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Using information provision and interactive risk maps to motivate testing for radon

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Abstract

Radon exposure in homes is a leading cause of lung cancer, but the rate at which householders test for it is low. In a pre-registered experiment with a nationally representative sample of adults (N = 1,700), we used psychological theory to design interventions to increase perceived risk from radon and motivate testing. Results show that providing information about radon increased belief that exposure would lead to negative consequences. Interactive maps that depict the geographical distribution of radon risk increased perceived likelihood of exposure, general worry and willingness to test for it, but the effects depend on the map's attributes. Maps that communicate risk using numeric frequencies of the number of homes in an area likely to be affected by radon (e.g., 1 in 5 homes) were more effective than ones that used simple statements (e.g., your home is at high risk). Adding an intermediate "moderate" risk category increased perceived risk compared to a binary high/low classification system among those in the moderate risk area, without altering perceptions of those at high risk. Other map features (colour and search functionality) had little impact. The best performing map led to 72% more people being willing to test for radon, compared to the map in use by the national Environmental Protection Agency at the time of the study. The results have implications for theories of risk perception and show the potential for techniques from psychological science to help mitigate a real-world environmental risk.

Keywords: radon; risk perception; risk communication; maps; information provision; public policy

JEL: C91; D90; D91; I12; Q53

Word Count: 6,040

Highlights

- Information about radon increases belief in negative effects but not perceived likelihood of exposure
- Numeric frequencies of risk increase willingness to test for radon
- Highlighting intermediate risk levels does not diminish perceived risk among higher risk levels
- No evidence that hazard map colour or search functionality affect risk perceptions
- 72% increase in number of people willing to test with best risk map compared to control map

1. Introduction

Radon is a major environmental risk. Exposure typically occurs in homes and constitutes one of the leading causes of lung cancer, second only to smoking (Gaskin, Coyle, Whyte & Krewski, 2018; Zeeb & Shannoun, 2009). Where deposits of uranium and toran lie in soil and rock below homes, radon is emitted and can seep through any cracks in foundations. As an invisible, odorless gas, radon can only be detected via a specific test, yet the rate at which householders undertake tests is notoriously low (e.g., Cholowsky et al., 2021; Poortinga, Bronstering & Lannon, 2011; Stanifer, Rayens, Wiggins & Hahn, 2021).

Working collaboratively with environmental policymakers in Ireland, we carried out a study that tested techniques derived from the existing literatures on environmental risk perceptions and risk perceptions more generally. Our specific aim was to increase householders' propensity to test for radon, by generating experimental evidence of superior communication strategies for the relevant policymakers. Our broad aim was to use the opportunity offered by the policy challenge to test multiple techniques from the psychological literature for effectiveness in mitigating a real-world environmental risk.

The online study involved a large, nationally representative sample of 1,700 adults. It was commissioned by the Environmental Protection Agency (EPA) in Ireland and informed by discussions with relevant officers. In line with best scientific practice, our research questions, the experimental design and data analysis plan were pre-registered (https://osf.io/rc935/).

1.1 Approach

We sought to experimentally test two approaches to that could be enacted by the regulator: providing the public with general information about radon and enabling individuals to find their personalised risk estimate. The logic for these approaches is straightforward. (1) People cannot perceive risk from a hazard they are unaware of and (2) the more accurately they can estimate their susceptibility to the risk, the better they can make decisions about mitigation. The following sections outline the rationale underlying our test of information provision and our four tests of ways to present personalised risk: using frequencies of risk versus categories, the risk scale used, use of colour and interactivity.

1.1.1 Knowledge

Radon testing kits are relatively inexpensive, [1] but even when offered freely uptake is low. Perhaps the most straightforward explanation for low testing rates is lack of knowledge. In the US, the public know little about radon (Bostrom, Fischhoff & Granger Morgan, 1992; Vogeltanz-Holm & Schwartz, 2018). While most people report having heard of it, radon is often confused with carbon monoxide; many erroneously believe that it causes immediately perceptible symptoms such as headaches. However, simply demonstrating gaps in knowledge does not necessarily imply that improving knowledge will improve risk mitigation behaviors (Rosenthal, 2011). People are often motivated to downplay or ignore information that could lead to conclusions they dislike (e.g., those that require effort - "I need to order a test for radon"; Kahan, Peters, Dawson & Slovic, 2017; Kelly & Sharot, 2021; Kunda, 1990). Hence, we tested whether providing more information about radon influences perceived risk.

1.1.2 Personalising risk: hazard maps

Perceived risk has strong links to whether people mitigate environmental threats, including radon (Bubeck, Botzen & Aerts, 2012; Champ, Donovan & Barth, 2013; Hazar, Karbakhsh,

[1] Radon testing kits range from $10 to $30 in the US and are approximately €40 in Ireland. Note that initiatives run by the funder for this research have shown very low testing rates even when tests are offered freely.

Yunesian, Nedjat & Naddafi, 2014; Sjoberg, 1989). However, risk perception is influenced by more than knowledge; subtle differences in how risks are communicated to the public can have large effects (Fischhoff, 1995; Lofstedt, 2019). Individualised or personalised risk estimates can motivate mitigation (e.g., Edwards et al., 2013). One way to personalise communication about environmental risks is through hazard maps, which depict the geographic distribution of the threat and allow householders to determine the specific level of risk where they live (Cao, Boruff & McNeill, 2016; Severtson, 2013). However, map features can affect perceptions of risk, meaning that decisions need to be made about how such maps are designed (e.g., Severtson & Vatovec, 2012; Thompson, Lindsay & Leonard, 2017).

1.1.3 Frequencies versus categories

One such decision concerns how different levels of risk are described. Risk communication research shows that numeric frequencies (e.g., "1 in 5 homes in this area is likely to have high radon levels") boost comprehension (Visschers, Meertens, Passchier & De Vries, 2009). However, underestimation of the likelihood of experiencing negative events is a prevalent cognitive bias ("optimism bias") and has been observed when people consider their susceptibility to radon compared to others living in their area (Sharot, 2011; Weinstein, 1984; Weinstein, Klotz & Sandman, 1988). Hence, one possibility is that too many householders will assume they are among the majority unaffected by radon, even if they live a high-risk area. As an alternative, many applied behavioural science frameworks emphasise the importance of simplicity for encouraging compliance with recommendations (e.g., Hansen, 2019). One reasonable hypothesis is that informing householders that their home is at "high risk" of radon would be more effective at motivating them to test. We therefore tested whether imparting numeric frequencies or simple categorisations altered willingness to test for radon.

1.1.4 Risk scales

Relatedly, the number of levels of risk communicated may have important implications for how risk is evaluated. Many environmental hazards can be communicated on continuous scales, for example parts per billion of a contaminant in water or Becquerels per cubed metre of radon. Cut-offs on the scales can then be used to identify locations at high risk (e.g. radon concentrations greater than 200 Bq/m^3). However, these markers often result in biases where positions just below a risk cut-off are perceived as higher risk than positions just above (Severtson & Henriques, 2009). Simplifying continuous scales into discrete categorisations can improve the accuracy of risk estimations (Thompson, Lindsay & Gaillard, 2015). However, we could find no empirical research that investigated the optimum number of risk categories. As a first step, we sought to test whether communicating risk using a binary categorisation (high vs. lower[2] risk) altered perceptions compared to a tertiary one (high, moderate, lower). Theory implies that the number of levels may be important. The Relative Judgement Model describes how people make decisions not based on the absolute value of an attribute but on how it compares to immediately available stimuli (Stewart, Gordon & Chater, 2005). One possibility is that a binary scale increases the salience of high-risk categories, because the contrast against the next level is greater than the contrast between multiple categories. However, the number of levels of an attribute can influence the weight given to that attribute in decisions, with attributes possessing more levels assigned greater importance (Wittink, Krishnamurthi & Reibstein, 1989). From a more practical perspective, since in our specific case, the categorization of what constitutes a "high-risk" from radon is fixed by policy, the intermediate option also reduces the proportion of householders informed they are

[2] Our lowest risk category was labelled as "lower" risk rather than "low" risk, as high levels of radon are possible anywhere in Ireland; householders everywhere would benefit from testing.

at lower risk. Consequently, we tested whether perceived risk and willingness to test were greater when there were two risk categories or three.

1.1.5 Risk and colour

Beyond decisions over how to communicate the level of risk, pre-attentive map properties, such as colour and region bordering, can influence information processing (Ash, Schumann & Bowser, 2014; Cleveland & McGill, 1984). Yellow-red colour schemes are commonly employed to signal risk, as most people in Western societies pre-consciously associate yellow with caution and red with danger (Meier, D'Agostino, Elliot, Maier & Wilkowski, 2012; Pravossoudovitch, Cury, Young & Elliot, 2014). However, novel colour schemes have the potential to increase salience (Ernst, Becker & Horstmann, 2020). Hence we also tested whether a yellow-black colour scheme, universally used to warn of radiation risk, would influence perceived risk more or less than a yellow-red scheme.

1.1.6 Interactivity

Location indicators help map users comprehend danger associated with risks (Klockow, Peppler & McPherson, 2014). The ability to search for one's postcode and inclusion of location markers such as county boundaries make maps easier to use than not having such features, but how ease of use relates to information processing is not straightforward. Literature on processing fluency suggests greater ease could lead to users trusting the information more (e.g. Reber & Schwarz, 1999), however the additional effort invested into identifying one's own risk level without this search functionality could lead to better engagement of deliberative cognitive systems, improving memory and increasing the value assigned to the information (e.g. Kruger, Wirtz, van Boven & Altermatt, 2004; Norton, Mochon & Ariely, 2012). Hence, our final question was whether search functionality influences perceived radon risk and willingness to test.

1.2 Policy impact

From a policy perspective, the aim was to establish ways to influence perceived risk and willingness to test for radon. We take risk perception to be comprised of distinct psychological dimensions: a general affective response (i.e. worry), perceived likelihood of being affected by the risk and expected severity of outcomes if affected (Ferrer et al., 2016; Walpole & Wilson, 2021; Wilson, Zwickle & Walpole, 2019). We assessed willingness to test for radon using a straightforward rating scale and a willingness-to-pay measure, to indicate the value users assign to determining the level of risk in their home with greater certainty (Breidert, Hahsler & Reutterer, 2006). For both measures, we were interested in whether new maps informed by the psychological literature would outperform the one that was already in use in the policy context and, if so, by how much. This map was hosted on the EPA's website at the time of the study.[3]

[3] Note that we pre-registered inclusion of the pre-existing map as a control in the study but did not state this research question explicitly.

2. Method

The experiment was programmed in Gorilla Experiment Builder (Anwyl-Irvine, Massonnié, Flitton, Kirkham & Evershed, 2020) and proceeded over multiple stages. First, we assessed knowledge of radon and this stage included the knowledge intervention and a first measure of perceived risk. Next, participants used a risk map and we measured perceived risk again, along with evaluations of the map and their willingness to test for radon. The study concluded with socio-demographic questions. The study was conducted in line with institutional ethics policy.

2.1 Participants

Each of the four map features we tested (the risk statement, the number of risk scales, colour, search functionality) had two levels and their factorial combination resulted in 16 test maps. We aimed for 100 responses for each, with an additional 100 participants using the control map that was in use by the EPA at the time of the study. The sample consisted of 1,700 adults recruited by a market research agency to be broadly nationally representative.[4] Hence this sample size allows for approx. 800 participants per level of each feature. Randomisation resulted in cell sizes for maps that varied between 83 and 111, and a minimum sample size of 757 for the levels of each manipulated feature. Table 1 displays the socio-demographic characteristics of the sample and shows they approximate the latest Census estimates well. There is a slight oversampling of those with degrees, those in the labour force and those who report living in an urban area. Importantly, results from statistical models we report in the following sections include socio-demographic controls, implying that any findings are not sensitive to these characteristics.

[4] RED-C Research & Marketing (www.redcresearch.ie)

Table 1.
Sample Socio-Demographics

		n	%	Census %
Gender	Men	858	50.5	49.6
	Women	834	49.1	50.4
	Other/Prefer not to say	8	0.5	
Age	18-39 years	633	37.2	38.3
	40-59 years	631	37.1	36.3
	60+ years	436	25.6	25.4
Education	Degree or above	793	46.7	42.0
	Below degree	907	53.4	58.0
Employment	In Labour Force	1149	67.6	62.3
	(of which, Employed)	1070	93.1	(92.1)
	(of which, Unemployed)	79	6.9	(7.9)
	Not in Labour Force	551	32.4	37.7
*Living Area**	Urban	1105	65.0	60.8
	Rural	595	35.0	39.1

**Note*. Living area was assessed via a self-report question.

Participants reported their postcodes before using the risk maps, which we compared against Geographic Information Systems (GIS) data to identify the level of radon risk in each participants area. This showed that that the sample was approximately evenly split across risk areas: 34.7% of respondents live in a lower-risk area (where 5% of houses are predicted to have levels of radon above the reference level), 33.5% live in a moderate-risk area (10% of houses likely affected) and 31.8% live in a high-risk area (at least 20% of houses likely affected).

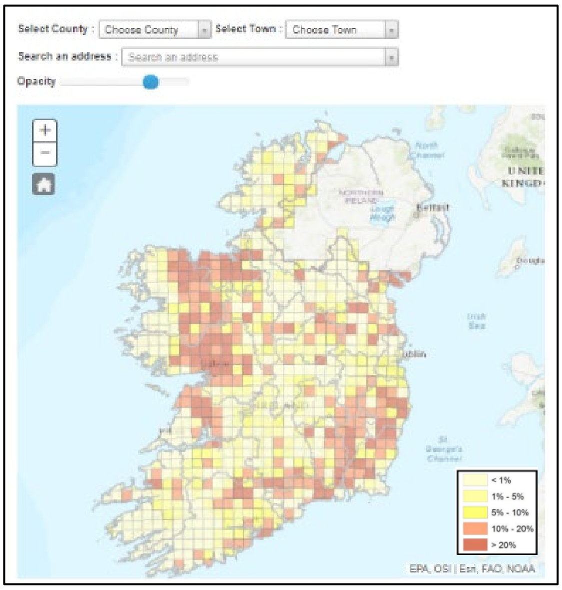
2.2 Materials, Design and Procedure

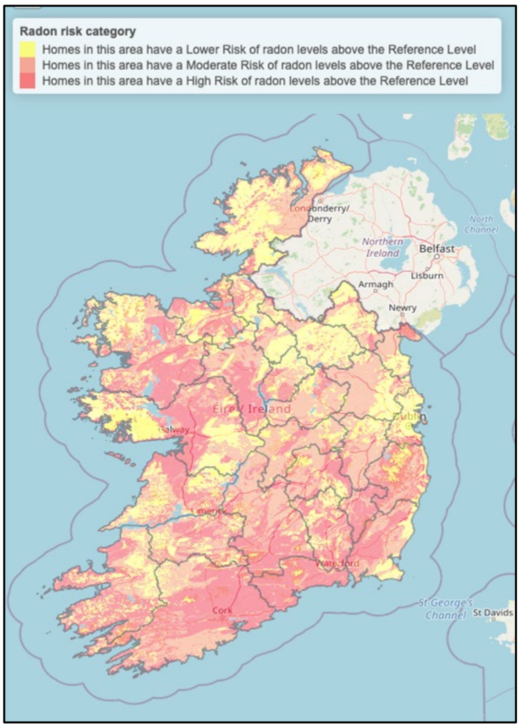
Participants first completed survey measures of their familiarity with and knowledge of radon. The knowledge questions probed basic factual knowledge of radon (e.g. it is a gas, exposure causes lung cancer), understanding of testing and remediation. The full set of questions and how participants responded are reported in the Online Supplementary Material (https://osf.io/rc935/). Half the participants were randomised to see the correct answers to the knowledge questions after making their guess. This approach allowed us to assess knowledge in the full sample while experimentally testing the effect of information provision on later responses (as in Timmons & Lunn, 2022). Participants then recorded their perception of radon as a risk on three questions, following recommendations by Wilson et al. (2019):

> When you think about radon for a moment, to what extent do you feel anxious or worried?
>
> How likely do you think it is that your home has high levels of radon?
>
> If your home were to have high levels of radon, how likely do you think it is that it would have a severe effect on you personally or on someone in your household?

All responses were recorded on 7-point rating scales from 1 “Not at all” to 7 “Extremely”. We also recorded whether participants knew the level of radon risk in their area, whether they had previously tested for radon and any mitigation measures in their home.

For the main experimental task, participants were randomly assigned to one of the 16 experimental maps or a control map (the pre-existing map in use by the EPA; Figure 1). The maps varied by the risk description (numeric frequency or simple categorisation, with frequencies and guides for high, moderate and lower risk provided by the EPA), the number of risk categories (two or three), the colour scheme (yellow-red or yellow-black) and interactivity (postcode search with clear county boundaries and extensive zoom functionality or limited zoom with no search function or county boundaries). Hence the design was a 2 x 2 x 2 x 2 between-groups design. Figure 1 shows two example maps that differ on each factor. We pre-registered our primary interest in the main effects of the risk description, number of categories and interactivity but we include colour throughout our analyses here for completeness. Participants were informed they could use the map for as long as they wished. When they clicked a button to indicate they were finished using the map, they were given a code to use on return to the survey. This code was necessary to proceed with the survey. We recorded length of time spent using the map and, where applicable, whether participants searched or used the zoom functionality.





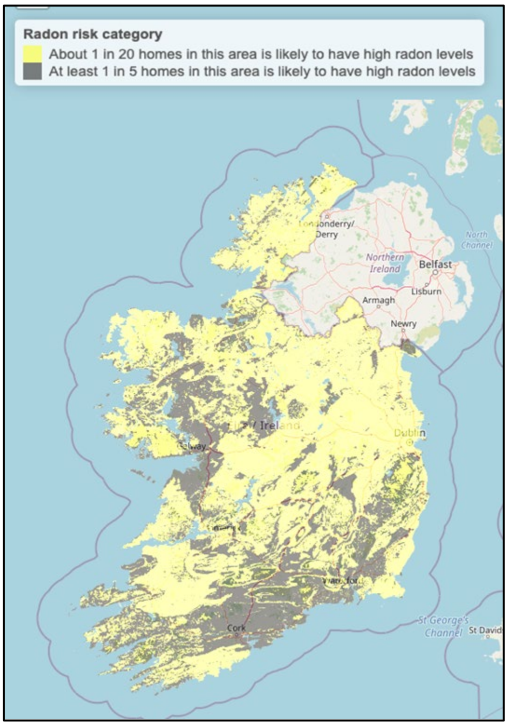


Figure 1. Pre-existing map (top) and example test maps (bottom). The left map shows a three-category map with search functionality, the yellow-to-red colour scheme and a legend that uses the simple statement. The right map shows a two-category map with limited search, the yellow-to-black colour scheme and a legend that uses the frequency statement.

Upon returning to the survey, participants were asked about the radon risk level in their area. They were then asked to evaluate the map, based on its ease of use, clarity, how memorable they found it and whether they'd recommend it to others with responses recorded on 7-point rating scales. Although we were interested in perceived risk and willingness to test for radon, these questions were ostensibly our primary questions of interest after participants had used to the map, adopting a similar approach used by Lunn et al. (2020). Participants were then asked about their perceived risk from radon using the same questions as before. Willingness to test for radon was measured using two questions. One asked how likely they would be to test for radon (on a scale from 1 'not at all' to 7 'extremely'). We also used an open-text willingness-to-pay question that asked for the most they would be willing to pay in order to learn for certain the level of radon in their home. The study concluded with exploratory questions about radon remediation, whether they would like more information about radon and socio-demographic background questions.

3. Results

In this section, we first show the effect of the knowledge intervention, followed by how the maps were used, the main analysis of the effects of map features on perceived risk, and finally a comparison of the best performing test map against the pre-existing control one. (For details on knowledge survey results and analyses of other variables including socio-demographic differences, see the Online Supplementary Materials.)

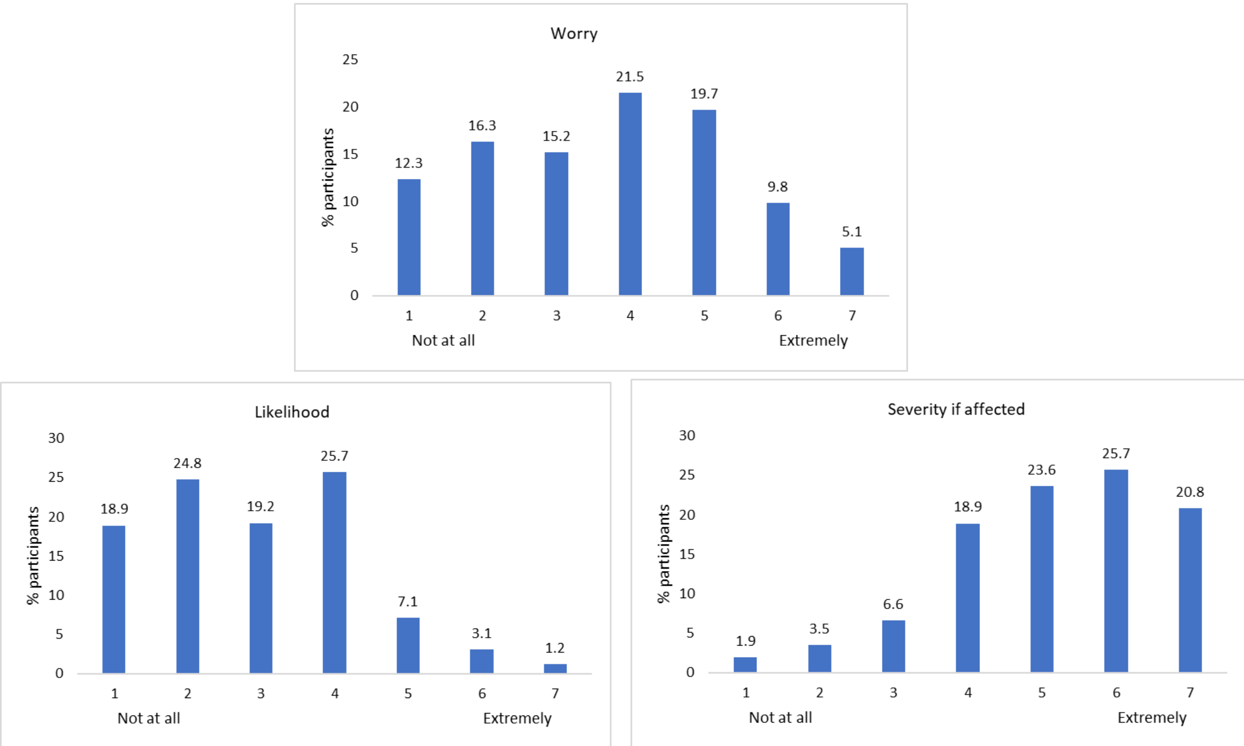


Figure 2. Distribution of responses to questions about perceived risk before using the radon risk map.

3.1 Knowledge Intervention

Figure 2 shows the distribution of responses to questions about perceived risk before using the map. While most believed they or someone in their home would be badly affected by radon ("severity"; $M = 5.2$, $SD = 1.5$), few believed their home was likely to be affected by radon ("likelihood"; $M = 2.9$, $SD = 1.4$). In general, worry about radon is close to the mid-point of the scale ("worry"; $M = 3.7$, $SD = 1.7$). Correlations between the three measures are statistically significant (*p*s < .001), although worry is correlated more strongly with likelihood (*r* = .55) and severity (*r* = .39) than they are with each other (*r* = .19).

Participants who saw the answers to the knowledge questions perceived greater risk from radon on two of the three measures than those who didn't. Ordinal logistic regression models show that they reported being more worried about radon (*M* = 3.8, *SD* = 1.7 vs. *M* = 3.6, *SD* = 1.7, respectively) and judged that the effects of radon would be worse for them or someone in their household (*M* = 5.3, *SD* = 1.4 vs. *M* = 5.1, *SD* = 1.5, respectively), even controlling for how many questions they answered correctly and socio-demographics (Table 2). They were not more likely to believe their home would be affected (*M* = 3.0, *SD* = 1.4 vs. *M* = 2.9, *SD* = 1.4, respectively).

Table 2.

Ordinal Logistic Regression Models Predicting Perceived Risk by Knowledge Intervention

	Worry		Likelihood		Severity	
	Coefficient [95% CI]	*p*-value	Coefficient [95% CI]	*p-value*	Coefficient [95% CI]	*p*-value
Saw Answers *(Ref: No Answers)*	0.23** [0.06, 0.40]	.007	0.13 [-0.04, 0.05]	.137	0.29** [0.12, 0.47]	.001
Quiz Score	0.05 [-0.03, 0.13]	.187	-0.02 [-0.11, 0.05]	.485	0.21*** [0.13, 0.29]	< .001
Socio-demographic Controls	Yes		Yes		Yes	
Participants	1,700		1,700		1,700	

*$p < .05$; **$p < .01$; ***$p < .001$

3.2 Map Use and Evaluation

The distribution of time spent on the map is heavily skewed, as expected from response time data. The median time spent was 82.8s, although this varied across maps. An OLS regression predicting time spent[5] shows that participants who saw a map that had greater search functionality spent longer using it than those who saw one without such functionality (*Mdn* = 87.5s, *SD* = 121.7 vs. *Mdn* = 80.8s, *SD* = 110.2, respectively). No other features were significant predictors (Table 3).

On maps that had search functionality, 96.1% of participants successfully searched for a postcode. A logistic regression model of whether the participant searched for their home shows no differences across different map designs (Table 3).

Participants evaluated the map they used on four questions (about ease of use, clarity, memorability and likelihood of recommending to others). Responses are highly correlated (all rs > .64, ps < .001) so we created an overall evaluation index by averaging responses to the four questions. This evaluation index is highly positively skewed, with an average response of 5.5 out of 7 (*SD* = 1.43), indicating that participants judged the maps positively overall.

[5] We model a $\log_{10}$-transformed variable of time spent on the map to normalise it, but report the raw figures in seconds for clarity.

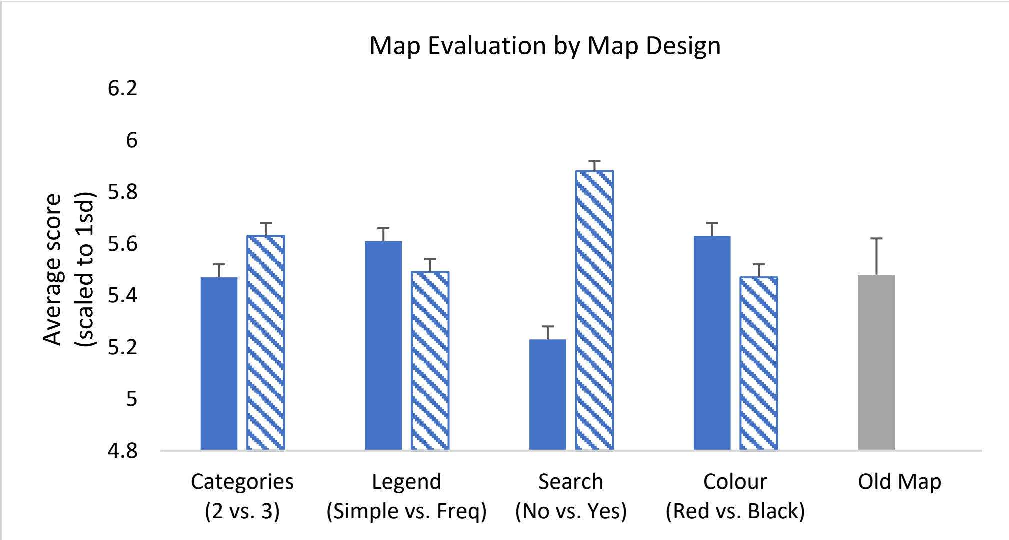


Figure 3. Average scores on the evaluation index by map features. Error bars are the standard error of the mean. The y-axis is scaled to one standard deviation to give an indication of effect sizes.

To facilitate modelling while meeting assumptions for proportional odds, we categorised the evaluation index into three groups (low, < 5 out of 7; moderate, 5 or 6 out of 7 and high, 7 out of 7). An ordered logistic regression model to test the influence of map features on evaluation shows that maps with extensive search functionality were evaluated more positively than maps with limited searching (Table 3; Figure 3). Maps with three categories were also evaluated more positively than maps with two, but the effect was weaker. Communicating risk through numeric frequencies rather than simple statements led to marginally lower evaluations and there was no evidence for an effect of colour.

Table 3.

Regression Models Predicting Willingness to Test and Willingness to Pay

	Time Spent		Search Use		Evaluation	
	Coefficient [95% CI]	*p*-value	Coefficient [95% CI]	*p*-value	Coefficient [95% CI]	*p*-value
Frequency Legend (*Ref: Simple*)	0.03 [-0.04, 0.10]	.451	0.07 [-0.26, 0.39]	.689	-0.17 [-0.36, 0.02]	.080
Three Categories *(Ref: Two)*	-0.02 [-0.09, 0.05]	.540	-0.07 [-0.39, 0.25]	.668	.254* [0.06, 0.45]	.011
Colour: Black (*Ref*: Red)	0.06 [-0.01, 0.13]	.118	0.14 [-0.18, 0.46]	.392	-0.13 [-0.32, 0.06]	.194
Search Functionality (*Ref*: Limited)	0.12** [0.05, 0.19]	.001			0.89*** [0.69, 1.10]	< .001
Socio-Demographic Controls	Yes		Yes		Yes	
Participants	1,589		890		1,589	

*$p < .05$; **$p < .01$; ***$p < .001$

3.3 Perceived Risk

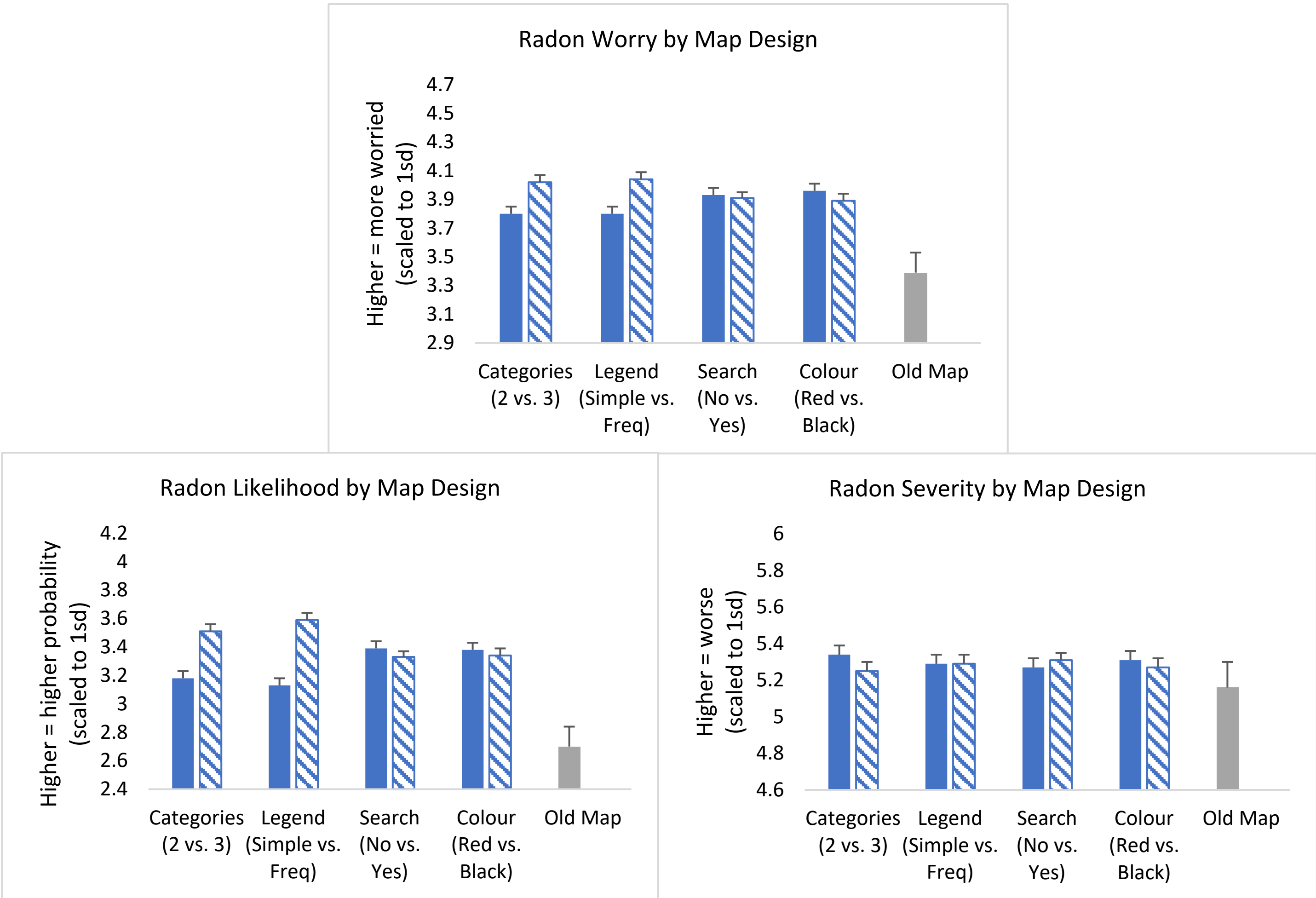


Figure 4. Average risk perception ratings after using the radon risk map by map features. Error bars are standard errors. Y-axes are scaled to one standard deviation to indicate effect sizes.

We ran ordinal logistic regression models to determine how features of the map influenced the three dimensions of perceived risk after using the map, controlling for socio-demographic characteristics and whether the participant saw the quiz answers before using the map (Table 4).[6] Participants reported greater worry after using maps with legends that communicated risk as a numeric frequency rather than a simple statement and after maps with three categories compared to ones with two (Figure 4). There are no differences based on colour or search functionality. The pattern is similar for participants' belief that their home could be affected by radon, but the effects are stronger (Figure 4). Turning to perceived severity if their home were affected by radon, there are no significant differences between the test maps, although the effect of the knowledge intervention is still evident.

Table 4.

Ordinal Logistic Regression Models Predicting Perceived Risk After Using Test Maps.

	Worry		Likelihood		Severity	
	Coefficient [95% CI]	*p*-value	Coefficient [95% CI]	*p-value*	Coefficient [95% CI]	*p*-value
Frequency Legend (*Ref: Simple*)	0.26*** [0.08, 0.43]	<.001	0.52*** [0.34, 0.69]	<.001	-0.05 [-0.23, 0.12]	.558
Three Categories *(Ref: Two)*	0.19* [0.02, 0.37]	.030	0.31** [0.13, 0.48]	.001	-0.14 [-0.32, 0.03]	.111
Colour: Black (*Ref*: Red)	-0.08 [-0.25, 0.10]	.379	-0.06 [-0.24, 0.11]	.481	-0.08 [-0.26, 0.09]	.347
Search Functionality (*Ref*: *Limited*)	0.01 [-0.17, 0.18]	.939	-0.06 [-0.24, 0.11]	.486	0.04 [-0.13, 0.22]	.642
Saw Answers *(Ref: No Answers)*	0.11 [-0.06, 0.28]	.211	0.08 [-0.10, 0.25]	.390	0.19* [0.01, 0.36]	.036
Socio-demographic Controls	Yes		Yes		Yes	
Participants	1,589		1,589		1,589	

**p* < .05; ***p* < .01; ****p* < .001

[6] Closely similar results are observed if the difference between risk ratings before and after the map are modelled rather than raw responses.

To test for differences in perceived risk by the level of risk in the respondent's area, we generated a variable for whether the participant learned that they live in a high-risk area or not (i.e., pooling the lower and moderate groups to allow comparability between the groups that saw different numbers of categories). We re-ran the above analyses interacting this variable with the different map features (Table 5). The results show that presenting three categories of risk increased worry in all risk areas. However, the positive effect of three risk categories on perceived likelihood of having radon is marginally weaker for those in high-risk areas than lower-risk areas. In other words, the effect of the number of categories on perceived likelihood is driven by participants in moderate-risk areas, who otherwise would have been informed they live in a lower-risk area. Importantly, the addition of the moderate-risk category did not diminish perceived risk among those in high-risk areas. The effect of the frequency statement, however, is significant for participants in all risk areas, meaning that this type of legend can be applied to maps without diminishing perceived likelihood even among those who learn that they have a lower probability of high levels of radon (e.g., 1 in 20 houses).

Table 5.

Ordinal Logistic Regression Models Predicting Perceived Risk with Area-Level Interactions.

	Worry		Likelihood		Severity	
	Coefficient [95% CI]	*p*-value	Coefficient [95% CI]	*p-value*	Coefficient [95% CI]	*p*-value
High Risk (*Ref: Lower Risk*)	1.09*** [0.61, 1.56]	< .001	2.36*** [1.86, 2.85]	< .001	0.06 [-0.42, 0.53]	.810
Frequency Legend (*Ref: Simple*)	0.27* [0.06, 0.47]	.010	0.57*** [0.37, 0.78]	< .001	-0.15 [-0.36, 0.06]	.153
High Risk x Legend	-0.05 [-0.47, 0.36]	.812	-0.04 [-0.45, 0.37]	.841	0.35 [-0.05, 0.76]	. .083
Three Categories *(Ref: Two)*	0.23* [0.03, 0.44]	.023	0.42*** [0.22, 0.63]	< .001	-0.16 [-0.36, 0.05]	.136
High Risk x Category	-0.12 [-0.53, 0.28]	.554	-0.38 [-0.79, 0.03]	.069	0.04 [-0.36, 0.45]	.839
Colour: Black (*Ref*: Red)	-0.13 [-0.33, 0.07]	.200	-0.07 [-0.28, 0.13]	.478	-0.12 [-0.29, 0.09]	.255
High Risk x Colour	0.16 [-0.25, 0.57]	.442	0.03 [-0.38, 0.44]	.898	0.12 [-0.29, 0.52]	.566
Search Functionality (*Ref*: Limited)	-0.02 [-0.22, 0.18]	.836	-0.10 [-0.31, 0.10]	.322	0.05 [-0.15, 0.26]	.599
High Risk x Search	0.22 [-0.19, 0.62]	.296	0.31 [-0.10, 0.72]	.139	-0.04 [-0.44, 0.36]	.840
Answers *(Ref: No Answers)*	0.15 [-0.03, 0.32]	.101	0.13 [-0.04, 0.31]	.132	0.20* [0.02, 0.38]	.027
Socio-Demographic Controls	Yes		Yes		Yes	
Participants	1,589		1,589		1,589	

$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

3.4 Willingness to Test

Responses to the question about how likely they would be to test their home for radon are distributed approximately evenly along the 7-point scale from "not at all likely" to "extremely likely", with an average at the midpoint (Figure 5; $M = 4.1$, $SD = 1.99$). An ordered logistic regression for the test maps, controlling for seeing the quiz answers and the participants' area risk, shows that participants who saw maps with three categories were more willing to test than those who saw maps with two categories, although this effect weakens and is not statistically significant when socio-demographic controls are added to the model (Table 6). Participants who read the frequency-based legend rather than the simple statement were more willing to test (Figure 6). Participants who saw the highest risk category as black were less willing to test and there is no effect of search functionality. Those who learned that they live in a high-risk area were more willing to test than those who learned they lived in a moderate risk area, who in turn were more willing to test than those who learned they lived in a low risk area (M = 5.3 vs. 4.7 vs. 3.3).

Table 6. *Regression Models Predicting Willingness to Test and Willingness to Pay*

	Willingness to Test		Pay at Least €40	
	Coefficient [95% CI]	*p*-value	Coefficient [95% CI]	*p*-value
Frequency Legend (*Ref: Simple*)	0.23* [0.05, 0.41]	.010	0.40* [0.03, 0.78]	.036
Three Categories *(Ref: Two)*	0.13 [-0.05, 0.31]	.147	0.27 [-0.11, 0.65]	.163
Colour: Black (*Ref*: Red)	-0.18* [-0.36, -0.01]	.037	-0.26 [0.63, 0.11]	.167
Search Functionality (*Ref*: Limited)	0.07 [-0.11, 0.24]	.461	0.14 [-0.23, 0.51]	.447
Answers *(Ref: No Answers)*	0.04 [-0.13, 0.22]	.644		
Radon Risk *(Ref: Lower)*				
Moderate	1.19*** [0.96, 1.42]	< .001	0.14 [-0.34, 0.63]	.563
High	1.92*** [1.66, 2.18]	< .001	0.55* [0.04, 1.06]	.036
Socio-Demographic Controls	Yes		Yes	
Participants	1,589		796	

*$p < .05$; **$p < .01$; ***$p < .001$

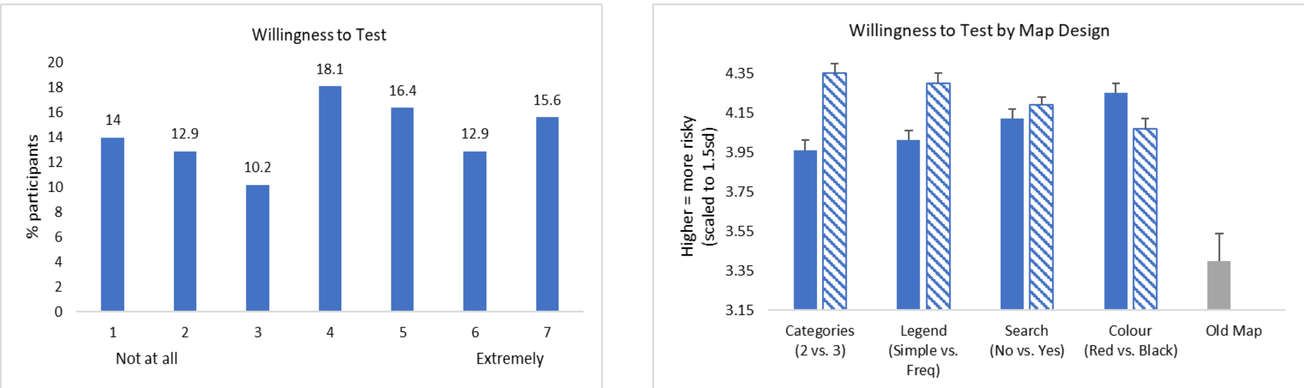


Figure 6. Distribution of responses to the willingness-to-test question and average responses by map design. Error bars are the standard error.

We also measured participants' "willingness-to-pay" for a test, i.e., the most they would be willing to pay in order to test their home for radon, using an open-text question. For this analysis, we exclude participants who saw the answers to the quiz as they were told the typical cost of a test (€40). Responses from the remaining participants were varied, with some (7.8%) reporting that they wouldn't pay for a test and 10% giving a response above €250. The median response was €75. Given this level of variation, we model simply whether the participant reported that they would pay at least the typical cost of a test (80.3% of the sample). Participants who read the frequency-based legend were more likely to report they would pay at least the cost of a test than those read the simple statement (83.7% vs. 77.8%). There is a similar effect for those who saw three risk categories compared to those who saw two categories (83.3% vs. 77.9%), although this difference is non-significant when controls for area risk are added (Table 6).

3.5 Specific Map Comparisons

Given the above analyses, we take the best performing map to be the one that communicates risk with three categories, has red as the highest risk colour, uses a frequency-based legend and has extensive search functionality. In this section, we compare this map to the pre-existing map on our outcome variables of interest. (We use Chi-Square tests to compare maps on willingness to pay at least €40 for a test and Mann-Whitney U tests otherwise.)

Participants reported being more worried about radon ($M = 4.3$ vs. 3.4; $Z = 3.38$, $p = .001$) and believing their home was more likely to be affected after using the test map compared to the control one ($M = 3.8$ vs. 2.7; $Z = 4.31$, $p < .001$). These differences are larger than those reported in the previous section. There is no difference in how severe participants judged it would be for themselves or someone in their home if they had high levels of radon ($M = 5.4$ vs. 5.2; $Z = 0.85$, $p = .390$).

Participants who used the test map reported they were more likely to test their home for radon than those who used the pre-existing map (M = 4.5 vs. 3.4; Z = 3.17, p = .002). Another way to test this difference is to check how many participants gave a response above the midpoint of the scale, indicating that they would be highly willing to test for radon. Over half of respondents who used the test map were highly willing (54.3%) compared to less than a third of those who used the control map (31.5%), a statistically significant difference (χ^2 = 11.44, p = .003; Figure 23). This equates to a 72% increase in the proportion of people reporting being highly willing to test. They were not, however, more likely to report they would pay at least €40 for a test (84.1% vs. 79.7%; χ^2 = 0.34, p = .563), noting that a large majority in both cases reported that they would pay the cost of a test.

4. Discussion

The results show the benefit of using methods from psychological science and the literature on environmental risk perception to inform communications with the public. One important finding is that information provision can influence perceived risk from radon. Participants who received the correct answers to a quiz about radon perceived the consequences of exposure to be worse immediately after reading the information compared to those who hadn't seen the information. This effect persisted after they learned the level of risk in their area.

Our test of radon hazard maps presents three further discoveries with important implications for their design. First, communicating risk in numeric frequencies (e.g. 1 in 5 houses have high levels of radon) increases how worried householders feel about radon and, in particular, how likely they believe their home could be affected by it compared to simple statements that they are high risk. Frequency statements also increase intentions to test for radon and the perceived value of a test. These findings highlight the link between risk perceptions and mitigation intentions and add to the literature on how to communicate environmental health risks effectively (Hazar et al., 2014; Visshers et al., 2009). The results also provide support for the idea that overoptimism may partly explain low testing rates (Sharot, 2011; Weinstein et al., 1988). Householders are more willing to test for radon when provided with accurate risk statistics than when simply informed that their home is at high risk, likely because they underestimate their susceptibility when told the former.

Second, maps that used three categories of risk increase perceived risk among those in moderate-risk areas without diluting perceptions of risk among those in high-risk areas. This implies that when people evaluate environmental risk presented on maps, they are unlikely to employ the same sorts of cognitive processes as those recruited when making judgements about absolute values (e.g. they are less reliant on comparisons against other attribute levels; Stewart et al., 2005). This has important practical implications. This finding is the first we are aware of that demonstrates a benefit to increasing the granularity of discrete zones when communicating risk, particularly to reduce the proportion of people who believe they are at the lowest level of risk. Further research is needed to determine if there is a ceiling to the number of discrete zones that should be used.

Third, we find that, despite their focus in the hazard map literature, pre-attentive properties have less influence on risk perception than how risk is communicated (e.g. Ash et al., 2014). Notwithstanding the strong association between the colour red and risk, there is little evidence that colour mattered for perceived risk of radon on any of the dimensions of risk we recorded (Pravossoudovitch et al., 2014).[7] Interactivity had even less of an influence. Although facilitating users to easily locate their home improved map evaluations on standard user-experience questions (e.g. ease of use), it had no effect on any dimension of perceived risk or on willingness to test. Ease of use is nonetheless an important component of user experience and hence hazard maps would probably benefit from employing such functionality, if resources permit.

Together, these discoveries suggest that maps that communicate risk using numeric frequencies, with three categories of risk, using a typical yellow-to-red colour scheme and with search functionality will benefit map users, increase perceptions of risk from radon and encourage testing. Compared to the map that was in use at the time of the study, the size of

[7] The mechanism may be subtler than we could detect, as those who saw high-risk regions illustrated in black were less willing to test than those who saw them in red.

the benefit is large: 72% more people report being highly willing to test their home for radon using the best performing map.

Map design features influenced worry and perceived susceptibility to radon, but not how people perceived the consequences of radon exposure, which instead was amplified by the knowledge intervention. Hence, taking both elements of this experiment together, the results imply that the public would benefit from combining radon risk maps with additional information about radon. Moreover, this delineation of effects on different dimensions of perceived risk has important implications for psychological theory and supports recent calls for the multi-dimensional nature of risk to be factored into its measurement (Wilson et al., 2017).

4.1 Limitations

This study presents an initial attempt to encourage householders to test for radon and was limited to assessing intentions. While the direction and magnitude of the effects we observe are encouraging, in particular for the use of numeric frequencies when communicating risk, the findings would benefit from being substantiated by experimental trials that assess real behaviour. Relatedly, our study examined responses conditional on being offered the chance to use an online radon map. It did not explore ways to attract householders to visit a webpage to engage in the first place. Moreover, testing itself is simply the first step for households with high levels of radon exposure; encouraging remediation among those shown to be at risk is a separate challenge (e.g. Vogeltanz-Holm & Schwartz, 2018).[8]

[8] Some remediation techniques are straightforward, such as sealing improving indoor ventilation or sealing major gaps in foundations. The most effective way is to install a radon sump, which typically costs approximately €950.

This study was commissioned by a public body to test communications with householders in Ireland. There is no reason to believe that the psychological mechanisms that people in Ireland rely on when evaluating risk from radon are different to elsewhere; our research questions were informed by international literature and low testing rates for radon are observed in multiple other countries (Cholowsky et al., 2021; Poortinga et al., 2011). That said, there is no guarantee that the findings extend to other nations, or indeed to other environmental hazards. The method we used offers a promising way to conduct similar tests of risk maps elsewhere or of different risks.

4.2 Conclusion

We show that radon risk maps are effective ways to communicate the likelihood of exposure to people, but that the design of these maps makes a large difference. Informing the design of the maps using psychological science and testing them experimentally allows them to be optimised to motivate householders to test for radon. The findings indicate strong candidate ways to communicate with householders in field trials to measure real testing behaviour. More broadly, the findings highlight the potential for techniques from psychological literature to mitigate a real-world environmental risk.

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