mediate the association between fuel poverty behaviours and mould contamination, and thus no change in the total effect was observed in either model.

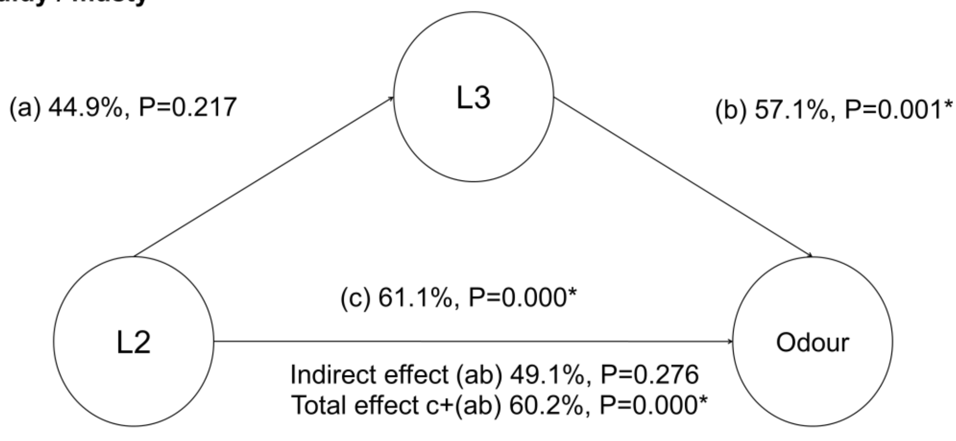
Figure A.4 Fuel poverty behaviours (L2) increases the risk of visible mould and mouldy odour, and is not mediated by ventilating to minimise damp and mould (L3)

(A) visible mould growth



Pathway	z-score	Probability %	SE	P value	Lower CI	Upper CI	Direction of association
c	0.739	77.0	0.172	0.000*	0.431	1.080	↑
a	-0.172	43.2	0.137	0.210	-0.384	0.186	-
b	0.502	69.2	0.156	0.001*	0.173	0.803	↑
ab	-0.086	46.6	0.080	0.280	-0.262	0.039	-
c+(ab)	0.652	74.3	0.150	0.000*	0.389	0.988	↑
Goodness of fit; RMSEA 0.000, CFI 0.975, srmr 0.056							

(B) Mouldy / musty odour



Pathway	z-score	Probability %	SE	P value	Lower CI	Upper CI	Direction of association
c	0.282	61.1	0.060	0.000*	0.1887	0.419	↑
a	-0.129	44.9	0.105	0.217	-0.380	0.026	-
b	0.179	57.1	0.056	0.001*	0.069	0.293	↑
ab	-0.023	49.1	0.021	0.276	-0.082	0.002	-
c+(ab)	0.259	60.2	0.054	0.000*	0.169	0.383	↑
Goodness of fit; RMSEA 0.000, CFI 0.989 srmr 0.052							

3.4 Energy efficiency mediated by fuel poverty behaviours

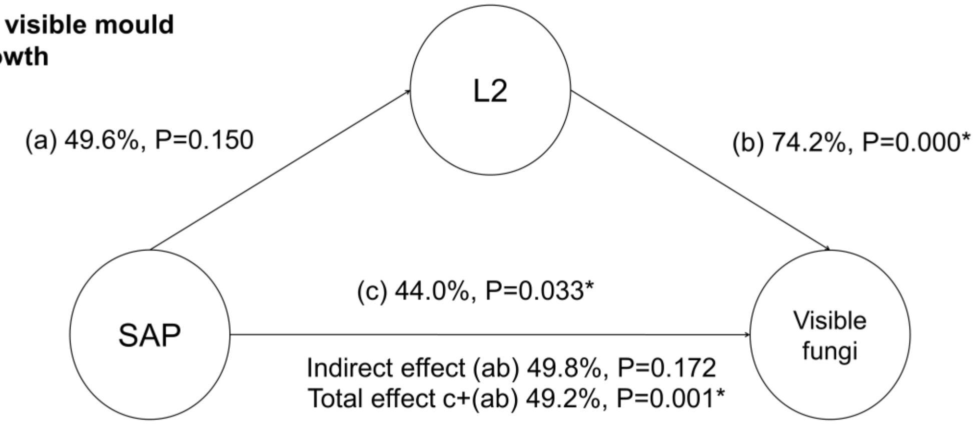
In our final mediation analysis, we assess the role of increased household energy efficiency (i.e. a unit increase in SAP rating), fuel poverty behaviours (L2), and risk of A) visible mould growth and B) a mouldy/musty odour. Both mediation models were considered a good fit (Figure A.5).

A unit increase in SAP rating in direct effects pathway (c) was associated with a 44% and 50% reduced probability for the presence of A) visible mould growth and B) a mouldy/musty odour, respectively. However, the association between SAP and risk of B) a mouldy/musty odour in direct effect pathway (c) was not statistically significant, which may be due to lack of power. On further investigation using multiple logistic regression we observed that a unit increase in SAP reduced the risk of visible mould growth (OR 0.96 95%;CI 0.93-0.99) and mouldy/musty odour (OR 0.95 95%;CI 0.92-0.98).

No association was observed between increasing SAP and fuel poverty behaviours in mediation pathway (a). Fuel poverty behaviours increased risk of A) visible mould growth and B) a mouldy/musty odour in mediation pathway (b) by 74% and 80%, respectively which correlate to the findings of our previous mediation analyses. Mediation analysis between (a) and (b) pathways (indirect effect ab) in both models for A) visible mould growth and B) a mouldy/musty odour remained insignificant, and total effects (c+(ab)) remained unchanged. Aalthough there is suggestive evidence that increased SAP may alleviate fuel poverty behaviours and risk of B) a mouldy/musty odour because of the influence of the indirect effect (ab) on total effects (c+(ab)). In this model the insignificant direct effect of pathway (c) combined with the indirect effects (ab) now reduces the risk of B) a mouldy/musty odour by 49% (P=0.03) in total effects (c+(ab)). When converted into odds ratios, the total effect estimates corresponded to a 4% and 3% reduced risk of A) visible mould growth (OR 0.96, P=0.001) and B) a mouldy/musty odour (OR 0.97, P=0.030), respectively (Appendix C).

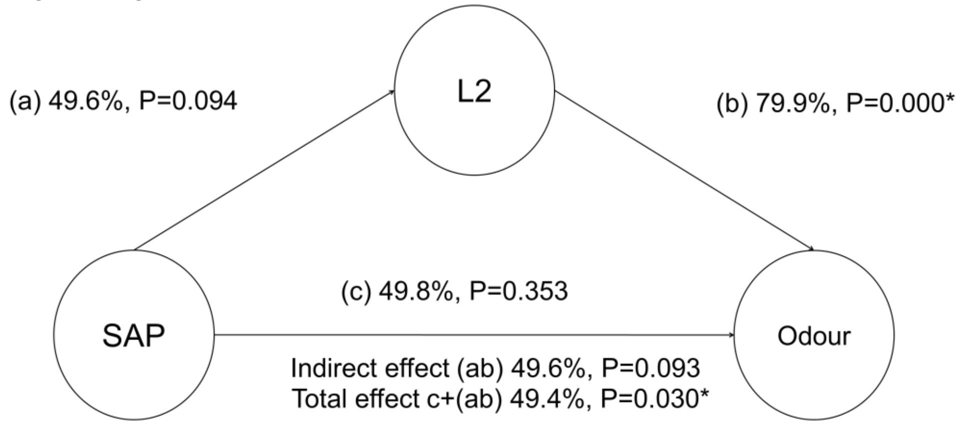
Figure A.5 Increasing energy efficiency (SAP rating) reduces the risk of visible mould and mouldy odour, and is not mediated by fuel poverty behaviours (L2)

(A) visible mould growth



Pathway	z-score	Probability %	SE	P value	Lower CI	Upper CI	Direction of association
c	-0.015	44.0	0.007	0.033*	-0.029	-0.002	↓
a	-0.009	49.6	0.007	0.150	-0.022	0.003	-
b	0.649	74.2	0.160	0.000*	0.376	0.982	↑
ab	-0.006	49.8	0.004	0.172	-0.014	0.002	-
c+(ab)	-0.021	49.2	0.006	0.001*	-0.035	-0.009	↓
Goodness of fit; RMSEA 0.000, CFI 0.973, srmr 0.055							

(B) Mouldy / musty odour



Pathway	z-score	Probability %	SE	P value	Lower CI	Upper CI	Direction of association
c	-0.006	49.8	0.007	0.353	-0.020	0.007	-
a	-0.011	49.6	0.006	0.094	-0.026	0.001	-
b	0.841	79.9	0.183	0.000*	0.539	1.280	↑
ab	-0.009	49.6	0.005	0.093	-0.021	0.001	-
c+(ab)	-0.015	49.4	0.007	0.030*	-0.030	-0.002	↓
Goodness of fit; RMSEA 0.000, CFI 1.000, srmr 0.044							

3.5 Demographic and built environment covariates

We considered other demographic and built environment covariates thought to increase the risk of mould growth. Demographic risk factors included participant age, multi-occupancy homes (more than one person), and socio-economic status, presence of pets, drying washing indoors and heating and ventilation patterns. We found that increased participant age was associated with a reduced risk of visible mould growth, with the greatest effect sizes in adults aged >64 years. This may be due to differences in behaviours, which may include the way older participants maintain and ventilate their home, or alternatively older participants may be less likely to report problems with damp and mould. Drying washing indoors increased risk of visible mould growth with the greatest effect in homes utilising a combination of tumble dryers, clothes hangers and heaters to dry clothes. Risk of visible mould contamination was greater in homes with greater awareness of the health risks, and in homes ventilating to minimise damp/mould. Increased number of rooms regularly ventilated and heated increased the risk of mould growth (Table A.3), which may be due to the interaction with other occupant behaviours and the built environment. Built environment risk factors included homes with more than one person per bedroom, being located in areas of increased index of multiple deprivation and increased distance to services i.e. rural and isolated properties. Architectural design, heating, lack of insulation and older buildings in terms of glazing units, not being on a water metre, insulation and heating systems were all potential risk factors (Table A.4). The distribution of demographic and housing characteristics between participants with low versus high risk perception groups, and those with/without fuel poverty behaviours (Appendix B) were similar, with the exception of employment status.

Table A.3 Demographic risk factors for increased visible fungal growth

Risk factor	Presence of visible fungal growth anywhere in the home				
	Percent (n/d)	unadjusted		adjusted	
		OR	95% (CI)	OR	95% (CI)
Residency period: <2.8 years	40 (59/149)	Ref		Ref	
2.8-8	56 (84/151)	1.9	1.1-3.2*	2.0	1.2-3.4**
8-18.5	49 (73/150)	1.4	0.9-2.5	1.4	0.8-2.4
>18.5 years	36 (54/151)	0.8	0.5-1.5	0.8	0.5-1.5
Adult age; 19-49 years	69 (112/162)	Ref		Ref	
50-63	52 (79/151)	0.5	0.3-0.8**	0.5	0.3-0.9*
64-74	30 (47/158)	0.2	0.1-0.3***	0.2	0.1-0.4***
>74	24 (35/146)	0.1	0.1-0.2***	0.2	0.1-0.3***
Household occupancy; single	33 (124/377)	Ref		Ref	
two	50 (89/179)	2.0	1.4-2.9***	1.9	1.4-2.9***
three + persons	78 (76/98)	7.0	4.1-12.1***	6.6	3.7-11.9***
Participant has children; no	38 (197/520)	Ref		Ref	
yes	72 (87/121)	4.2	2.6-6.7***	3.9	2.3-6.5***
Receipt of working tax credits; no	43 (252/593)	Ref		Ref	
yes	68 (34/50)	2.9	1.5-5.5**	2.7	1.4-5.4**
Receipt of child tax credits; no	42 (235/566)	Ref		Ref	
yes	66 (51/77)	2.8	1.5-4.9**	2.3	1.3-4.2**
Current smoker; no	45 (216/485)	Ref		Ref	
yes	43 (68/157)	0.9	0.7-1.4	0.9	0.6-1.3
Participant will benefit from health information; no	44 (127/289)	Ref		Ref	
yes	47 (133/283)	1.1	0.8-1.6	1.2	0.8-1.7
Believes damp/fungi impacts health; no	35 (157/444)	Ref		Ref	
yes	91 (109/120)	18.1	9.6-34.0***	23	10.9-49.9***
Ventilates the home to minimise damp/fungi; no	14 (14/102)	Ref		Ref	
yes	54 (275/505)	7.5	4.1-13.7***	7.3	3.9-13.2***
Uses extractor fan when cooking; no	36 (65/183)	Ref		Ref	
yes	50 (220/437)	1.8	1.3-2.7**	1.9	1.3-2.8**
Uses bathroom extractor fan; no	38 (68/180)	Ref		Ref	
yes	49 (216/440)	1.6	1.1-2.3*	1.7	1.2-2.4**
Presence of a cat; no	40 (181/452)	Ref		Ref	
yes	55 (96/175)	1.8	1.3-2.6**	1.8	1.3-2.6**
Presence of a dog; no	40 (201/497)	Ref		Ref	
yes	58 (76/130)	2.1	1.4-3.1***	1.9	1.3-2.9**
Participant spends > 14 hours indoors;					
an average weekend day; no	44 (50/114)	Ref		Ref	
yes	47 (157/331)	1.2	0.7-1.8*	1.0	0.6-1.6
an average week day: no	47 (58/124)	Ref			
yes	50 (155/310)	1.1	0.7-1.7	1.0	0.6-1.6
Participant dry's washing indoors; no	34 (61/177)	Ref		Ref	
yes	48 (221/459)	1.8	1.3-2.5**	1.6	1.1-2.3*
Drying method: none	34 (62/180)	Ref		Ref	
Tumble dryer only	45 (644/143)	1.5	1.0-2.3*	1.5	0.9-2.2
Clothes hangers / heaters	51 (101/198)	1.9	1.4-2.9***	1.7	1.1-2.5*
Combination of the above	54 (55/102)	2.2	1.3-3.7**	1.9	1.1-3.4*
Rooms carpeted / has a rug; <2 rooms	42 (111/262)	Ref		Ref	
3	49 (77/157)	1.3	0.9-2.0	1.2	0.8-1.8
4	45 (56/124)	1.1	0.7-1.8	1.1	0.7-1.8
>5 rooms	46 (38/82)	1.2	0.7-1.9	1.2	0.7-2.1
Frequency of vacuuming: <5 / month	40 (64/160)	Ref		Ref	
6-10	46 (64/139)	1.3	0.8-1.9	1.3	0.9-2.1
10-30	48 (79/165)	1.4	0.9-2.1	1.5	0.9-2.3
>30	47 (62/132)	1.3	0.8-2.1	1.2	0.7-1.9
Number of rooms ventilated; <3 rooms	37 (72/195)	Ref		Ref	
3	47 (80/172)	1.5	0.9-2.3	1.6	1.0-2.6*
4	50 (61/122)	1.7	1.0-2.9*	1.8	1.0-3.2*
>6	56 (72/129)	2.2	1.3-3.5**	2.2	1.3-3.6**
Number of rooms heated; <2	36 (62/174)	Ref		Ref	
3-4	49 (107/218)	1.7	1.1-2.7*	1.7	1.1-2.7*
5	52 (48/93)	1.9	1.1-3.5*	1.9	1.0-3.7*
>6	57 (61/107)	2.4	1.4-4.2**	2.2	1.2-3.9**

- adjusted model for adult sex, month of survey, employment status, date of tenancy, date of glazing, loft insulation and heating systems upgraded

* 0.01≤p<0.05, ** 0.001≤p<0.01 & *** p<0.001

Table A.4 Built environment risk factors for increased visible fungal growth

Risk factor	Presence of visible fungal growth anywhere in the home				
	Percent (n/d)	unadjusted		adjusted	
		OR	95% (CI)	OR	95% (CI)
Permitted people - occupancy; 2 people	39 (100/255)	Ref		Ref	
Overcrowded (-7 - <2 persons/house)	50 (66/131)	**1.6**	**0.9-2.5***	1.6	0.9-2.6
Under occupied (>2 persons/house)	46 (123/269)	1.3	0.9-1.9	1.3	0.9-1.9
Occupancy per bedroom; <1 person	39 (64/164)	Ref		Ref	
1 person per bedroom	41 (134/239)	1.1	0.7-1.6	1.0	0.7-1.6
>1 person per bedroom	69 (82/119)	3.5	2.1-5.8***	3.4	1.9-5.8***
Index of Multiple Deprivation; 9-21	50 (92/183)	Ref		Ref	
21-30	57 (93/163)	1.3	0.8-2.1	1.3	0.8-2.2
30-49	34 (50/149)	0.5	0.3-0.9*	0.5	0.2-0.9*
>49 most deprived	34 (54/160)	0.5	0.3-0.8**	0.5	0.3-0.8**
IMD distance to services; score <6	36 (60/166)	Ref		Ref	
6-21	44 (72/162)	1.4	0.8-2.6	1.3	0.6-2.6
21-33	40 (66/166)	1.2	0.6-2.2	1.1	0.6-2.2
>33	57 (91/161)	2.3	1.2-4.3*	2.3	1.2-4.2*
Property built: >1982	29 (45/153)	Ref		Ref	
1967-1981	40 (68/168)	1.6	0.8-3.1	1.6	0.8-3.0
1955-1966	55 (78/143)	2.9	1.6-5.3**	2.8	1.5-5.3**
<1954	51 (97/189)	2.5	1.4-4.6**	2.5	1.3-4.8**
Participant lives in a house; no	37 (140/382)	Ref		Ref	
yes	54 (146/269)	2.1	1.4-3.0***	1.9	1.3-2.9**
Semi-detached / detached property; no					
yes	36 (140/393)	Ref		Ref	
	58 (145/252)	2.4	1.6-3.7***	2.3	1.5-3.5***
Wall constructed from block/brick; no	34 (31/90)	Ref		Ref	
yes	48 (224/471)	1.7	0.9-3.1*	1.8	0.9-3.5
Gas heating; no	49 (142/292)	Ref		Ref	
yes	41 (142/348)	0.7	0.5-1.1*	0.7	0.5-1.1
Boiler type; condensation boiler	52 (81/157)	Ref		Ref	
Combi boiler	40 (76/189)	0.6	0.4-1.1	0.6	0.4-1.1
Back / normal boiler	45 (64/141)	0.8	0.4-1.4	0.8	0.4-1.3
Property flue open/no fan; no	47 (188/402)	Ref		Ref	
yes	35 (23/65)	0.6	0.3-1.2	0.6	0.3-1.1
Property has a radon sump; no	44 (273/618)	Ref		Ref	
yes	43 (15/35)	0.9	0.4-2.0	0.9	0.5-2.1
Property on a water meter; no	45 (247/548)	Ref		Ref	
yes	39 (41/105)	0.8	0.4-1.4*	0.8	0.5-1.4
Reported dampness problems; no	48 (223/464)	Ref		Ref	
yes	63 (24/38)	1.9	0.9-3.5*	2.3	1.1-4.8*
Levels of energy efficiency; SAP>72	28 (41/147)	Ref		Ref	
65-72	42 (59/140)	1.9	1.1-3.3*	1.9	1.1-3.4*
60-65	59 (92/157)	3.7	2.1-6.2***	3.8	2.1-6.6***
SAP <65 (low energy efficiency)	51 (80/157)	2.7	1.5-4.8**	2.7	1.5-4.8**
Loft insulation <250mm; no	41 (219/530)	Ref		Ref	
yes	68 (50/74)	2.9	1.7-5.2***	3.0	1.7-5.4***
Cavity wall insulation or is as built; no	53 (48/91)	Ref		Ref	
Yes	43 (230/530)	0.7	0.5-1.0*	0.6	0.4-0.9
Age of double glazing; <5 years	27 (24/89)	Ref		Ref	
5-10	47 (105/223)	2.4	1.1-5.4*	2.6	1.1-5.9*
>10	47 (160/343)	2.4	1.1-5.3*	2.3	0.9-5.4*
Age of wall insulation; <5 years	16 (34/41)	Ref		Ref	
5-10	44 (17/39)	1.5	0.5-4.8*	1.7	0.5-5.8
>10	45 (256/569)	1.6	0.6-4.2*	1.8	0.6-5.3
Age of loft insulation; <5 years	32 (24/74)	Ref		Ref	
5-10	45 (181/404)	1.7	0.8-3.4*	1.6	0.7-3.9
>10	47 (84/177)	1.9	0.9-4.0*	1.7	0.7-4.2
Age of heating system; <5 years	31 (42/137)	Ref		Ref	
5-10	65 (39/60)	4.2	2.0-8.8***	4.5	2.1-9.8***
>10	45 (205/452)	1.9	1.1-3.1*	1.9	1.2-3.4*

- adjusted model for adult sex, month of survey, employment status, date of tenancy, date of glazing, loft insulation and heating systems upgraded

* $0.01 \le p < 0.05$, ** $0.001 \le p < 0.01$ & *** $p < 0.001$

4.0 Discussion

To our knowledge this is the first study to examine fuel poverty behaviours, risk of mould contamination and adult risk perception concerning the potential health effects. Fuel poverty remained a risk factor for increased visible mould contamination and a mouldy/musty odour in social housing, regardless of increased risk perception of the potential health effects and use of mechanical ventilation. Our findings support the use of household energy efficiency measures to reduce the risk of mould contamination, though these must be supported by the provision of effective awareness messages, and appropriate heating and ventilation strategies.

4.1 Risk perception, fuel poverty & risk of visible mould growth

We found that assessing dichotomous exposure variables for high risk perception was associated with a reduced risk of visible mould contamination. A weaker association was found between adult risk perception and the provision of adequate heating and ventilation. Not heating the home due to cost and inadequate heating was associated with a 2-3 fold increased risk of visible mould contamination, which corresponds to previous work assessing risk factors associated with cold (Critchley and others 2007) and mouldy (Oreszczyn and others 2006) homes. Oreszczyn and others (2006) reported that having difficulty in paying bills and being dissatisfied with heating were associated with an increased risk of mould severity (OR 2.2 95%;CI 1.55-2.70 and OR 2.05 95%;CI 1.55-2.70, respectively).

Our findings may be modified by the reliance on self-reported fuel poverty behaviours, which may vary between individuals due to different perceptions of adequate heating. For example, some occupants may have a preference for living in colder homes versus those suffering from residual heating problems (Critchley and others 2007). Other measures of SES such as the receipt of benefits and increased deprivation were also found to be risk factors for visible mould contamination, which support our findings associated with fuel poverty i.e. lower income households. Utilisation of self-reported fuel poverty behaviours and measures of SES could be improved by monitoring how behaviours interact with the built environment, and modify indoor environmental conditions over time. Not only will this strengthen future work, it will help resolve shortcomings of existing mould predictive models (Vereecken and Roels 2012), and help identify high risk properties that may modify indoor mould diversity and the exacerbation of asthma (Sharpe and others 2014a).

4.2 Fuel poverty behaviours mediated by adult risk perception

Increased adult risk perception of potential health risks did not mediate the association between fuel poverty behaviours and increased risk of mould contamination. In contrast, Shenassa and others (2007) reported that the association between dampness/mould and depression was independently mediated by participant's perception of control over one's home and physical health. While this study assessed different exposures and outcomes, the differences in the mediatory effect of perception could be due to a number of factors, including varying perceptions of comfort (e.g. levels of adequate warmth) that are inextricably linked to health (Critchley and others 2007), or a lack of awareness since nearly half of participants stated that they would benefit from receiving health information. Notwithstanding this, participants believing damp/mould impacted their family's health was associated with an increased risk of mould contamination. An increased perception of the potential health risks may introduce an element of reporting bias. This did not modify the effect sizes of our estimates when we included participants believing damp/mould impacted their family's health into adjusted models. A similar impact has been found between the communication of climate change risks, which were associated with a generally high public awareness about climate change, but coupled with a low perception of risk (Bichard and Kazmierczak 2012).

Participant responses may be influenced by perceived health risks and other physiological health impacts in low income populations, who are unlikely to benefit from energy efficiency interventions due to the cost of fuel (Anderson and others 2012). Also, our study population included a high proportion of older participants who may have a low awareness of safe temperatures and associated health effects. This may be further compounded by poor knowledge and awareness, and the invisibility of fuel poverty (Tod and others 2012). Another study on European housing stock found that adults >65 years old were more satisfied with heating systems, insulation and ventilation than younger adults (Ezratty and others 2009). Assessing the impact of behaviours is complicated and participants' health may introduce reporting bias. For example asthmatic individuals may elicit different behaviours (Adams and others 1997) to non-asthmatics, including different coping strategies ranging from preventative/corrective measures to reduce exposures to those that compensate and make trade-offs between health risks and benefits (Crosland and others 2009). Further analyses showed that participant demographic and housing characteristics were similar in households with a low versus high risk perception and in those with and without fuel poverty behaviours.

4.3 Fuel poverty behaviours mediated by use of mechanical ventilation

Self-reported use of extractor fans in the bathroom and kitchen increased the risk of visible mould growth, though mechanical ventilation did not modify the association between fuel poverty and mould contamination. This finding may be due to a combination of installed extractor fans being ineffective in removing excessive dampness in high moisture generating properties and/or reporting bias. We aimed to assess the potential of bias by assessing heating and ventilation patterns. Ventilating to minimise damp and mould, and increased heating and ventilation were associated with an increased risk of visible mould contamination. This may also be a result of a lower risk perception concerning the provision of inadequate heating and ventilation. Our findings correspond to previous work that found ventilation rates to be generally poor in households, and while increasing frequency of opening windows mitigates risk of mould, the overall effects are limited by overall ventilation strategies of individual households (Sharpe and others 2014c). Combined with fluctuating heating patterns or not heating the whole property are likely to lead to condensation problems and mould growth (Sharpe and others 2014b).

The complex interaction between heating and ventilation is illustrated by previous research. The use of extractor fans (Zock and others 2002) and the provision of natural ventilation such as increased frequency of opening windows reduces the risk of visible mould (Garrett and others 1998), although opening windows at night time may increase indoor mould spore concentrations (Dharmage S and others 1999). Increasing indoor temperatures from heating has been shown to be associated with both a reduction (O'Connor and others 2004) and increase (Kercsmar CM and others 2006) in mould spore concentrations. The resultant impact on IAQ is likely to be a combination of both factors and the interaction with other occupant behaviours and the built environment.

The adoption of increased energy efficiency must be delivered alongside the most cost effective ventilation strategy that is appropriate for the occupancy, size, age and type of property. This will help ensure that optimum ventilation performance (Wargocki 2013) and cross air flow rates are achieved (Cao and others 2014) to reduce humidity levels (BSI 2011) and remove pollutants (Rim and Novoselac 2010). Measures may include the appropriate design/placement of ventilation systems for maximum air flow (Sharpe and others 2014c) in different build types (Das and others 2013), air filtration (Stephens and Siegel 2013), positive pressure and heat recovery (Manuel 2011; Sharpe and others 2014c). The effectiveness of mechanical ventilation is reliant on the quality of installation and maintenance, and occupant behaviours. Future work should consider the use of home awareness initiatives delivered both independently and alongside improved mechanical ventilation. Furthering our understanding into occupant behaviours and resultant fluctuations in heating and ventilation patterns is necessary to assess how variations in temperature, humidity and vapour pressure modifies mould in low and high energy efficient homes.

4.4 Energy efficiency mediated by fuel poverty behaviours

One of the most important parameters affecting mould growth (following moisture production) is household energy efficiency (Oreszczyn and others 2006). Our findings in both multiple logistic regression and mediation analyses corresponds to the findings of Oreszczyn and others (2006) who reported a 65% reduction in risk of mould severity in the most energy efficient homes (SAP >70). Fuel poverty behaviours did not mediate the association between increasing household energy efficiency and mould contamination, which suggests that fuel-poor households may not benefit from energy efficiency improvements. This correlates to the findings of Anderson and others (2012) who reported that lower income populations may not benefit from home improvements. However, there appears to be a reduction in risk between energy efficiency and mouldy/musty odour (Figure A.5), which suggests that increased energy efficiency may alleviate fuel poverty and associated risk of mould severity. This is in agreement with the knowledge that energy efficiency reduces mould severity (Oreszczyn and others 2006), which is defined by the presence of a mouldy/musty odour in our study. The presence of an odour in energy efficiency homes may be driven by lack of ventilation, which has been shown to be a risk factor for allergic symptoms in children (Hägerhed-Engman and others 2009). This is likely to be further complicated by fuel poor populations choosing to maintain relatively low indoor temperatures despite receiving energy efficiency upgrades (Critchley and others 2007), and variations in the built environment.

4.5 Demographic and built environment covariates

We identified a number of factors associated with an increased risk of visible mould contamination, which are in agreement with existing knowledge (Sharpe and others 2014b) and adds strength to our findings. Oreszczyn and others (2006) reported similar findings to ours with one exception concerning architecture type. This study found that flats increased risk of mould severity, whereas we found that living in a semi-detached / detached house to be a risk factor. This is may be due to an interaction between varying heating and ventilation patterns. Flats have greater thermal properties owing to reduced surface areas being exposed to the outdoor climate and have lower transmission rates of mould spores, but they require greater ventilation rates in order to maintain humidity levels (Sharpe and others 2014b). We also found that reduced available bedroom space per occupant increased the risk of mould, which may have implications for current housing policy. For example, the UKs bedroom tax in social housing, which forms part of the 2013 welfare reforms, and benefit cuts (National Housing Federation 2014).

4.6 Strengths and Limitations

Strength of our study lies in our mediation analyses and estimated odds ratios correspond to our dichotomous analyses (Table A.2) concerning fuel poverty and risk perception. Further investigations into other potential covariates were found to correspond to existing knowledge, though we had insufficient power to include other potential risk factors into our mediation analyses. Another strength includes the use of detailed property data obtained from asset stock condition records and SAP ratings, which is the chosen methodology for delivering the EU performance of building directive

(EPBD) (Kelly and others 2012). We assessed fuel poverty behaviours utilising similar exposure definitions (Oreszczyn and others 2006) and outcomes for mould contamination adopted by previous research(Fisk WJ and others 2007; Quansah and others 2012). Our findings also correlated with the social housing provider's records of participant's report reporting dampness and mould contamination (Table A.4). While some demographic differences existed between the study and target population, our sample was representative of the target homes. We obtained information about 18% of households, which exceeds the 10% sample frame required to accurately extrapolate and compare data to the complete housing stock managed by the social housing provider (Webb 2012). We also found that participants with low versus high risk perception, and those with and without fuel poverty behaviours were similar in terms of demographics and housing characteristics. The exception was employment status, which may introduce an element of bias, though we accounted for this in adjusted models.

A number of limitations exist. We were unable to identify previous research utilising comparable risk perception scores, which prevented us from validating the use of this scale, despite a search of current literature. However, the use of occupant awareness and risk perception has been utilised in previous studies assessing the uptake of energy efficiency measures (Bichard and Kazmierczak 2012) and exposure to damp / mould and perceived control over one's home and depression pathways (Shenassa and others 2007). Focusing on social housing meant that we were unable to assess other motivation factors associated with the uptake of energy efficiency measures in owner-occupied homes (Organ and others 2013). The area we examined (Western Cornwall, UK) has a mild, damp climate and we may not be able to extrapolate our findings to other populations in the UK or elsewhere. SAP calculations do not consider occupant behaviours and may lead to inaccuracies i.e. differences between predicted and actual energy efficiency when occupied (de Wilde 2014) confound energy efficiency /

environmental performance (Kelly and others 2012). We utilise self-reported exposure and outcome variables that could introduce an element of bias, though these have been previously shown to correlate well with home inspection surveys or measurement techniques to assess indoor exposures (Hernberg and others 2014). We used probit to calculate the associated risk of mould contamination and then calculated odds ratios using the z-scores (Appendix A). Our odds ratios estimates did not correlate exactly with conversion tables published by Collett (2003) due to rounding up of error, which may overestimate the effect sizes when we convert z-scores. We did not assess participant existing knowledge and awareness of the importance of maintaining the built environment to reduce dampness problems (Sharpe and others 2014b). Participants are responsible for reporting any building defects to the social housing provider and previous research suggests a general lack of awareness of common buildings failures (Small 2009).

We were unable to assess the impact of behaviours and the built environment on mould contamination throughout the year due to our cross-sectional study design. This is important because mould contamination may be modified by variations in climatic conditions. However, Howden-Chapman P and others (2005) found that variations in rainfall and ambient temperature in New Zealand did not modify the presence of mould contamination. Socio-economic scores have not previously been shown to be a risk factor for damp/mould (Ezratty and others 2009), though housing conditions and aspects of the immediate environment have been found to strongly influence satisfaction with the dwelling / area (Van Kamp and others 2009) and health-related quality of life (Braubach 2009). We did not assess how the immediate surrounding area and geographic location may modify behaviours, heating and ventilation patterns and variations in the indoor microbial profile. We used the IMD score and distance-to-services domain to explore potential differences between increased levels of deprivation and more rural environments. Both factors were shown to increase the risk of mould contamination. This requires further research because variations in location are likely to modify microbial exposures due to variations in outdoor air spora (Zukiewicz-Sobczak and others 2013) resulting from changes in temperature and rainfall (Flannigan B and others 2011).

4.7 Study implications

Our study has cost and resource implications for housing policy concerning existing builds and future housing interventions. Populations residing in cold, damp and mouldy homes have been found to be associated with a number of poor health outcomes including stress (Gilbertson and others 2012), depression (Shenassa and others 2007) and increased risk of respiratory and allergic symptoms (Weinmayr and others 2013). These symptoms may persist in fuel poor populations regardless of one’s risk perception and use of energy efficiency and ventilation in fuel poor populations. Future housing interventions should aim to exceed a SAP rating greater than 71 to lower risk of mould contamination, which must be delivered with awareness messages, measures to help fuel-poor populations, and improved ventilation strategies to increase air flow in energy efficient homes. Interventions must be supported by the provision of better guidance, advice and awareness, specifically with respect to those in fuel poverty. Future work should assess how resident behaviours modify indoor mould growth and the presence of different moulds associated with allergic diseases.

5.0 Conclusion

Fuel poverty behaviours affected around a third of participating households and represents a risk factor for increased exposures to damp and mouldy conditions. Increased risk perception and use of mechanical ventilation did not modify the associated risk of mould contamination in these homes. Our findings suggest that current heating and ventilation strategies are ineffective in lowering indoor exposures to mould associated with damp environments, especially in fuel-poor populations. A multidisciplinary approach is required to assess the complex interaction between occupant behaviours, risk perception, the built environment and the effective use of heating and ventilation strategies.

Supporting information

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Conflict of Interest

We declare that none of the authors involved in writing this paper have any conflict of interests with respect to the content of this article.

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Appendices – Supporting Tables

Appendix A Representation of study compared to target homes

Variable		Study Participant homes				Target homes			
	n	(%)	mean	range	sd	n	(%)	Mean	sd
Indices of Multiple Deprivation 2010	670		34.2	9.4-60.9	16.6	3966	35.2	15.7	3966
Mean build age	668		1968	1880-2013	21.3	3850		1964	24.2
Build age of properties; Pre 1930	17	2.5				248	6		
1930-1965	298	44.6				1882	48		
1965-1980	176	26.4				903	23		
1980+	177	26.5				919	23		
Property type; Bedsit	2	<1.0				14	1		
Bungalow	127	19.0				514	13		
Flat	265	39.7				1377	35		
House	274	41.0				2007	51		
Number of properties: terraced / flat	405	61.4				2287	60.1		
Semidetached / detached	255	38.6				1518	39.9		
External wall construction;									
Artificial stone	23	3.9				119	3.5		
Block / Brick	483	83.9				2761	81.9		
Concrete panel	45	7.8				325	9.6		
Granite	7	1.2				81	2.4		
Timber frame	18	3.1				85	2.5		
Primary heating fuel;	655					3835			
heat pump (wet & air system)	48	7.3				212	5.5		
gas	360	54.9				2286	59.7		
oil	79	12.1				364	9.5		
fire / stove	30	4.6				113	2.9		
electricity	63	9.6				348	9.1		
boiler / community heating	41	6.3				342	8.9		
room / storage heaters	34	5.2				170	4.4		
Average SAP rating	616		65.7	24-88		3462		65.3	9.6
Loft insulation depth; >250mm	617	87.8				3703	68		
Wall insulation; as built	11	1.7				87	2		
cavity	532	83.7				2825	76		
external	88	13.8				755	20		
internal	5	<1				55	2		
Windows double glazed	639	99.8				3744	99.9		
Boiler type; back boiler	42	8.4				216	7		
combi	196	39.2				1225	39		
condensing	89	17.8				668	21		
condensing combi	70	14.0				476	15		
normal	102	20.4				524	17		
range cooker boiler	1	<1				1	<1		

Appendix B Summary of demographic and housing characteristics between low / high risk perception scores and fuel poverty

Variable	Participant perception of risk living with mould >postcard size				Participants stated that they don't heat the home due to cost			
	n	Low risk perception score 0-4	n	High risk perception score 8-10	n	no	n	yes
Mean adult age, years	54	56	397	63	387	62	166	54
Number male participants, %	58	47	415	34	407	40	175	30
Participants with children, %	58	24	405	16	404	19	172	24
Seen a doctor for asthma in the last 12 months, %	54	20	367	22	377	18	159	25
Seen a doctor for allergy in the last 12 months, %	48	15	351	9	358	10	154	12
Unemployed, % In employment, % Retiree, %	55	0 24 38	405	17 16 46	399	11 19 47	173	12 27 24
Mean household energy efficiency (SAP)	51	65	393	66	379	66	161	66
Mean IMD score	58	33	421	34	411	34	176	34

Appendix C Calculating odds ratios from the probit (z-score) estimates

SEM models for visible mould and mouldy/musty odour and corresponding Figure	#	z-score	Logit value (*p*) = z-score x (π/√3)	Odds ratio = exp(logit)	P Value
Figure 3 Fuel poverty behaviours (L2) and risk of visible mould and mouldy odour, mediated by risk perception (L1)					
Figure 3A Visible mould growth					
Direct effect	c	0.683	1.239	3.452	**0.001**
Mediation model	a	0.590	1.070	2.916	0.334
	b	-0.069	-0.125	0.882	**0.015**
Indirect effect	ab	-0.041	-0.074	0.928	0.575
Total effect	c+(ab)	0.642	1.164	3.204	**0.000**
Figure 3B Mouldy/musty odour					
Direct effect	c	0.912	1.654	5.229	**0.000**
Mediation model	a	0.548	0.994	2.702	0.320
	b	0.002	0.004	1.004	0.935
Indirect effect	ab	0.001	0.002	1.002	0.961
Total effect	c+(ab)	0.913	1.656	5.238	**0.000**
Figure 4 Fuel poverty behaviours (L2) and risk of visible mould and mouldy odour, mediated by ventilating to minimise damp and mould (L3)					
Figure 4A Visible mould growth					
Direct effect	c	0.739	1.340	3.821	**0.000**
Mediation model	a	-0.172	-0.312	0.732	0.210
	b	0.502	0.911	2.486	0.001
Indirect effect	ab	-0.086	-0.156	0.856	0.280
Total effect	c+(ab)	0.652	1.183	3.263	**0.000**
Figure 4B Mouldy/musty odour					
Direct effect	c	0.282	0.511	1.668	**0.000**
Mediation model	a	-0.129	-0.234	0.791	0.217
	b	0.179	0.325	1.384	**0.001**
Indirect effect	ab	-0.023	-0.042	0.959	0.276
Total effect	c+(ab)	0.259	0.470	1.600	**0.000**
Figure 5 Increasing energy efficiency (SAP rating) and risk of visible mould and mouldy odour, mediated by fuel poverty behaviours (L2)					
Figure 5A Visible mould growth					
Direct effect	c	-0.015	-0.027	0.973	**0.033**
Mediation model	a	-0.009	-0.016	0.984	0.150
	b	0.649	1.177	3.245	**0.000**
Indirect effect	ab	-0.006	-0.011	0.989	0.172
Total effect	c+(ab)	-0.021	-0.038	0.963	**0.001**
Figure 5B Mouldy/musty odour					
Direct effect	c	-0.006	-0.011	0.989	0.353
Mediation model	a	-0.011	-0.020	0.980	0.094
	b	0.841	1.525	4.597	**0.000**
Indirect effect	ab	-0.009	-0.016	0.984	0.093
Total effect	c+(ab)	-0.015	-0.027	0.973	**0.030**