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Some like it hot: the role of environmental concern and comfort expectations in energy retrofit decisions

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Abstract

This study investigates the role of environmental concern and comfort expectations in the decision to retrofit a dwelling and their implications for the rebound effect. We ex-ante elicit individual preferences for deep thermal energy-saving measures in residential buildings by means of a Discrete Choice Experiment (DCE) among 3,161 owner-occupiers and tenants in Germany. Besides room temperature, we include air quality, level of control over the system, noise reduction, and aesthetics of the dwelling as proxies for indoor comfort. Our model also accounts for monthly payments related to the implementation of the measure – and customized based on tenancy status, building type, and size of the dwelling – as well as technical energy cost savings. Econometric estimation provides significant results for most of the parameter coefficients. Findings show that thermal comfort preferences are heterogeneous: 33% of the respondents attach positive values to an increase in indoor temperature that would result from the deep retrofit, providing evidence in favor of a technical rebound effect. While environmental concern explains heterogeneity in most of the attributes, its interaction with thermal comfort is not significant. Thermal comfort is, however, the least important attribute in the analysis.

JEL Classification: C25, D12, Q40, R20

Keywords: Rebound; Mixed logit; Residential buildings; Energy efficiency

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1 Introduction

Over the past two decades, household energy consumption and preferences for energy-efficient measures in the residential sector have been the object of intense research, following both the revealed- and stated-preferences approaches. Within the latter field of studies, one of the first conjoint analysis to look into preferences for energy-savings measures at home was conducted by Poortinga et al. (2003). The authors found that the installation of an energy-efficient heating system is more acceptable than any change in heating or ventilation habits. Jaccard and Dennis (2006) elicited Canadian homeowners' preferences for energy efficient versus non-efficient home renovations and different heating systems. Capital and annual heating costs, purchase subsidy, and comfort level (proxied by air quality) were used to describe the alternatives of a discrete choice experiment (DCE) on home renovations. Banfi et al. (2008) made Swiss home owners and tenants (treated as independent samples) face the decision to either keep their housing at their status-quo or to live in a retrofitted dwelling. Attributes of their DCE were type of windows and façade improvements, ventilation, and price. Environmental benefits and energy savings were not included due to hurdles in assessing them. A study with similar attributes was performed among Korean households by Kwak et al. (2010). More recently, Achtnicht (2011) investigated German homeowners' preferences for a modern heating system versus thermal insulation. Besides acquisition costs, the author also included the annual technical energy-saving potential, the investment payback period, CO_2 emission reduction, the opinion of an independent energy adviser, public and/or private funds, and the period of time during which the contractor is obligated to fix free of charge any deficiency in the retrofit. CO_2 emission reduction resulted to be significant only in the choice of heating system but did not matter for insulation. The mismatch in preferences for insulation and heating upgrades between landlord and tenants in New Zealand was the core of the work of Phillips (2012). Attributes included ceiling, floor and wall insulation, window and heating replacements, cost (or increase in rent) as well as the building energy label. Econometric estimations of the model were conducted separately for the two samples. The authors found tenants' WTP to be higher than their energy savings to signal the possible presence of non-monetized benefits in terms of comfort and health conditions. Following Marsh et al. (2011), the authors set the dwelling in which respondents were living at the time of the DCE as status quo and formulated attributes in terms of an additional layer of insulation or replacement of the current heating technology. Finally, Alberini et al. (2013) looked into Swiss homeowners including thermal comfort, an attribute mostly neglected by previous studies. The authors discovered that thermal comfort improvements and CO_2 emission reduction do matter.

With some exceptions, all these studies have a focus on (i) homeowners as the main research group, (ii) single-family homes as type of building, (iii) the trade-off among several retrofit measures, most often either insulation of part of the building envelope or installation of a more energy-efficient heating system, and (iv) financial aspects of the retrofit decision rather than comfort-related ones. Indoor comfort, in particular, nowadays triggers the interest of engineers and social scientists alike, being an umbrella concept hard to unequivocally measure and define (Heesen and Madlener, 2014). ASHRAE (2013) (and the European Standard EN 15251, see Cen, 2007) identifies one of its dimensions with thermal comfort. The meaning of thermal comfort itself is far from trivial as this concept encompasses air temperature and radiant heating, levels of air humidity and purity, as well as the presence of air draughts (Galvin, 2015)[1]. Although some studies found that thermal considerations are the most dominant factor in the perception of comfort (see e.g. Huebner et al., 2013), also air quality, visual, acoustic, ergonomic and psychological considerations affect occupants' comfort perception. Given the multidimensionality of comfort, we argue that the implementation of energy-saving measures is not necessarily driven by the desire to increase thermal comfort.

Insofar as implementing comprehensive building retrofit measures carries the potential to deeply alter (hopefully for the better) indoor comfort conditions, it is important to include comfort into any analysis. Recent studies point out that the decision to retrofit should go beyond mere cost-benefit considerations and include less quantifiable aspects,

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[1] For an exhaustive review of all factors affecting thermal comfort we refer to Rupp et al. (2015).

e.g. increase in comfort (Knight et al., 2006). Lutzenhiser et al. (2001) found that the wish to improve indoor comfort is the most highly rated motivational factor in home retrofit decisions in California. We believe that studies including comfort aspects in relation to the decision to retrofit have so far only focused on one or two comfort dimensions at a time. To the best of our knowledge, however, no study has explicitly attempted to account for comfort in all its dimensions with the purpose to ex-ante identify what type of expectations drive the decision to retrofit, which is the aim of this work. In this first-of-its-kind work, we moreover hypothesize that expectations about thermal comfort in the aftermath of the retrofit are – among other factors – responsible for an increase in the demand for energy services. Against the background of the rational choice theory, the ex-ante detection of thermal comfort expectations in favor of an increase in indoor temperatures can help disentangling technical sources of rebound effects from more behavioral ones. We choose to conduct a Discrete Choice Experiment (DCE) to explore our research hypotheses with data gathered from an extensive sample of German households. Our reasoning for preferring this methodology is as follows: firstly, we look at the motivations (and thus barriers to adoption) of deep thermal retrofits whose implementation – at least in Germany – is lagging behind policy expectations; secondly, by enabling respondents to trade off attributes of the DCE, preferences are elicited without the need to recall information about past retrofits in order to evaluate the alternatives. Thirdly, our sample also includes tenants, a category whose involvement in the investment decision is often little or non-existent. We posit that given the high tenancy rate in Germany (ca. 50%), the perspective of this segment of the population might help overcoming the landlord-tenant dilemma.

Findings from the estimation of mixed logit models confirm that retrofit alternatives providing better air quality, higher control over the system, noise reduction, higher savings as well as an improvement in the aesthetics while incurring lower investment costs are preferred, other things being equal. With 33% of our sample preferring retrofit solutions that lead to higher room temperature in the aftermath, our results also point to the clear presence of a comfort-taking rebound effect. While environmental concern and gender explain heterogeneous preferences for most of the attributes, heterogeneity of thermal comfort remains unexplained after controlling for socio-demographics and allowing for correlation among the attribute levels. Air quality is, however, the most important attribute in the analysis.

The remainder of this paper is organized as follows. Section 2 contains our research hypothesis as well as a description of the sample and the methodology adopted to test them. Special attention is given to the design of the DCE and our attribute choice. In section 3 we introduce the econometric specification of our model and the estimation technique. Our contribution is made clear both in this section, where our results are presented, and in the concluding section 4, where some implications and limits of this manuscript are further discussed.

2 Methodology

2.1 From the qualitative interviews to the research hypotheses

With the purpose to better understand comfort dynamics in highly-retrofitted residential buildings we initially conducted semi-structured qualitative interviews among 12 tenant households living in buildings retrofitted according to passive house standards.[2] Interviews were carried out in June 2013 and their analysis was useful for informing our research hypotheses as much as for wording the DCE attributes to validate them.

Across the 12 households, the dwelling was said to be "warm enough but not too much" and "rather warm than cold" while the temperature in the past winter was described as "not very pleasant", "comfortable" or "never too warm". Frustration from operating the system through thermostats emerged. It seemed that thermostats were "either too rough or responded too late", "difficult to deal with". When ventilation was installed in addition to a more energy-efficient heating system, respondents' opinion about it was divided: on

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[2] The retrofit took place within the EnEff:Stadt pilot project "Integrated Neighbourhood Energy Concept, Karlsruhe-Rintheim". Further information about this project are available at http://www.eneff-stadt.info/en/pilot-projects/project/details/integrated-neighbourhood-energy-concept-karlsruhe-rintheim/.

the one hand, the device was said to be “too loud”, “a bit noisy”, and not contributing to save more energy since cold air was blown in; on the other hand, the general idea of forcing ventilation in a highly-retrofitted building was perceived to be “nice”. Radiators were appreciated for their manual-valve regulation and quick responding times but floor heating was praised in some instances, too. Insulation was perceived to be “not necessary”, or even “bad” in some cases, while in others it was labeled as a “very good” measure. When asked to rank their renovation preferences, respondents most often placed windows in first position, followed by a new heating system. Insulation was mentioned as first preference only in two cases. These interviews also provided us with insights about the living room as the most heated environment when at home. Finally, when asked to elaborate on the perceived benefits of living in a retrofitted dwelling, respondents declared that saving money is more important than the environment. If they were wealthy, however, they would put environment first as long as saving money “does not reduce comfort”. Overall, comfort was mainly described by respondents through room temperature and air quality (with particular reference to smell, the presence of draughts, and humidity).

Lorch (2008) and Shove (2003) clarified that comfort is also about individual and cultural attitudes. It might result from anything that is perceived as “natural”. Comfort, or acceptance of the indoor climate, also seems to depend on external weather and one’s believe on the ability to make oneself comfortable; for this reason, higher degrees of system control are thought to lead to higher tolerability of discomfort. According to the adaptive comfort theory (de Dear and Brager, 2001; de Dear et al., 2013), the mere impression of being able to control the indoor temperature already improves the thermal comfort perception, as a field study has recently revealed (Luo et al., 2016). Automated versus manual control was also the object of the analyses of D’Oca et al. (2014) who concluded that passive interaction is negatively correlated with the achievement of personal comfort. Moreover, Hauge et al. (2011) believe that besides perceived personal control and operability of the system, what makes an energy-efficient building more desirable is its architecture and aesthetics. Together with thermal comfort, aesthetics was one of the most important drivers of the implementation of energy retrofit measures, according to results from a survey among German single- and two-family houses (Novikova et al., 2011). Finally, Jakob (2006) stresses how the benefits of retrofit come among others from “operating ease, protection against external noise, additional safety”. Based on results from a principal component analysis, Michelsen and Madlener (2012) also found “improved ease of use” of the heating system as a proxy for comfort to be a significant decisional factor. Finally, Wilson et al. (2015) summarized in energy savings, increase in thermal comfort, reduction in draughts, as well as air condensation and increase in property values the main reasons for homeowners to invest in energy-efficient measures.

On the basis of the findings from the interviews and the literature reviewed above we formulated the research hypotheses as follows:

- **Hypothesis 1**: Individuals prefer retrofit scenarios characterized by higher room temperatures, other things being equal; moreover,
- **Hypothesis 2**: The higher the potential for technical savings in energy costs, the bigger the expectation of higher room temperatures;
- **Hypothesis 3**: Individuals prefer retrofit solutions able to guarantee better air quality;
- **Hypothesis 4**: Reducing the noise coming both from the outside of the building and from the inside matter;
- **Hypothesis 5**: Refurbishments that reduce the ability to interact with the system to adjust the level of comfort are disliked;
- **Hypothesis 6**: Retrofit measures that improve the external appearance of the dwelling without compromising the interior design are preferred to solutions that neglect this aspect or even worsen the internal appearance of the dwelling.

2.2 The sample

The DCE was conducted in winter 2015/2016 among 3,161 owner-occupiers and tenants in Germany. It was part of a broader survey carried out using the computer-assisted web interviewing (CAWI) technique and designed according to the guidelines in Dillman et al. (2009). In addition to choice data, the survey provided us with data on (i) ventilation and heating habits (e.g. room temperature in winter, window-opening behavior); (ii) environmental concern, measured through the revised version of the New Ecological Paradigm (NEP) scale, capturing values, attitudes, and beliefs regarding the environment (Dunlap and Liere, 1978; Dunlap et al., 2000); (iii) dwelling characteristics e.g. age, size, type of retrofit measure already implemented; and (iv) other socio-demographics such as gender and age of the respondent.

Respondents were sampled from the online panel "Respondi" and received a small monetary incentive upon successful completion of the survey [3]. Although respondents were randomly sampled, we cannot be sure that the procedure followed by the professional panel provider was fully probabilistic or that the panel population is very similar to the German population for the variables of interest. As a consequence, following Hensher et al. (2005, 120), we do not feel confident extending the causal relationships found in our data to a larger population of interest. The sample is composed of 1,884 tenants (59.60%) and 1,277 owner-occupiers (40.40%). About 46% are women while the sample age falls within the range of 18-80 years, with an average of about 45. The majority of respondents comes from the states of NRW, Bayern and Baden-Württemberg, with shares of about 22%, 15% and 11%, respectively. Circa 26% of the respondents own a university degree, while a significant part of them (about 36%) has attended school until the 10th class. With an average sample score of 56.29 and a standard deviation of 8.23 on the NEP scale, 50.59% of our respondents reported a score above average and are, therefore, considered to be "green".

When it comes to net household income, about 52% of the participants declared that the household was disposing of an overall income of less than 2,600 €/month. The income class registering the highest share (18.16%) ranged from 2,600 € to 3,600 €/month, upper extreme excluded.

Overall, respondents seem to be quite satisfied with the comfort conditions of their

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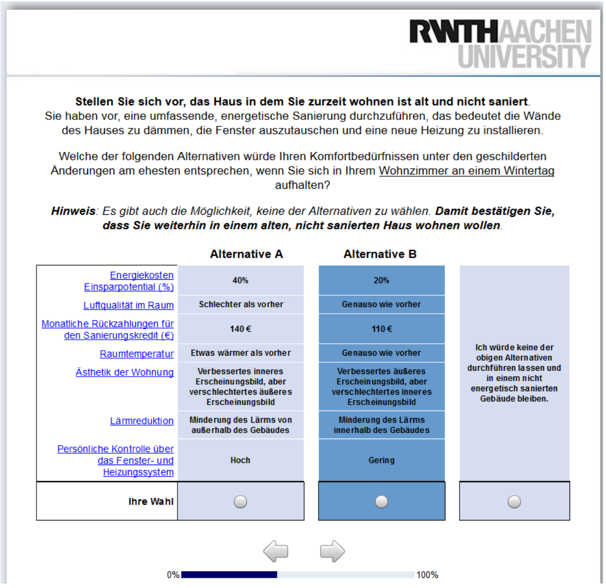
[3] Determination of the minimum sample size based on Hensher et al. (2005, 185).

dwellings. Perceived comfort was computed as the sum of thermal comfort, noise protection, and air quality measured on a five-point scale ranging from “Very satisfied” to “Very unsatisfied”. The sum across the three items was therefore ranging from 3 to 15. On average, the perceived comfort scored 11.58 points, with a standard deviation of 2.47.

In selecting our sample we included screening questions to leave out any individual not involved in the household decision-making process on energy-related matters, subtenants, or individuals sharing a flat with people other than their relatives.

2.3 The design of the Discrete Choice Experiment

The DCE consisted of presenting to each respondent 6 choice cards described by a set of randomly varying attribute levels (as shown in Figure 1) and two holdouts identical for all respondents and between each other. In each choice card respondents were given a scenario describing the hypothetical yet realistic situation in which the subject is living in an old building and considering the option to implement a comprehensive energy-saving retrofit, i.e. install a new heating system, replace the old windows with new ones, and insulate the building envelope.



Stellen Sie sich vor, das Haus in dem Sie zurzeit wohnen ist alt und nicht saniert.
Sie haben vor, eine umfassende, energetische Sanierung durchzuführen, das bedeutet die Wände des Hauses zu dämmen, die Fenster auszutauschen und eine neue Heizung zu installieren.

Welche der folgenden Alternativen würde Ihren Komfortbedürfnissen unter den geschilderten Änderungen am ehesten entsprechen, wenn Sie sich in Ihrem Wohnzimmer an einem Wintertag aufhalten?

Hinweis: *Es gibt auch die Möglichkeit, keine der Alternativen zu wählen.* ***Damit bestätigen Sie, dass Sie weiterhin in einem alten, nicht sanierten Haus wohnen wollen***.

	Alternative A	Alternative B	
Energiekosten Einsparpotential (%)	40%	20%	Ich würde keine der obigen Alternativen durchführen lassen und in einem nicht energetisch sanierten Gebäude bleiben.
Luftqualität im Raum	Schlechter als vorher	Genauso wie vorher	
Monatliche Rückzahlungen für den Sanierungskredit (€)	140 €	110 €	
Raumtemperatur	Etwas wärmer als vorher	Genauso wie vorher	
Ästhetik der Wohnung	Verbessertes inneres Erscheinungsbild, aber verschlechtertes äußeres Erscheinungsbild	Verbessertes äußeres Erscheinungsbild, aber verschlechtertes inneres Erscheinungsbild	
Lärmreduktion	Minderung des Lärms von außerhalb des Gebäudes	Minderung des Lärms innerhalb des Gebäudes	
Persönliche Kontrolle über das Fenster- und Heizungssystem	Hoch	Gering	
Ihre Wahl	○	○	○

Figure 1: Example of a choice card: case of an owner-occupier

The reasons for focusing on deep thermal retrofit strategies are threefold: first of all, these measures are the least implemented ones due to their high investment costs (Galvin and Sunikka-Blank, 2013); then, this is the type of retrofit that can most effectively contribute to the realization of the ambitious emission reduction targets set by the German government. Finally, according to EnEV (2014), partial retrofits have to fulfil either standards set on U-values whose aim is to reduce the heat transferred through the building envelope, or standards concerning the quantity of heating energy consumed, indicated with Q_P and measured in kWh of primary energy consumed per square meter of useful area per year (kWh/m^{2}a). Both standards have to be contemporaneously satisfied only in the case of comprehensive retrofit; in other words, one can comply with the law by replacing the windows or an old heating system, but this might undermine the effectiveness of the measure e.g. in the presence of thin walls. Consequently, comprehensive retrofits are also the ones expected to affect comfort the most. As also explained in Capper and Scott (1982), subsequent marginal improvements in energy efficiency do not carry the same effect on energy consumption as a deep thermal retrofit does.

Each time respondents had to choose which of two retrofit alternatives best delivered the ideal comfort in their living room on a winter day. If none of the two alternatives matched with their comfort expectations, respondents could instead indicate their preference for not having their dwelling retrofitted. If tenants, the interviewees had to imagine that the landlord was consulting them about the possible implementation of such measures. Each alternative was unlabeled, i.e. named “Alternative A” and “Alternative B”. Attributes and their levels are reported in Table 1. Pop-up windows with detailed explanation of the attributes were available to respondents throughout the whole exercise. We are aware of the fact that some of the respondents might have thought that the increase in room temperature is not a physical consequence of the retrofit but rather results from a change in their heating settings. During the cognitive pretest, however, none of the respondents interpreted the choice exercise in this way. We are, therefore, confident that the exercise was correctly understood.

Besides room temperature, air quality, level of control over the indoor temperature, noise reduction and also aesthetics of the dwelling were included as proxies for indoor comfort. Not only the scenario description but also monthly costs differed by tenancy status in order to account for tenants being able to only indirectly affect the investment decision, which is eventually made by the landlord.

Table 1: Attributes and their levels

Attribute	**Level**
A1. Room air quality (AIRQ)	1.1 As before* 1.2 Better than before 1.3 Worse than before
A2. Room temperature (TEMP)	2.1 As before* 2.2 Slightly warmer than before
A3. Monthly payment for the system/ monthly increase in rent (COST)	3.1 Low, customized 3.2 Intermediate, customized* 3.3 High, customized
A4. Control over windows and heating system (CONTR)	4.1 High 4.2 Intermediate* 4.3 Low
A5. Noise reduction (NOISE)	5.1 Reduction of noise from inside and outside the building 5.2 Reduction of noise from outside the building 5.3 Reduction of noise from inside the building* 5.4 No reduction of noise from outside nor inside the building
A6. Aesthetics of the flat (AESTH)	6.1 Improved inside and outside appearance 6.2 Improved inside appearance 6.3 Improved outside appearance 6.4 Improved outside appearance but worsened inside appearance 6.5 Improved inside appearance but worsened outside appearance*
A7. Potential savings in energy costs (SAV)	7.1 20% 7.2 40%* 7.3 80%

*= reference levels in the regression analysis

We also accounted for monthly payments and potential savings in energy costs related to the implementation of the measure[4]. The specification of levels for the latter two attributes was particularly complex as it required computing costs and benefits from the retrofit decision. To this purpose we designed a matrix where investment costs were further based on building type (i.e. single- versus multi-family houses) and size of dwelling. A simulation tool developed by the Institute for Energy Efficient Buildings and Indoor Climate (EBC) – one of our sister institutes at the E.On Energy Research Center, RWTH

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[4] The cost of implementing the comprehensive retrofit measure – regardless of whether expressed as a monthly payment or as an increase in rent – does not describe consumers' utility. We acknowledge that the inclusion of price as an attribute in discrete choice experiments is a debated matter (Breidert et al., 2006).

Aachen University – provided us with output on both investment costs and final energy savings depending on the recommended measures to implement. The majority of packages consisted in the installation of a new heating system and the retrofit of external walls but in some cases also floor, ceiling and roof insulation were recommended.[5] The single measures constituting the deep thermal retrofit were chosen to minimize the primary energy demand and ensure that the standards set within the KfW-Effizienzhaus 100[6] were met. The energy savings thus obtained were eventually converted into potential savings in energy expenses taking into consideration the switch from a gas-driven heating system to electricity-driven ones (e.g. heat pumps). The monetary attribute was further customized based on tenancy status: for owner-occupiers, investment costs were transformed into monthly payments for the next 20 years following the KfW credit line n°151 (KfW, 2016). In the case of tenants, the monthly increase in rent was computed following the model contained in Enseling and Hinz (2009, 20 ff.). To this end, we assumed the rent before retrofit to be lower than rents of comparable flats in the area. Article 558 of the Tenancy Law contained in the German Civil Code (Bürgerliches Gesetzbuch, BGB) applies here, allowing the landlord to transfer to the tenant the energy-related costs of the retrofit through an increase in the yearly rent by an amount that we assumed to be around 4% (Popescu et al., 2012). Overall, 12 categories were created for the attribute COST and the final levels shown to respondents are reported in Table 2.

The choice of attributes and their levels was confirmed (and partially improved) through the performance of cognitive pretesting among a small sample of individuals differing in gender, age, and level of education, as well as pretesting among colleagues at our research institute.

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[5] This tool considers investment costs inclusive of materials and installation. Within the tool prices were updated on April 30, 2015. Economic parameters were set following Hinz and Schettler-Köhler (2012) and CO_2 emission reductions were computed considering the heating system only.

[6] The KfW-Effizienzhaus 100 is the retrofit standard set by the German development bank KfW when taking a credit to conduct a retrofit that meets EnEV requirements.

Table 2: Customization of the monetary attribute

Tenancy status	Type of building	Dwelling size (m^2)	Attribute level (€)	Resp. (%)
Owner	Multi-family	<40-59	40 55 70	2.06
		60-99	80 110 140	10.57
		100-159	160 220 280	8.92
		160-200+	210 280 350	3.23
	Single-family	<40-119	130 180 230	3.83
		120-200+	180 240 300	11.80
Tenant	Multi-family	<40-59	24 32 40	18.32
		60-99	50 65 80	28.03
		100-159	100 135 170	8.48
		160-200+	130 170 210	1.11
	Single-family	<40-119	80 110 140	2.06
		120-200+	110 150 190	1.61

The design of the DCE was generated using the computer optimized Complete Enumeration method offered by the Sawtooth Software®. Logit estimation of data simulated from dummy respondents provides small errors for main effects as well as interaction terms (highest D-efficiency).

3 Data analysis

3.1 Econometric modeling of comfort preferences

The choice data is the basis for the econometric analysis conducted within the classical approach to inference in the framework of the Random Utility Theory (McFadden, 1974). Estimation was performed specifying a mixed logit model with random parameters (θ) in utility space. The random parameters follow the distribution $\theta \sim N(b, W)$, with b and W representing the mean and covariance of the parameters in the population, respectively. It derives that θ can be thought of summarizing the tastes of the population as a whole. In comparison to the standard logit model, mixed-logit probabilities do not exhibit the "independence from irrelevant alternatives" and this allows to account for correlation in unobserved utility across each respondent's choice tasks (Revelt and Train, 1998). Following the notation in Train (2009), the true utility respondent n gains from choosing alternative j in the choice task t is given by

$$U_{njt} = V_{njt} + \varepsilon_{njt}, \tag{1}$$

where $V_{njt} = \beta_n' x_{njt}$, i.e. V_{njt} is a linear function of observable attribute levels x and unobservable coefficient vector β_{njt}. [7] ε_{nj} is the unknown random term iid extreme value whose role is to capture aspects of the utility unobservable by the researcher. [8] In each of the T choice cards, respondents N pick the alternative that maximizes their utility. It derives that respondent n will choose alternative i in the choice task T if and only if $U_{nit} > U_{njt}$. Because utility is known to the decision-maker n but not observable by the researcher, the latter has to attach a certain probability P_{nit} to alternative i in the choice

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[7] To keep the notation simple, we hereby exclude the vector of respondent-invariant and observable socio-demographics s_n. These observed factors are related to respondent's utility through a function specifiable by the researcher $V_{nj} = V(x_{nj}, s_n)$. Socio-demographics are individual and choice invariant characteristics that generate heterogeneity in the mean b of the β distribution. This source of unobserved heterogeneity should not be confused with the one deriving from individual and choice-specific random noise (Louviere et al., 2000; McFadden and Train, 2000).

[8] We refer to Train (2009) for a more comprehensive interpretation of ε_{nj} and to Louviere et al. (2002) for an elaborated discussion of the possible sources of unobserved variability and heterogeneity.

task t being chosen. This can be written as:

$$\begin{aligned} P_{nit} &= Pr(U_{nit} > U_{njt}), \forall j \neq i, && (2)\\ &= Pr(V_{nit} + \varepsilon_{nit} > V_{njt} + \varepsilon_{njt}), \forall j \neq i, && (3)\\ &= Pr(\varepsilon_{njt} - \varepsilon_{nit} < V_{nit} - V_{njt}), \forall j \neq i, && (4) \end{aligned}$$

and can also be interpreted as the probability that n will choose i in choice task t if the observed utility from i is higher than the unobserved utility from choosing alternative j. Given the portion of utility dependent on β_n, the conditional probability takes on the standard logit form:

$$L_{nit}(\beta) = \frac{exp(\beta_n' x_{nit})}{\sum_{j=1}^{J} exp(\beta_n' x_{njt})}, \tag{5}$$

from which it derives that the mixed logit combined probability of an individual choosing alternative i across all T choice tasks can be written as:

$$P_{ni} = \int \prod_{t=1}^{T} \left(\frac{exp(\beta_n' x_{ni})}{\sum_j exp(\beta_n' x_{nj})} \right) f(\beta) d\beta, \tag{6}$$

where $f(\beta)$ is the mixing distribution of the logit function computed at the different values of β, specifying the distribution of β among the respondents. Since eq. (6) cannot be integrated, b and W and all individual β_ns result from the maximum simulated likelihood estimator (see Stern, 1997 for a review of studies on the estimation of open-form models by simulation). We later relax the assumption of normal parameters being independent from each other. Following Revelt and Train (1998), $\beta_n \sim N(b, \Omega)$, where $\Omega = LL'$, being L the lower triangular Choleski factor.

All estimations presented in the next section were obtained adopting the user-written mixlogit command (Hole, 2007) in Stata® v.14.1. We used 500 Halton draws to avoid biased parameter estimates, and burnt 45 initial sequences. In all regressions the likelihood function was maximized by using the Newton-Raphson algorithm, which is not sensitive to variable ranges (Louviere et al., 2000, 269). Moreover, the "difficult" option was specified to help the estimator overcome non-concave regions.

We refer to Hensher and Greene (2002) for a further explanation of the empirical challenges of estimating a mixed logit model.

3.2 Results

Across all choice tasks and respondents, alternative A, B, and the none option were chosen in 32.41, 35.91, and 31.68% of the cases, respectively. When considering the distribution of the none option by tenancy status, age of the respondent, and type of building we observe that in 61.75% of the cases this alternative was picked by a tenant, 56.42% of the times by older individuals [9], and only in 18.76% of the cases by a respondent living in a single-family house. Accommodating this alternative-specific constant implied expanding the dataset to achieve the final size of N=56,898 observations [10].

With the purpose to identify the most adequate way of including the cost variable, we run the model coding COST as continuous linear (see columns 1 and 2 of Table 3) and categorical (see columns 3 and 4). Additionally, the distribution of the COST parameter can be specified as either fixed (columns 1 and 3) or random (models 2 and 4).[11] Table 3 reports the raw parameters estimates[12] from mixed logit regressions for the cases 1-4. Because all parameters are in the form of log odds, a direct interpretation of their meaning is not possible. Furthermore, attributes were effect-coded across all estimations (see Hensher et al., 2005)[13], rendering the interpretation of coefficients even less trivial. However, it is possible to comment on the sign of the coefficients and see that it comes as expected for all parameters. The NONE variable, which also represents the average of all unobserved effects, significantly entered the model with a negative sign that indicates

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[9] In our sample an individual is defined as "older" if her age is above the sample average of 45 years

[10] 3,161 respondents*6 choice cards*3 alternatives=56,898 total observations.

[11] It is often the case that all parameters but price are estimated as normally distributed random variables because individuals are assumed to have rather homogeneous preferences about price. An example is represented by Revelt and Train (1998).

[12] Raw output parameters from mixed logit models are log odds accounting for the presence of the "none" option with an alternative-specific constant. The odds of an event happening is the ratio of the probability of success over the probability of failure. When estimating logit models, probabilities are transformed into log odds.

[13] The following base categories taken from Table 1 were omitted from the estimations: A1.1, A2.1, A3.2, A4.2, A5.3, A6.5, and A7.2. The coefficients for the omitted categories can be computed as the negative sum of the coefficients of the non-omitted levels since each main effect is the difference between the grand mean and the mean of the level coded as 1. The usage of this coding scheme has the advantage of separating the effect of the alternative-specific constant from the impact of the attributes; in fact, in effect coding the intercept is equal to the grand mean of all the observations for one attribute.

respondents' aversion towards living in an old and non-retrofitted dwelling. The negative sign brings evidence for the presence of heuristic behavior; in fact, respondents seem to associate extra utility to the implementation of the comprehensive retrofit measure. We believe this being an artefact of the experiment, as inertia (or status-quo bias) is usually observed in real-life situations. By looking at the Akaike Information Criterion (AIC) for the four models, the difference between AIC in model 3 and the other models is larger than 2.5 points; therefore, we can affirm that model 3 is the preferred one. The same conclusion can be drawn when looking at the Bayesian Information Criterion (BIC).[14] Together with the AIC and BIC we also report the unadjusted McFadden's Pseudo R^2. Since signs are consistent across model specifications (1)-(4), we focus on column (3) showing the best model fit based on AIC and BIC.

When interpreting the coefficients it is important to bear in mind that respondents were asked to elaborate their expectations about comfort with respect to the living room on a winter day. The signs of the parameter estimates thus reveal that on average respondents prefer retrofit solutions that improve the quality of the indoor air (hypothesis 3) and dislike situations in which this attribute results to be worsened after retrofitting (positive and negative sign of AIRQ_better and AIRQ_worse, respectively). The positive and negative signs of COST_low and COST_high, respectively, indicate that on average a higher utility is associated to less expensive retrofit solutions. As hypothesized (hypothesis 5), individuals dislike giving away control of their comfort to automatic technologies (CONTR_high positive and CONTR_low negative). Moreover, the positive and significant sign of NOISE_in/out coupled with the negative sign of NOISE_none brings evidence in favor of hypothesis 4. Thus, the implementation of refurbishment measures that reduce noise (either from the outside or from the inside, e.g. due to the installation of a more silent heating technology) are generally preferred to measures that do not. Among all attribute levels reported for model (3), AESTH_out is the only one with a non-significant parameter estimate, meaning that respondents are indifferent to refurbishments which only improve the appearance of the façade. The positive sign of

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[14] Rules of thumb for the AIC and BIC can be found in Hilbe (2011) and Raftery (1995), respectively.

AESTH_in/out together with the negative sign of AESTH_out+in- provides evidence in favor of hypothesis 6.

Table 3: θ parameters from mixed logit model with alternative-specific constant

Variable	(1)		(2)		(3)		(4)	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
AIRQ_better	.498***	.164***	.520***	.135*	.536***	.190***	.550***	.187***
	(.020)	(.054)	(.020)	(.071)	(.021)	(.052)	(.022)	(.054)
AIRQ_worse	-.636***	.289***	-.666***	.288***	-.680***	.339***	-.701***	.346***
	(.023)	(.037)	(.023)	(.040)	(.024)	(.036)	(.027)	(.038)
TEMP_warm	.083***	.160***	.088***	.160***	.089***	.197***	.092***	.201***
	(.011)	(.031)	(.011)	(.033)	(.012)	(.029)	(.012)	(.030)
COST	-.006***		-.010***	.011***				
	(.000)		(.000)	(.001)				
COST_low					.374***		.382***	.248***
					(.019)		(.021)	(.045)
COST_high					-.412***		-.418***	.163**
					(.020)		(.021)	(.067)
CONTR_high	.223***	.197***	.231***	.194***	.235***	.228***	.242***	.221***
	(.018)	(.047)	(.018)	(.053)	(.019)	(.044)	(.019)	(.053)
CONTR_low	-.198***	.117	-.208***	.171***	-.207***	.197***	-.213***	.184***
	(.018)	(.082)	(.018)	(.054)	(.019)	(.051)	(.019)	(.060)
NOISE_in/out	.170***	.015	.177***	.037	.176***	.030	.179***	.098
	(.022)	(.092)	(.023)	(.085)	(.023)	(.104)	(.023)	(.094)
NOISE_out	.035	.000	.036	.042	.048**	.008	.047**	.026
	(.021)	(.106)	(.022)	(.089)	(.022)	(.115)	(.023)	(.117)
NOISE_none	-.260***	.219***	-.273***	.224***	-.278***	.275***	-.283***	.221***
	(.023)	(.065)	(.024)	(.063)	(.025)	(.057)	(.025)	(.064)
AESTH_in/out	.192***	.122	.195***	.229***	.206***	.219***	.213***	.271***
	(.026)	(.154)	(.027)	(.082)	(.027)	(.083)	(.028)	(.075)
AESTH_in	.111***	.153	.122***	.084	.117***	.139	.121***	.180*
	(.026)	(.101)	(.027)	(.126)	(.027)	(.127)	(.028)	(.097)
AESTH_out	.012	.033	.014	.067	.015	.064	.014	.074
	(.026)	(.124)	(.027)	(.101)	(.027)	(.179)	(.027)	(.148)
AESTH_out+in-	-.217***	.071	-.229***	.042	-.227***	.147	-.231***	.127
	(.026)	(.172)	(.027)	(.135)	(.028)	(.104)	(.029)	(.128)
SAV_20	-.410***	.095	-.423***	.194***	-.438***	.181***	-.449***	.229***
	(.019)	(.100)	(.020)	(.050)	(.020)	(.059)	(.021)	(.050)
SAV_80	.440***	.273***	.456***	.284***	.468***	.297***	.481***	.319***
	(.019)	(.037)	(.020)	(.038)	(.020)	(.038)	(.022)	(.038)
NONE	-1.626***	3.376***	-1.977***	3.394***	-.780***	3.322***	-.786***	3.320***
	(.089)	(.089)	(.097)	(.096)	(.074)	(.088)	(.074)	(.088)
N° of Obs.	56,898		56,898		56,898		56,898	
N° of Resp.	3,161		3,161		3,161		3,161	
LR χ^2	6,868.57		7,004.22		6,705.44		6,707.82	
d.f.	31		32		32		34	
p	0.000		0.000		0.000		0.000	
AIC	32,222		32,088		31,870		31,871	
BIC	32,499		32,375		32,156		32,175	
Pseudo R^2	0.1760		0.1795		0.1741		0.1742	

*** = p<0.01; ** = p<0.05; * = p<0.1; Standard errors in brackets

When it comes to potential savings in energy costs, individuals like that the implementation of such measures allows them to potentially save 80% of the bills (positive sign SAV_80) while technical savings of around 20% are not considered to be sufficient with respect to the reference level of 40% (negative sign of SAV_20). Most importantly, respondents allocate positive value to indoor temperatures that after the retrofit are higher than before, in comparison to situations in which the temperature remains constant (positive TEMP_warm coefficient). This result confirms the presence of a technical rebound effect as postulated in hypothesis 1. Finally, there is significant heterogeneity in respondents' preferences across the four models and in particular in (3) and (4); for instance, by looking at model (3), we observe heterogeneity in the attitudes towards different levels of indoor air quality, thermal comfort, control over the system, no reduction of noise, improved internal design and external appearance of the building, as well as potential energy cost savings.

From the parameter estimates of model (3) at the individual level we also computed the relative attribute importance (Orme, 2010). In Table 4 it can be clearly seen that air quality is the most important attribute, followed by savings on the energy bill and monthly costs due to the implementation of the retrofit. Finally, room temperature is the least important attribute. This result comes unexpectedly since in the literature thermal comfort is mentioned as one of the major dimensions of comfort and being among the most important reasons for retrofitting. Such a result might be explained in light of the fact that Germany is not plagued by fuel poverty (see e.g. the case of the UK in Milne and Boardman, 2000) and therefore thermal comfort is something that German households are used to; this hypothesis also seems to be confirmed by our descriptives on comfort. In 2015, the share of the total German population in arrears on utility bills, unable to keep homes adequately warm, and living in dwellings with leakages and dump walls, was 4%, 4.1%, and 12.8%, respectively, while the estimated EU-28 average was 9%, 9.4%, and 15.2%, respectively (Eurostat, 2016). Alternatively, it could also be an artefact of the experiment. We exclude, however, that the number-of-levels effect plays a role here since NOISE and AESTH have the highest number of levels and are among the least important attributes.

By looking at the cumulative distribution function of the random variables (from

Table 4: Model 3 – Estimated average attribute importance

Attribute	%
Air quality	27.67
Savings on bill	20.38
Monthly costs	17.90
Noise	10.25
Control	10.09
Aesthetics	9.77
Room temperature	3.94
Total	100.00

model 3), we deduced the share of respondents preferring each level.[15] Almost all respondents like the idea of enjoying better air quality – with respect to the levels before retrofitting – and a reduction of the noise from outside to a mere reduction of the noise coming from the technology inside the building. About 94% of the respondents would rather save 80% of the energy costs than 40%, while almost all respondents prefer 40% to 20% energy cost savings. Furthermore, about 82% of respondents are in favor of a measure that improves both the internal and external image of the building over a retrofit strategy that improves the external appearance of the building but compromises its internal appearance. Moreover, 80% of the respondents would improve the internal appearance to the extent that improving the external appearance comes at the cost of a worsened interior design. When it comes to personal control over the system, high levels are perceived as better than intermediate control by 84% of the respondents. Finally, post-retrofit room temperatures higher than pre-retrofit scenarios seem to be desirable only for about 33% of our sample.

3.3 Heterogeneity in comfort preferences

With the purpose to explain at least part of the unobserved heterogeneity in comfort preferences we turned to the investigation of some socio-demographics.[16] Here “Fem” indicates an individual of female gender, “Old” a respondent whose age is above the

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[15] The shares are given by $\Phi(\frac{\beta}{sd_\beta})$*100.

[16] Following Louviere et al. (2000, 336) all socio-demographics variables were effect-coded. When dummy-coded, the regression output was not meaningfully different.

sample average of 45 years, “Rich” is a respondent belonging to a household with a net monthly income above €2,000, the lower limit of the average income group. Moreover, we indicated with “Green” an individual that is environmentally concerned and with “Ten” someone currently renting the dwelling. In order to avoid omitted-variable bias each socio-demographic was interacted with all attributes. This model was estimated setting the number of Halton draws for the simulation to 50 and the variables entered the model with fixed coefficients. We then run another regression where we only included those interactions significant in the previous step, with the exception of all terms involving the TEMP attribute (that have been included even if insignificant). Here we set the number of draws to 500. Mean parameters are reported in Table 5. We find significant effects of being female, older, richer and greener on preferences for better indoor air quality. In particular, being female or green as a negative effect on the evaluation of an eventual deterioration in the quality of the air. Higher levels of system control are preferred by greener individuals and females, the latter particularly disliking alternatives with lower control. When it comes to noise reduction, females and older individuals are sensitive to noise coming from both inside and outside but, most importantly, both categories dislike retrofit solutions not reducing the noise at all. The latter does not apply to the greens, who attach a positive utility to the reduction of noise coming from the outside only. For what concerns aesthetics, females are more keen on implementing retrofit measures that improve the interior design of the dwelling, whereas what matters more to the greens is that both the internal and external appearance of the building are improved. Higher technical savings in energy bills are positively valued by richer and greener respondents. Interestingly, women attach a negative utility to higher savings whereas tenants seem to prefer lower energy cost savings but attach a considerable disutility to higher increases in rent. Especially older respondents attached a positive value to choosing the “none-of-the-previous” option during the experiment. Finally, none of the interactions between the socio-demographics and TEMP was significant, a result that comes as unexpected as women and older individuals are commonly thought to have preferences for higher room temperatures for biological reasons. This result can, however, also partially stem from the fact that 45 years is not a good threshold for the identification of a sensitive segment of the population based on age.

Table 5: Socio demographics and comfort preferences: θ parameters

Interaction terms[17]	**(5)**			
	Mean	**s.e.**	**SD**	**s.e.**
Fem*AIRQbetter	.043**	.018		
Fem*AIRQworse	-.065***	.020		
Fem*TEMPhigh	-.006	.012		
Fem*CONTRhigh	.047**	.018		
Fem*CONTRlow	-.058***	.019		
Fem*NOISEin/out	.055**	.022		
Fem*NOISEnone	-.089***	.023		
Fem*AESTHin	.046**	.022		
Fem*SAV80	-.033**	.016		
Fem*NONE	.153**	.069		
Old*AIRQbetter	.023	.016		
Old*TEMPhigh	.009	.012		
Old*NOISEin/out	.082***	.022		
Old*NOISEnone	-.089***	.023		
Old*NONE	.335***	.069		
Rich*AIRQbetter	.061***	.018		
Rich*AIRQworse	-.040	.020		
Rich*TEMPhigh	-.011**	.012		
Rich*SAV80	.046***	.017		
Green*AIRQbetter	.083***	.018		
Green*AIRQworse	-.104***	.020		
Green*TEMPhigh	.006	.012		
Green*COSTlow	.047**	.018		
Green*COSThigh	-.039**	.019		
Green*CONTRhigh	.036**	.016		
Green*NOISEout	.067***	.022		
Green*NOISEnone	-.069***	.023		
Green*AESTHin/out	.082***	.025		
Green*AESTHout+in-	-.069***	.025		
Green*SAV20	-.102***	.019		
Green*SAV80	.135***	.019		
Green*NONE	.270***	.069		
Ten*TEMPhigh	-.005	.012		
Ten*COSTlow	.103***	.018		
Ten*COSThigh	-.115***	.019		
Ten*SAV20	.033**	.017		
TEMPwarm*SAV20	-.052**	.026	.003	.087
TEMPwarm*SAV80	.007	.025	.144	.098
TEMPwarm*COSTlow	-.042	.026	.246***	.079
TEMPwarm*COSThigh	.002	.026	.145	.154
N° of Obs.	56,898			
N° of Resp.	3,161			
LR χ^2	6631.47			
d.f.	76			
p	0.0000			
AIC	31,642			
BIC	32,224			
Pseudo R^2	0.1737			

*** = p<0.01; ** = p<0.05; * = p<0.1

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[17] Attribute levels included in the regression but not reported here. Standard deviations reported only for the random interaction terms.

An additional model based on model (3) relaxes the unrealistic assumption of uncorrelated coefficients (model (6)); in fact, one would for instance expect that individuals with the desire to enjoy higher room temperatures would also show a positive attitude towards higher technical energy savings, should the latter be perceived as a proxy for the deepness of the retrofit.[18] Table 6 provides the estimation results with standard deviations in the diagonal and covariances in the lower part of the W matrix. Allowing for correlation results in a decrease in part of the variance of the residual in favor of an increase in the variance of the unobserved portion of the utility (Revelt and Train, 1998). This, in turn, produces greater coefficients in magnitude. The joint significance of the off-diagonal elements of the covariance matrix W was tested through a likelihood-ratio test (χ^2 distributed with degrees of freedom equal to the 104 off-diagonal elements).

$$L-R \quad test = 2(LLfinal - LLinitial) = 2*(-15513.17+15902.767) = 389.597. \quad (7)$$

Because $\chi^2(104)$= 154.314, we rejected the null hypothesis of coefficients being uncorrelated. The sign of the log odds and levels of significance are comparable to those contained in Table 3, column (3). As expected, the magnitude of the mean terms and standard deviations of the odd ratios increases.

The covariance matrix W helps understanding the extent to which heterogeneity was captured by the parameters in the model: the fact that several off-diagonal elements in the lower part of W are significantly different from 0 signals the presence of unobserved heterogeneity which might be explained through heuristics in the decisional process. Pearson's correlation coefficients ρ (between levels belonging to different attributes) were, therefore, computed from the W matrix [19] and ρs above 0.3 were reported in the upper part of the W matrix. It can be seen that attitudes towards air quality are correlated with noise reduction, aesthetics, and the "none" option whereas higher room temperature (A2.2) is positively correlated with reduction of noise from outside the building (A5.2).

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[18] By allowing correlation to take place among the randomly specified parameters (and therefore the alternatives), it is possible to capture unobserved effects that induce correlation within and between alternatives of a choice card (Hensher et al., 2005).

[19] $\rho_{xy} = \frac{cov_{xy}}{\sigma_x * \sigma_y}$.

Table 6: θ, W, bs, and Pearson's coefficients from Model (6)

	A3.1	A3.3	A1.2	A1.3	A2.2	A4.1	A4.3	A5.1	A5.2	A5.4	A6.1	A6.2	A6.3	A6.4	A7.1	A7.3	None
Mean	.495***	-.538***	.849***	-1.184***	.130***	.389***	-.353***	.255***	.096***	-.447***	.309***	.214***	.043	-.420***	-.667***	.680***	-.629***
	(.027)	(.028)	(.036)	(.049)	(.018)	(.028)	(.030)	(.032)	(.032)	(.038)	(.039)	(.037)	(.039)	(.045)	(.036)	(.033)	(.085)
		A1.2	**.765*****						.486	-.374		.428		.354			.368
		A1.3	-.762***	**1.029*****				-.347	-.507	.314		-.388		.377			-.438
		A2.2	-.005	.006	**.334*****				.392								
		A4.1	.118***	-.094**	-.020	**.519*****		.368									.362
		A4.3	-.098***	.109**	.034	-.197***	**.546*****										
		A5.1	.103***	-.099*	.012	.053	-.023	**.277*****				.692	-.411				
		A5.2	.099**	-.139***	.035	-.021	.005	.049**	**.266*****			.354	-.449	-.502			
		A5.4	-.188***	.213***	-.039	-.059	.058	-.156***	-.138***	**.658*****							
		A6.1	.074	-.113*	-.006	.004	-.012	.045	.021	-.047	**.631*****						
		A6.2	.104**	-.127**	-.003	.044	.003	.061**	.030	-.105*	.125**	**.317*****					.396
		A6.3	-.007	-.027	-.027	.015	-.036	-.059*	-.062*	.052	-.060	-.025	**.518*****				
		A6.4	.208***	.298***	.037	-.036	.023	-.052	-.009	.121*	-.320***	-.156***	-.155**	**.769*****			
		A7.1	-.041	.146***	.026	-.063*	-.014	.018	-.039	.054	-.028	.013	-.025	.073	**.795*****		
		A7.3	.057	-.201***	.028	.048	.001	-.021	.056	-.055	.028	.028	.013	-.077	-.590***	**.824*****	
		None	1.125***	-1.800***	.007	.752***	-.626***	.267*	.210	-.555***	.390*	.503**	.227	-.818***	-.390**	.562***	**3.998*****
N° of Obs.:	56,898																
N° of Resp.	3,161																
LR χ^2:	7,484.62																
d.f.	137																
p:	0.000																
AIC:	31,300																
BIC:	32,526																
R^2:	0.194																

*** = p<0.01; ** = p<0.05; * = p<0.1; Standard errors for W matrix not reported but available from the authors upon request

Additionally, high control over the system (A4.1) is positively correlated with reduction of noise from the inside and outside (A5.1) as well as with NONE. Finally, noise reduction and aesthetics of the dwelling are also correlated. It is worth noticing that with an increase in complexity in models (5) and (3) with correlation, the two model selection criteria, i.e. AIC and BIC, diverge in signaling the preferred model. This is due to the fact that while BIC assumes that the true model is among those estimated, the AIC considers all models as attempts to describe a highly complex and unknown reality. The reader should not worry about those differences.

With the purpose to judge upon the quality of our data, we also included in the survey a section on clarity of the attributes and attribute non-attendance. Indeed 95.25% of the respondents found attributes of the DCE clear. Among those who experienced difficulties in understanding the task, we found that the monetary attribute was most often unclear whereas room temperature was mentioned only in very few cases. Control over the system, noise reduction, and aesthetic of the dwelling were declared to be the most often ignored aspects, with shares in 39.32, 39.23 and 38.58% of the cases, respectively. On the other extreme, the potential energy savings were reported to be ignored only by 31.92% of the respondents. Two identical choice tasks whose attribute levels do not vary across them were introduced to check for the consistency of respondents' preferences throughout the exercise. It turned out that respondents were consistent in 72.07% of the cases, which seems acceptable in comparison to a probability of 43.56% of randomly choosing the same alternative across the two holdouts. Another sign of the fact that the DCE was taken into serious consideration by respondents is provided by the small share of "straightliners" within the sample (0.82%), i.e. respondents who always chose the same alternative across the 8 choice cards.

3.4 Comfort preferences and direct rebound effect

It is well known that the implementation of energy-saving measures in residential buildings (e.g. wall insulation) leads to higher indoor temperatures *ceteris paribus.* Coupled with the installation of a more energy-efficient heating system, the temptation to enjoy warmer dwelling might be real especially among fuel-poor households (see e.g. Milne and Boardman, 2000). Individuals' habits (Maréchal, 2010) and expectations about thermal comfort in the aftermath of retrofitting affect the final demand for energy services. When occupants come to expect higher room temperatures as a result of the retrofit measures – i.e. expectations about thermal comfort are changed – or when the retrofit is conducted with the purpose of achieving higher room temperatures, we witness an increase in the demand for energy services known as "direct rebound effect" (Sorrell and Dimitropoulos, 2008). More in particular, we label this rebound effect as "technical" because it derives from the acceptance of a physically-induced increase in indoor temperature of a dwelling that, cet.par., inevitably occurs whenever an energy-saving measure is implemented (Galvin, 2015). To the extent that the achievement of indoor comfort affects the household final demand for energy, comfort can be used as a proxy for energy services. The most recent works on this topic have gone a long way in explaining the different components of rebound effects from retrofit in buildings and in disentangling its multiple sources. Hamilton et al. (2011), for instance, linked intended and unintended changes in comfort to the presence of this phenomenon. Besides the price effect (or income effect, in its most traditional sense), Galvin (2015) identifies several other possible sources of rebound effect. Most interestingly, the author stresses the presence of a physical effect most often neglected in rebound studies, i.e. the pure "comfort-taking effect" which arises whenever the dwelling is naturally warmer because the retrofit maintains it in such thermal conditions. Although there are many studies eliciting preferences for retrofit measures or attempting to measure rebound effects from heating in residential buildings (see e.g. Haas and Biermayr, 2000; Madlener and Hauertmann, 2011; Chitnis et al., 2014; Aydin et al., 2015), we find a gap in the empirical investigation of the relationship between comfort expectations and rebound effects.

In this section we aim at detecting the presence of direct technical rebound effects (as defined above) resulting from the implementation of comprehensive energy-saving measures in residential buildings. We seek to achieve this through developing a better understanding of *ex-ante* thermal comfort expectations in retrofit decisions. The majority of quantitative studies usually relies on revealed preferences or measurement data to quantify the rebound effect; while the latter type of data succeeds in its stated aim, it fails to fully explain the reasons why a certain demand for energy services is observed. For instance, if an increase in room temperature after retrofit is registered, one cannot know the occupier's intentions behind such an increase. On the other hand, traditional survey methodologies rely on the ability of the respondents to explain why (or why not) a certain refurbishment was chosen over another. It is often hard, however, to perfectly recall all the motives behind a retrofit decision that took place years before the time of the interview, given the long-run nature of this investment decision.

Insofar as the sign of TEMP_warm coefficient is positive and significant we can argue that respondents attach a positive value to higher temperatures after the retrofit in comparison to a solution in which the temperature remains the same, which brings evidence for the presence of a technical rebound effect. With the aim to further investigate rebound effect, we interacted temperature with technical energy savings and costs (see interaction terms at the bottom of Table 5). The non-significant term TEMP_warm*SAV_80 indicates that thermal comfort preferences are irrespective of any consideration about the potential savings in energy costs brought by the implementation of comprehensive retrofit measures meaning that there is no evidence for preference heterogeneity around the mean of the parameters TEMP_warm and SAV_80. TEMP_warm*SAV_20 indicates that low technical energy savings become less acceptable when temperature gets warmer, a finding that does not support hypothesis 2. In order to be sure that thermal comfort preferences are not affected by economic considerations of all kinds (and that retrofit costs was not used as a proxy for energy cost savings), we also interacted higher room temperature with COST_high and COST_low. Once again, the interaction terms are not significant.

4 Discussion and conclusion

The aim of this study was to better understand the role of environmental concern and comfort expectations in the decision to retrofit and, consequently, also on the final demand for energy services. Analysis of the extensive stated-preference data collected from a sample of the German households delivered significant coefficients with the expected sign, the only exception being those on improvements in the external appearance of the buildings. Results also confirm the presence of unobserved heterogeneity that could be partially explained by the usage of socio-demographics such as gender, age, income, environmental concern, and tenancy status. Gender, and environmental concern in particular, explain heterogeneity in preferences the most. However, none of the socio-demographics could produce significant coefficient estimates when interacted with the variable for increase in temperature; thus, the heterogeneity for thermal comfort remains unexplained.

Insofar as respondents show ex-ante expectations for higher room temperatures or passively accept the higher thermal comfort naturally brought by a change in the physics of the building, we can conclude that the sample brings evidence in favor of the presence of a technical rebound effect. The study thus contributes to the debate on rebound effects by pointing out that comfort matters not just because it explains the decision to retrofit, but also since it determines how effective the measure will be in reducing CO_2 emissions and achieving the often ambitious energy and climate policy targets set by governments. The relatively low share of respondents preferring higher room temperature after the retrofit should be taken, moreover, as a lower limit; in fact, this share would be downward biased if respondents perceived as “bad” choosing alternatives with higher temperatures. Such result could also be explained by Germany not being a fuel-poor country; in fact, with its basic social security and assistance system, the German state is tackling fuel poverty by providing the poorest with a monetary subsidy for the full payment of their electricity bills. Respondents from countries notoriously suffering from fuel poverty, like the UK, are therefore expected to show both higher preferences for thermal comfort as well as attach higher importance to this aspect of energy-efficient renovations. Furthermore, higher room temperature was the least important attribute, a finding that contradicts a whole literature that sees in improvements of thermal comfort one of the major reasons for energy retrofitting. Based on the analyses conducted within our sample, we argue that indoor comfort is more about air quality, and potential savings on energy bills than aesthetics and room temperature. Such a result could be also explained by respondents' belief that air quality has a bigger impact on health than room temperature does.

In a scenario in which the demand for energy services, i.e. room temperature, is expected to rise as a mere consequence of a change in the physics of the building, the potential energy savings are still fully realized. This might lead the policymaker to derive positive conclusions, especially in the light of our findings. The questions left open are, however, twofold: first, it is not clear whether even higher energy savings could be achieved if expectations around thermal comfort stayed the same; and, second, it is also unknown whether those who keep their attitude towards comfort unchanged but find themselves in a warmer environment eventually adjust to the new comfort situation by adequately changing their heating habits, or whether they rather develop less environmentally-friendly behaviors, e.g. to ventilate for longer periods and thus leading to a "behavioral" rebound effect. To conclude, we believe that policymakers should take into consideration the technical component of the rebound effect when benchmarking policies targeted at improvements in the energy efficiency of buildings. Indeed, this aspect of the rebound effect is less counter–intuitive and as such more predictable than other behavioral components of the rebound effect.

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