

Measuring societal attitudes and behaviours towards radon indoors: A case study of Slovenia

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ABSTRACT

Public opinion surveys play a crucial role in assessing public awareness, knowledge, and radon risk perception in the context of national Radon Action Plans. However, many of these surveys are constructed without a solid foundation in behavioural theories, health protection theory, or social science methodology. This lack of foundation can lead to misguided priorities in radon mitigation interventions and ineffective communication strategies, ultimately resulting in low compliance with testing and mitigation in private homes. By developing and testing scales that measure a wide range of theory-based socio-psychological concepts influencing protective behaviour of individuals facing radon risk, this study provides researchers, authorities, and practitioners with a useful and versatile survey tool to explore the complexity of human behaviour in the context of radon. The results of this survey, conducted in Slovenia with a representative sample of respondents from low, middle, and high radon risk areas (N = 2012), offer a foundation for assessing gaps and strategies to increase testing and remediation of homes. The findings suggest that communication interventions need to be more precisely tailored to specific population groups and should go beyond enhancing awareness, knowledge and radon risk perception. Effective strategies should evoke emotions, share personal stories, highlight successful mitigation cases, and use personal testimonies from individuals affected by lung cancer. Moreover, incorporating positive social norms can inspire more individuals to engage in testing and mitigation measures. Assessing theory-driven socio-psychological concepts through a survey allows researchers and policymakers to craft more effective strategies aimed at promoting radon testing and mitigation, thereby enhancing overall public health.

1. Introduction

With the pressing urgency of protecting public health from exposures to radon, national authorities responsible for the implementation of Radon Action Plans (RAPs) increasingly rely on public opinion surveys to evaluate public awareness about radon and to gauge residents' adherence to testing and mitigation when radon concentrations in dwellings exceed national reference levels (Perko et al., 2023). Unfortunately, such surveys are often constructed based on what is deemed "interesting to know" rather than being firmly rooted in behavioural theories and social science methodology principles (Tomkiv et al., 2021), (Bouder et al., 2021). Poorly executed surveys in terms of theory and methodology may lead to a misguided emphasis on different radon mitigation interventions and flawed messaging within radon communication strategies, consequently leading to a low compliance with

testing and mitigation in private homes. This holds utmost significance, as public opinion surveys are prominent as a tool, particularly in the context of radon programs initiated by the International Atomic Energy Agency (Davydov et al., 2021), (Djounova et al., 2023), (Tushe et al. RAP, 2022) World Health Organisation (Zeeb et al., 2007) and within European Union Member States (EU MS) (Perko et al., 2023). In EU MS, these surveys also support authorities to meet the mandates outlined in Council Directive 2013/59/Euratom (EC et al., 2014) which emphasizes the need to "enhance public awareness and educate local decision-makers, employers, and employees regarding the risks associated with radon, including its relationship with smoking", as stipulated in Annex XVIII (10) (Martell et al., 2023).

Recent systematic reviews on the societal aspects of radon (Muric et al., 2023) and naturally occurring radioactive material (NORM) (Turcanu et al., 2022) highlight a notable research gap, particularly with

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regards to the psychosocial, economic, and cultural dimensions that influence human behaviour in the context of radon. These reviews noted important methodological flaws in the studies of people's risk perceptions, perspectives, attitudes, expectations, emotions, and protective behaviours, notably through public opinion surveys. The authors advocate for the measurement of theory-based concepts that can potentially influence human behaviour (Tomkiv et al., 2021), emphasizing the importance of adopting representative and appropriate sampling methods, rigorous measurement techniques, and construct validation (Muric et al., 2023). Furthermore, public opinion surveys should place greater emphasis on behavioural outcomes, such as dwelling mitigation, rather than solely concentrating on measuring radon risk perception or radon awareness (Hevey et al., 2023), (Hevey, 2017).

Previous research indicated that a key aspect of radon control strategies directed at the public has been to educate, encourage, and make radon salient to the public (Apers et al., 2023a). However, simply providing comprehensive information that increases awareness and knowledge does not necessarily improve risk mitigation behaviours (Witte et al., 1998a). As stressed by Hevey (2017) p.2, "there are seventeen of stages that need to occur for an individual to act following an information programme". Hevey and colleagues (Hevey et al., 2023) note that research needs to examine the lack of mitigation action from a comprehensive psycho-social-environmental lens. In addition to risk perception, knowledge, and awareness derived from existing theories, it is imperative to consider a wide spectrum of psychological and sociological concepts. These concepts should encompass factors such as the emotional responses triggered by radon information and the potential stigma associated with having high radon levels. (Hevey, 2017), (Maier et al., 2023), (Weinstein et al., 1998a), (Weinstein et al., 1992a).

In addition, the individual's beliefs about radon control behaviours are also critical and include the intentions to perform the behaviours, perceived control over successful radon management, beliefs about how burdensome the behaviours will be, confidence to successfully manage radon, confidence that the mitigation will be effective, the cost of the work and the aesthetic impact of the work on one's dwelling (Clifford et al., 2012), (Irvine et al., 2022). Furthermore, the individual exists in a social network and therefore the extent to which important others in one's area have performed radon control and want the individual to perform radon control are important (Khan et al., 2019a), (Cori et al., 2022). The extent to which individuals are aware of the key authorities involved in radon control, believe that these authorities are trustworthy and perceive them to be competent to address radon will also impact radon control behaviours (Turcanu et al., 2020), (Hevey, 2017).

Building upon these foundational concepts that influence human behaviour and recognizing the methodological need for validated and reliable measurement instruments, this study is designed with the following objectives:

- i) To develop survey items that pertain to the societal aspects of radon and to establish valid and reliable measurement scales for the assessment of socio-psychological theory-driven concepts;
- ii) To examine which of these concepts are associated with actions such as radon testing and mitigation;
- iii) To offer empirical evidence that can guide awareness and communication strategy aimed at increasing the number of radon tests and mitigations, as demonstrated for the particular case study of Slovenia.

As the questionnaire is developed, tested, and analysed as a modular tool, providing flexibility for potential users to use specific scales or items for each concept, the manuscript comprises dedicated subsections for each concept in the Results section. These subsections independently cover the origin of the investigated concept, previous findings from studies where the concept was applied, statistical results specific to Slovenia, and an integrated discussion of these aspects.

2. Radon management in Slovenia

Slovenia's geological composition renders numerous municipalities susceptible to radon (Vaupoti et al., 2010a) (Fig. 1). Annually, there are 1500 reported cases of lung cancer, with approximately 10% attributable to radon exposure and radon-related lung cancer results in the loss of approximately 60–100 lives each year (Birk et al., 2022), (Sisko, 2020). To prevent radon-related health risks, the Slovenian Radiation Protection Administration (SRPA) established a Radon Action Plan (RAP) in consultation with relevant ministries, technical support organizations, and educational groups (Hevey et al., 2023), (Government and Slovenia, 2020). The reference level for the average annual radon concentration in enclosed residential and occupational spaces stands at 300 Bq/m³. To reduce the risk of radon exposure and the resulting cases of lung cancer in the population, authorities are diligently encouraging voluntary radon testing and mitigation in households that exceed the reference level. Mandatory radon testing is required in designated radon priority areas for public and workplace spaces. These initiatives align with the European Safety Standard directive (EC et al., 2014), which mandates EU Member States to conduct radon mapping, promote construction techniques that mitigate radon infiltration in new buildings, and disseminate vital information to the public regarding radon risks and mitigation strategies, among other measures (Perko et al., 2023).

Three entities offer radon testing services in Slovenia: Radonova (for residential properties), the Jozef Stefan Institute, and the Institute for Safety at Work (for comprehensive tests, encompassing schools, as well as residential properties). Residents in radon risk areas have access to free tests for their dwellings, although the number of tests is limited. The first radon test is conducted during the heating season, for a period of 30–90 days. If the results of radon tests are lower than the reference level of 300 Bq/m³, further tests are not required until changes affecting radon concentration occur, such as rebuilding a house or implementing energy efficiency measures like new windows or insulation. If the radon concentration exceeds 300 Bq/m³, a second test is taken during the summer period (Perko et al., 2023). In cases where the radon concentration in a dwelling exceeds 300 Bq/m³, remediation is advised, such as construction interventions including sub-slab depressurization, additional sealing of cracks, and implementation of insulation under the floor. A post-construction test is required to check the effectiveness of the measures taken. The average cost of remediation for a standard dwelling in Slovenia is a few thousand euros, but it is expected to be less than 10,000 euro (Perko et al., 2023). Throughout the period of this study, no state subsidies were available for mitigation in private dwellings.

If more than 30% of tests in an area exceed 300 Bq/m³, the area becomes a "priority area". A list of radon priority areas in Slovenia is provided in the National RAP (Government and Slovenia, 2020), (Article 5 (2)). In this study, we refer to these areas as "high radon risk areas". The RAP also identifies other municipalities that can be considered "candidates" for becoming a priority area. In this study, we refer to these areas as "medium radon risk areas" (Fig. 1). For the purpose of analysis, high and medium risk areas are sometimes analysed together and referred to as "radon risk areas". Additional radon measurements are also performed in other areas, which we refer to as "low radon risk areas".

Communication interventions targeting employers, employees, local decision-makers, and the public in general focus on increasing awareness of radon risks and are developed in the form of folders, publications, seminars, expert meetings, workshops, and special publications for children (Hevey et al., 2023). This study is the first comprehensive analysis of people's perceptions, attitudes, and behaviors regarding radon in Slovenia.

3. Method and data

A representative sample of the Slovenian population was surveyed

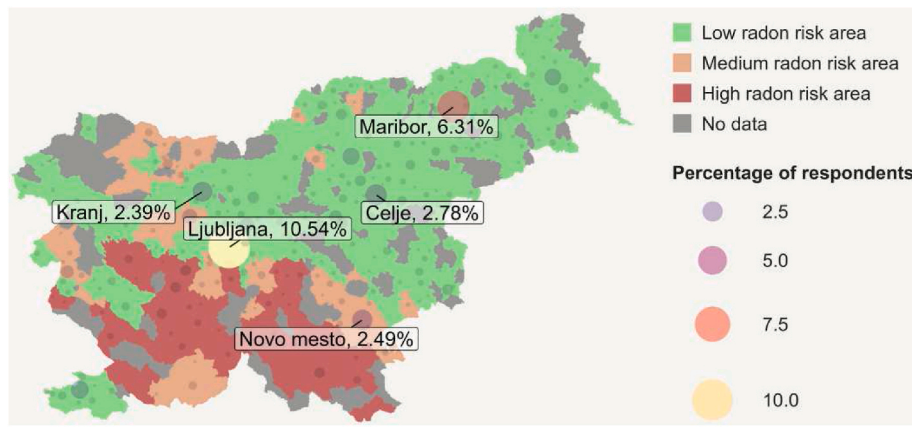


Fig. 1. Sampling respondents for the assessment of perceptions, attitudes, and behaviour in Slovenia’s radon priority areas.

using Computer-Assisted Web Interviewing. The panel consisted of 25,000 potential respondents, from which respondents for this study were randomly selected. The sample included 2012 respondents, representative of the (18+) Slovenian population in terms of gender, age, and region, with stratification based on the total number of inhabitants in Slovenia. The response rate was 27.6%. Of the respondents, 77.5% lived in low radon risk areas, 14.2% lived in medium risk areas, and 8.3% lived in high risk areas (Fig. 1). The survey had an average duration of 19 min and was conducted between November 29th and December 8th, 2022. The survey included a short video providing basic information about radon and the mitigation of high radon levels in a dwelling. By showing the video selectively to those people that demonstrated low awareness and low radon related knowledge, we aimed to provide relevant information to those who needed it most in order to respond to subsequent questions (Fig. 2). To ensure high data quality, a pilot study for the questionnaire was conducted with a sample

size of 300 in a radon priority area in Belgium (Perko et al., 2021), followed by a soft launch with 264 panel members selected randomly in Slovenia.

Most survey items are formulated as questions or statements, with answering categories expressed by using Likert-scales adjusted to the context of the statement or question. Agreement with a statement is typically measured on a scale ranging from “strongly disagree”, to “disagree”, “neither agree, nor disagree”, “agree”, to “strongly agree”. The answering category “Other” was included for all closed questions with predefined answering options in order to ensure completeness. The option of “no answer” or “I don’t know” were also available. Knowledge items were measured with “agree” and “disagree” responses (Table 1). The sequence of the aspects investigated in the survey and the number of items retained for each of aspect are presented in Fig. 2. Items and concepts used in this study draw on the state of the art in social studies of radon or have been adapted from relevant theories for the context of

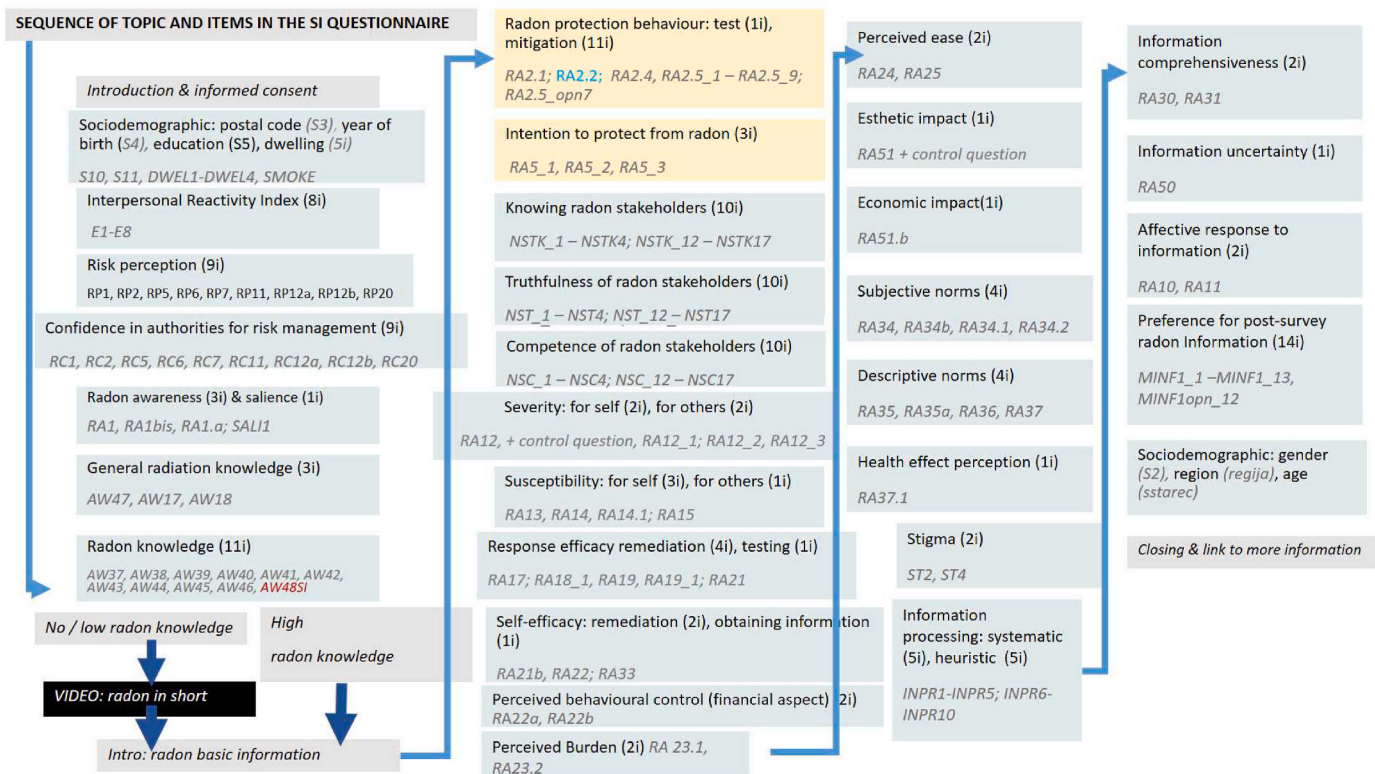


Fig. 2. The sequence of socio-psychological aspects and number of items (i) in the questionnaire (average duration 19 min).

Table 1
Knowledge items.

Knowledge items	Correct answer %	Incorrect answer %	Don't know %
AW47 Exposure to radiation always leads to radioactive contamination. ^b	22.6 (disagree)	53.8 (agree)	23.6
AW17 The human body is naturally radioactive. ^{a and b}	30 (agree)	33.3 (disagree)	36.7
AW18 With time, every radioactive substance becomes more and more radioactive. ^b	46.3 (disagree)	23.7 (agree)	30
AW37 Radon causes headaches. ^a	14.33 (disagree)	34.2 (agree)	51.5
AW38 Radon exposure is linked to lung cancer. ^a	41.5 (agree)	5.2 (disagree)	27.4
AW39 Radon is a radioactive liquid. ^a	50.9 (disagree)	8.2 (agree)	15.1
AW40 Radon has a strong odor. ^a	48.6 (disagree)	2.8 (agree)	22.8
AW41 Radon is invisible. ^a	66 (agree)	2.7 (disagree)	5.5
AW42 Radon levels are usually higher in the attic than the basement. ^a	38.2 (disagree)	7.9 (agree)	28
AW43 Testing is the only way to determine if a home has an elevated radon level. ^a	64.3 (agree)	2.2 (disagree)	7.6
AW44 Radon can enter homes through cracks in walls and floors. ^a	53.5 (agree)	4.8 (disagree)	15.8
AW45 Health effects of radon do not show for years. ^a	58.6 (agree)	4 (disagree)	11.5
AW46 The risks from radon exposure increase the longer you are exposed to it. ^a	65.5 (agree)	2 (disagree)	6.7
AW48si Concentrations of indoor radon are expressed in Becquerel per cubic meter. ^a	30.6 (agree)	2	41.3

^a Specific radon knowledge (only respondents familiar with radon).

^b General knowledge (all respondents).

radon (Tomkiv et al., 2021). The references to the original studies are included in the respective sections.

3.1. Analysis

Two types of scales used in the study: reflective and formative. The key difference between reflective and formative scales is the causal direction of the relationship between the items and the construct being measured. Reflective scales assume that the construct causes the observed relationships between items, while formative scales assume that the items define the construct. It is important to choose the appropriate type of scale for the construct being measured to ensure valid and reliable measurement of the construct.

Reflective scales were derived using Principal Axis Factoring analysis without rotation, and retaining items with factor loadings larger than 0.5: Intention to protect from radon, Severity, Susceptibility, Self-efficacy, Perceived behavioural control, Perceived burden, Subjective norms, Descriptive norms, Stigma and Affective response to information (see Table A in annex). For all scales, Cronbach's alpha coefficient, which measures the reliability of the scale, was 0.70 or larger, indicating a reliable scale. Table A in annex summarises these unidimensional constructs, the items included and the scale attributes.

Formative scales were constructed for radon knowledge (Table 1) and response efficacy by aggregating (summing up) responses collected on the Likert scale. Table B in annex presents items measuring response efficacy and items correlations.

Table C presents attitudes measured by only one item: perceived ease, visual and economic impact and information comprehensiveness. In addition, awareness of radon was measured with one item ("Do you know about radon?" Yes/I have heard of it/No).

The analysis of statistical associations between socio-psychological

concepts and the behavioural intention to protect was performed using Pearson's correlation test (see Table 2). All analyses were conducted using SPSS v25. Statistical significance was set at $p < 0.05$.

4. Results and discussion

4.1. Radon protection behaviour: do people test and mitigate?

Radon protection behaviour is defined as the process of testing for radon, mitigating the dwelling if radon levels exceed acceptable limits,

Table 2
Associations between behavioural intention and socio-psychological constructs.

Construct	Behavioural intention ^a (test and mitigate)			Comment
	Pearson's corr. Coeff. (r)	Sig. (p-value)	Sample size (N)	
Awareness	0.09	0.001	1671	Significant but very weak
Knowledge	0.07	0.004	1690	Significant but very weak
Salience	0.09	0.001	1552	Significant but very weak
Risk perception	0.26	0.001	1587	Moderate
Severity	0.29	0.001	1550	Moderate
Perceived susceptibility	0.35	0.001	1456	Moderate
Health effect perception	0.21	0.001	1496	Low
Confidence in authorities	0.04	0.16	1577	Not significant
Trust in a scientific organ. (IJS)	0.04	0.16	1293	Not significant
Trust in contractors for mitigation (building industry)	0.12	0.008	512	Low but contractors and not well known
Trust in measurement companies	0.18	0.005	241	Low but companies are not well known
Trust in authorities (SNSA)	0.01	0.81	717	Not significant
Response efficacy	0.11	0.001	1395	Moderate
Self-efficacy	0.19	0.001	1591	Moderate
Perceived burden	-0.03	0.27	1495	Not significant
Financial burden for testing	0.23	0.001	1656	Low
Financial burden for mitigation	0.22	0.001	1635	Low
Confidence in finding a contractor	0.14	0.001	1607	Low
Perceived behavioural control	0.26	0.001	1630	Moderate
Perceived ease	0.03	0.23	1373	Not significant
Aesthetic impact	0.03	0.23	1334	Not significant
Impact on financial value of a house	0.09	0.001	1562	Very low
Subjective norms	0.35	0.001	1083	Moderate, but almost 50% of people don't know the position of friends and family on radon
Descriptive norms	0.23	0.001	1236	Moderate
Stigma	0.05	0.03	1622	Significant but very weak
Information comprehensiveness	-0.01	0.72	1581	Not significant
Uncertain information	-0.01	0.62	1552	Not significant
Affective response	0.41	0.001	1629	The strongest association

^a A strong correlation means that the variables tend to move together linearly, but it doesn't necessarily mean that changes in one variable cause changes in the other. Causation requires additional analysis and evidence.

and subsequently re-testing the dwelling after implementing mitigation measures (Hevey, 2017). Various studies, both in Europe (Mc Laughlin et al., 2022), (Perko et al., 2023) and elsewhere, e.g. (Larsson, 2015), (Evans et al., 2015), have consistently indicated that only a small proportion of residents actively perform these behaviours. Our data show that only 8.6% of respondents living in high radon risk areas reported having tested their dwellings for potential radon concentration, compared to 2% of respondents in low radon risk areas in Slovenia.

Out of the 68 respondents in our sample whose dwellings were tested for radon concentrations, eight respondents living in high and medium radon risk areas (out of $N = 36$ who tested) reported that the radon levels in their dwelling exceeded the national reference level and further actions were required. In low radon risk areas, six respondents (out of $N = 26$ who tested) reported exceeded levels of radon in their dwellings. These findings emphasize the importance of testing radon concentrations, both in low and in medium/high radon risk areas. It is worth noting that our results are consistent with previous reports, as authorities have reported that up to 30% of tests conducted in radon priority areas exceed the national reference level (Vaupoti et al., 2010b).

When all respondents in the survey were asked whether they or someone else had taken action to remediate their current residence for radon, only seven respondents in all of the Slovenian sample stated that their building was remediated after discovering a radon problem. 53 respondents stated that radon protective measures were integrated in their home during the building process. Among the 60 respondents who were aware of mitigation actions to reduce high radon concentrations in their dwelling, most relied on natural ventilation methods, such as regularly opening windows to ventilate their living spaces, instead of installing sustainable technical solutions. However, some respondents did install ventilation systems, such as forced ventilation, heat recovery, or air-to-air exchange. Notably, technical solutions like installing a radon membrane were used only in a few cases.

Overall, these findings suggest that evidence-based, strategic, and theory based intervention campaigns are needed to encourage and support more residents in high and moderate radon risk areas to take mitigation actions; further research is needed to determine the effectiveness of different communication strategies as suggested by Boudier et al. (2021).

4.2. Intention to protect from radon: what is the public willingness to adopt radon protection measures?

The intention to test and mitigate is a significant predictor of, and can be used as a proxy for, actual behaviour (Ajzen, 1988). Considering that only a limited number of residents actively adopt these behaviours (Mc Laughlin et al., 2022), (Perko et al., 2023), assessing these intentions with a survey remains a valuable choice.

We found that the intention to test and remediate for radon, when advised to do so, is low, regardless of whether the area is high and medium-risk, or low-risk. Over 60% of respondents expressed no intention to test radon concentrations in their homes if advised. Moreover, only 30% of the respondents in high and medium-risk areas and 25% in low-risk areas intended to measure radon in their homes as a precaution. These results indicate that residents exhibit a low level of intended protective behaviour when it comes to radon testing and mitigation. Moreover, more than 70% of the population may not follow the advice to remediate, which suggests that increasing mitigation rates is even more challenging than increasing radon testing rates. Last but not least, the aforementioned intentions to test and mitigate are probably even overestimated, because those with low initial radon knowledge were exposed to an informational video, as described in the method section.

4.3. Are people aware of radon and how much people know about radon?

The study distinguishes between radon awareness (Cronin et al.,

2020) (Poortinga et al., 2011) and radon knowledge (Desvousges et al., 1992), (Nwako et al., 2020), (Hahn et al., 2014), (Ryan et al., 1998), (Golding et al., 1991), (Kennedy et al., 1991), (Peterson et al., 1996). Radon awareness is the state of being conscious of the existence of a radon health risk, while radon knowledge refers to the understanding a person has acquired about the risks associated with radon exposure through learning, experience, or campaigns. While awareness represents the initial step in the psychological process of taking behavioral action (Hevey, 2017), findings from prior research suggest that enhancing radon knowledge may be one of the factors promoting radon testing within dwellings (Desvousges et al., 1992), (Nwako et al., 2020), (Hahn et al., 2014), (Ryan et al., 1998), (Golding et al., 1991), (Kennedy et al., 1991), (Peterson et al., 1996). (Davis et al., 2018).

Our study found that the majority of respondents (74.2%) were aware of radon (i.e. knew or had heard about it), but a quarter of the population (24.5%) was not aware of it. The analysis of radon awareness showed only minor differences between low, medium and high radon risk areas. Medium risk areas had the highest level of awareness, while high risk areas had somewhat less respondents who were aware of radon.

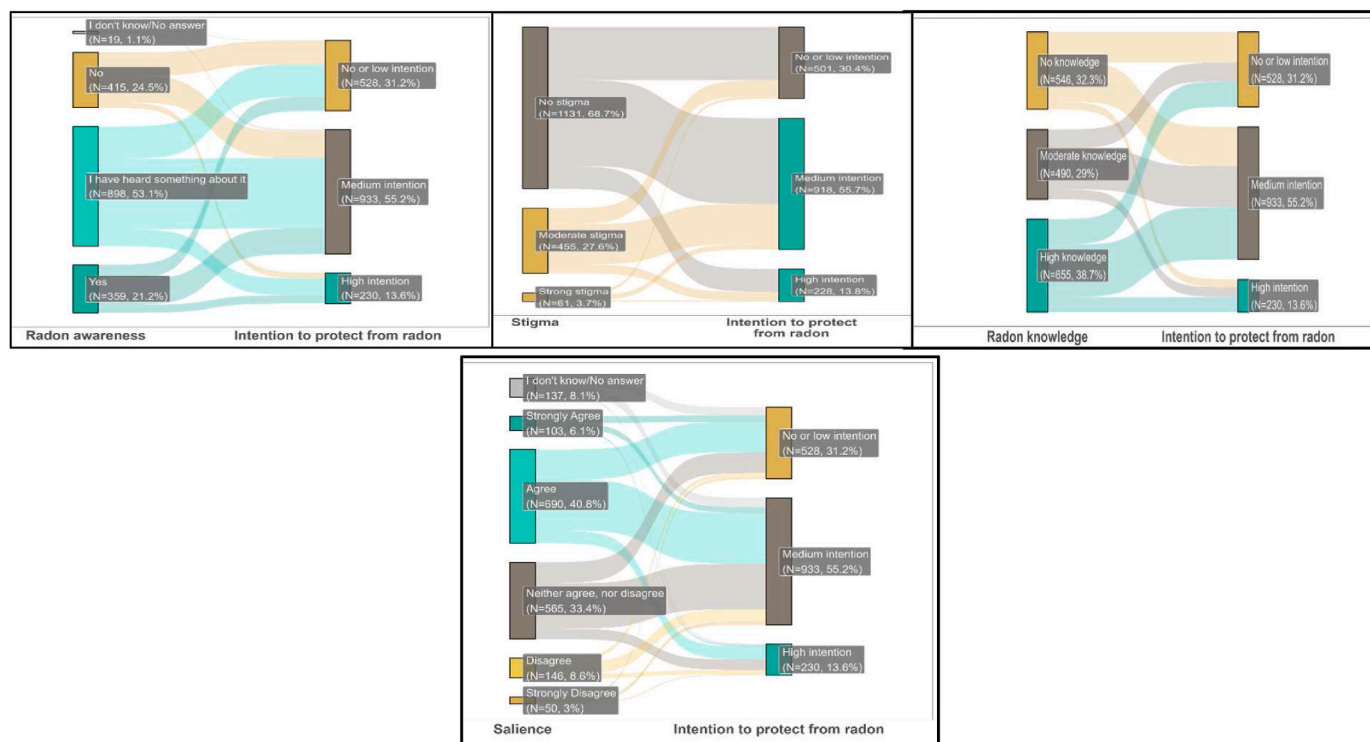
The results confirm the lack of consistency between being aware of radon and following the advice to test and mitigate if advised. For example, out of the 20% of respondents who reported they knew about radon, only approximately one-third of them would test their homes if advised, while another third would definitely not test, and the remaining third were neutral (Fig. 3).

In our study, a total of 1493 respondents (out of a sample of 2012) who indicated that they knew or heard about radon were asked to indicate whether they agree or disagree with 11 statements related to radon exposure (Table 1). Additionally, all respondents were asked three questions relating to general knowledge about radioactivity.

Overall, respondents aware of radon demonstrated relatively high knowledge of radon-related topics, with 92% of people in high radon risk areas recognizing correctly that radon is an invisible gas. This fact is also well known among residents in medium and low radon risk areas. Additionally, 89% of respondents across all areas in Slovenia were aware that the risk from radon exposure increases with longer exposure periods. More than 80% of respondents in all radon risk areas also correctly identified that testing is the only way to determine if a home has an elevated radon level. From this perspective and in comparison with similar studies and questions (Hahn et al., 2014), (Ryan et al., 1998), we can conclude that Slovenians have relatively high knowledge about radon, with individuals from high radon risk areas tending to provide the most accurate responses while those in low and medium risk areas lag slightly behind.

However, the study disclosed some important knowledge gaps. The results showed that respondents had a low level of understanding regarding the symptoms of radon exposure, with only 10% correctly identifying that radon does not cause headaches. This is in line with the study of Ryan et al. (Hahn et al., 2014). We also found that up to 52.9% of people in Slovenia are not familiar with Becquerel per cubic meter, the unit used to measure radon concentrations indoors and often communicated to residents (Apers et al., 2023a), (Perko et al., 2020a).

In order to successfully convey the risks associated with radon and the necessary protective measures to the public, it is crucial to first evaluate the baseline level of understanding of topics related to radioactivity and ionizing radiation (Apers et al., 2023a), (Perko, 2014). This assessment is particularly important since radon communication occurs within the broader framework of radiation risk communication (Perko et al., 2012). The analysis of our survey results indicates that the general population has limited knowledge regarding exposure to radiation risks. Of particular concern is the significant proportion of individuals who hold the misconception that "exposure to radiation always leads to radioactive contamination." This misinformation could present a challenge, particularly in understanding the difference between radiation and irradiation in relation to radon. It may inadvertently foster a stigma



Salience: "Radon may be a problem, but I haven't paid much attention to it because there are more important things to deal with"

Fig. 3. Weak associations between intention to protect from radon with awareness ($r = 0.09$), Stigma ($r = 0.05$), knowledge ($r = 0.07$) and salience ($r = 0.09$).

against individuals residing in regions designated as radon-prone areas (Khan et al., 2019b). However, the study also revealed a higher level of knowledge among the general population concerning the concept of decay, as many knew that every radioactive substance becomes less radioactive with time. This knowledge can potentially facilitate more straightforward efforts in communicating about radon (Perko et al., 2014), (Davis et al., 2018).

The correlation between knowledge and intention to test and mitigate was very weak, albeit statistically significant (Fig. 3 and Table 2). This indicates that other factors beyond knowledge may play a more substantial role in shaping respondents' intentions to test and mitigate as suggested by Hevey et al. (2023) and Davis et al. (2018).

4.4. Is radon indoor seen as an important topic by respondents?

The term "salience" refers to the level of importance or relevance that an individual or group assigns to the topic of radon (Weinstein et al., 1990), (Witte et al., 2000), (Evans et al., 2015). "Salience" has been measured as (dis)agreement with the statement "Radon may be a problem, but I haven't paid much attention to it because there are more important things to deal with" (Smith et al., 1995). The results suggest that radon risk is not a high-priority issue for most people in Slovenia, with every second person agreeing that radon could be a problem but that is not a pressing issue. It is surprising to note that there were no significant differences observed between individuals residing in low, medium, or high radon risk areas in their prioritisation of the radon risk.

We found that individuals who prioritize other issues over radon may have lower intention to test and mitigate against radon exposure. There was a weak but statistically significant correlation between agreement with the statement "Radon may be a problem, but I haven't paid much attention to it because there are more important things to deal with," and "intention to test and mitigate" for radon (Fig. 3 and Table 2).

4.5. Risk perception: how do people perceive radon risks, radiological and other risks?

Previous studies show that radon risk perception is positively associated with radon testing (Davis et al., 2018). This has been confirmed also in our study, with a moderate association: participants who perceived a higher risk of radon exposure were more likely to express the intention to test and mitigate for radon in their dwelling (Fig. 5 and Table 2).

Results indicate that, on the whole, participants perceive a low to moderate risk from radon, while other radiological (e.g., from radioactive waste) or environmental risks (e.g., from climate crisis) are perceived as moderate to high. This conclusion is drawn from the mean scores, all of which surpass the threshold of 3.5 (on a scale from 1 = no risk at all, to 6 = very high risk). The study found that the perception of radon risk among respondents varies depending on how the risk is presented. "Indoor air pollution due to radon" was perceived as the most risky among the radon-related risks, followed by "The presence of naturally radioactive gas radon indoors" and "Natural radiation from the soil or from space" which is perceived as the least risky among the radon-related risks (Fig. 4). Specifically, 31.1% of respondents rated the risk as high or very high for the "indoor air pollution due to radon" statement, while only 26.4% of respondents rated the risk as high or very high for the "presence of the naturally radioactive gas radon indoors" statement. These findings can inform communication strategies how to convey the risks associated with radon exposure, thereby encouraging more people to test and mitigate their dwellings in case of high levels of radon, as suggested by the Potsdam radon communication manifesto (Bouder et al., 2021).

4.6. Perceived severity: what are people's beliefs regarding the severity of negative consequences due to radon?

The severity of radon exposure is determined by people's beliefs regarding the seriousness of its negative consequences for themselves

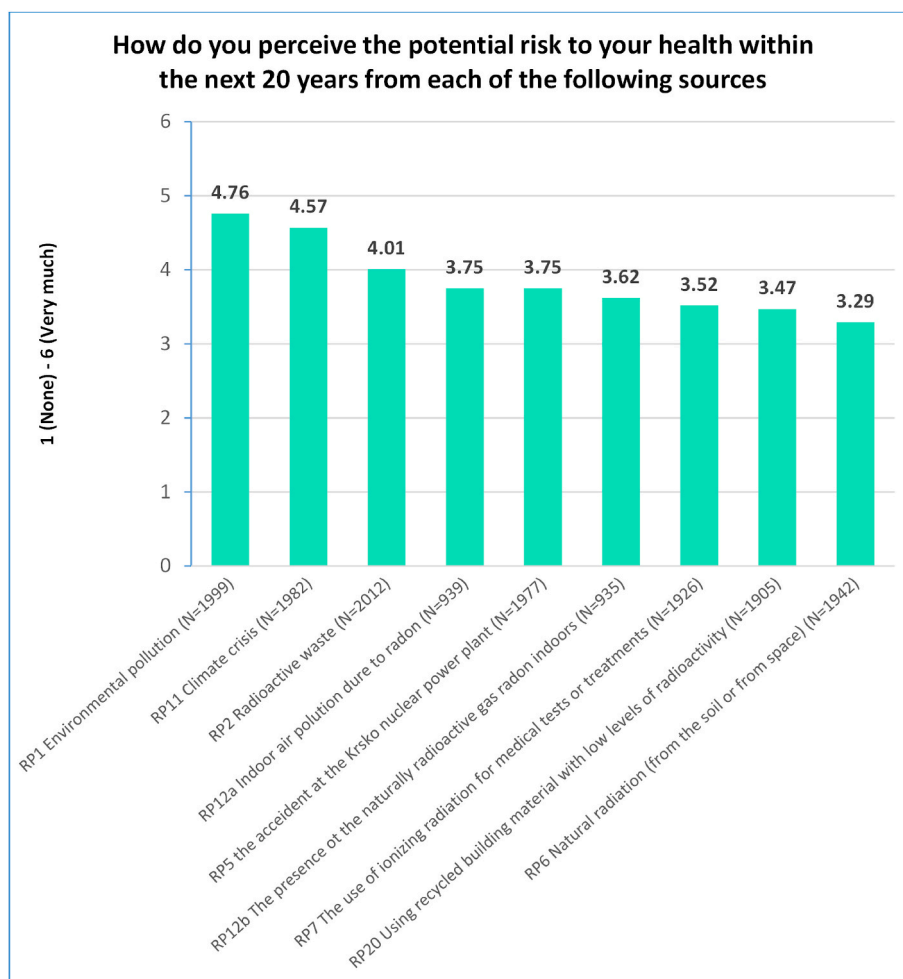


Fig. 4. Perception of radon risk compared to other environmental or technological risks.

and for others (Mazur et al., 1990), (Rinker et al., 2013), (Witte et al., 2000). For instance perceived severity, social influence, and current smoking were recognized as the strongest predictors of radon testing intentions by Rinker et al. (2013).

Our findings suggest that respondents view radon as having a significant severity, with high levels of agreement that not taking action when there is a high radon concentration in their homes would pose a severe threat to their health. Interestingly, we found no significant differences in perceived severity between people living in different radon risk areas. One particularly noteworthy result is related to the information video and participants' radon knowledge. Respondents with low or no knowledge of radon issues had a significantly lower perception of severity compared to those with a higher level of knowledge about radon issues. This is striking since the former were exposed to an informative radon video while the latter were not. Respondents who perceived higher severity of negative consequences associated with radon exposure were more likely to report a stronger intention to test and mitigate radon levels (Fig. 6 and Table 2). Witte (Witte et al., 2000) also found that strong fear appeals in radon communication intervention produce high levels of perceived severity and susceptibility, and are more persuasive than low or weak fear appeals. Weinstein et al. (1991) similarly found that perceptions of susceptibility and illness severity were significantly correlated with orders of radon test kits and with testing intentions.

4.7. Perceived susceptibility: do people believe that radon increases the likelihood of health issues?

Perceived susceptibility is an individual's belief about the likelihood of acquiring a disease or experiencing negative health consequences as a result of taking or not taking action to remediate a potential hazard (D'Antoni et al., 2019), (Weinstein et al., 1991) and (Niemeyer et al., 1999). In the context of radon exposure, perceived susceptibility can be divided into susceptibility for yourself and susceptibility for others. The study revealed that more than half of respondents believed they could develop lung cancer due to radon if they did not address high concentrations in their homes. A majority of respondents also believed that their neighbours would fall ill if they did not remediate high radon concentrations in their homes. Interestingly, 51% of respondents found it unlikely that they would become ill if they did not remediate high radon concentrations. Respondents who perceived themselves or others to be susceptible to negative health consequences from radon exposure were more likely to express a strong intention to test and mitigate radon levels in their homes (Fig. 5 and Table 2). These results align with Weinstein (Weinstein et al., 1991), who found that susceptibility is significantly correlated with the purchase of radon test kits and intentions to conduct radon testing. Interestingly, the level of susceptibility related to radon exposure is not different in different radon risk areas. More research is needed to investigate the relationship between communication intervention, level of knowledge and susceptibility.

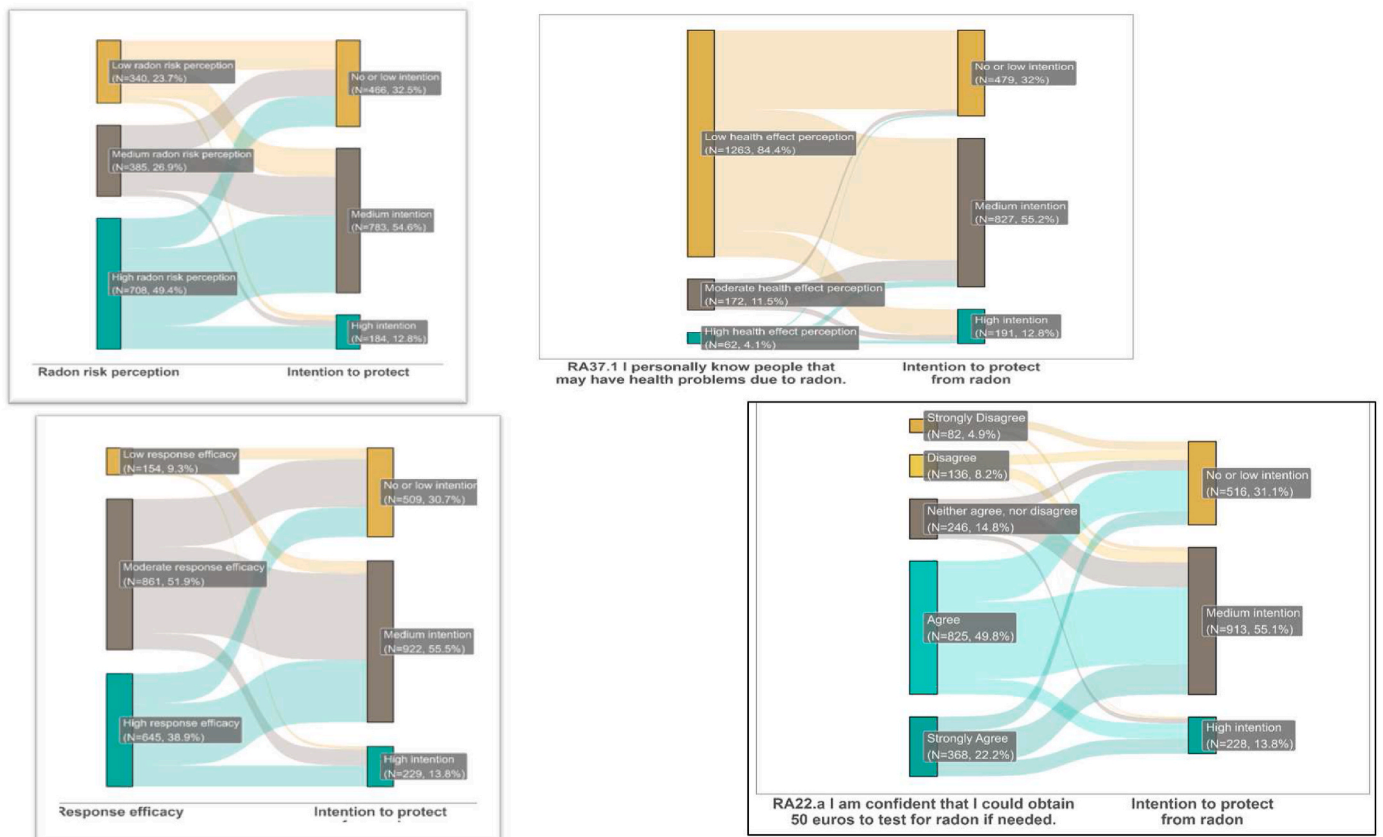


Fig. 5. Moderate associations between Intention to protect from radon with risk perception ($r = 0.26$), perceived health effects ($r = 0.21$), response efficacy ($r = 0.11$) and financial burden for testing ($r = 0.23$).

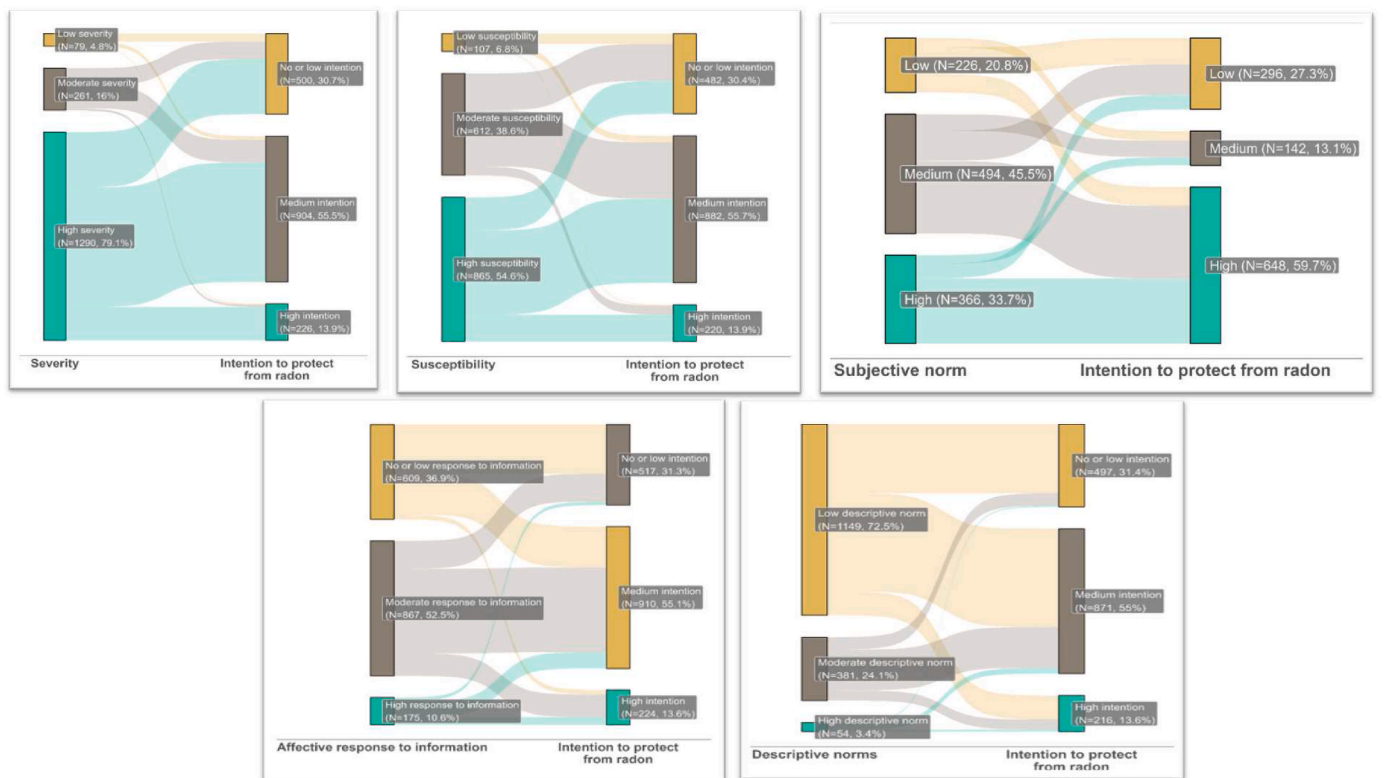


Fig. 6. Strong associations between Intention to protect from radon with severity, susceptibility, subjective norms, descriptive norms and affective response ($r \geq 0.25$).

4.8. Are individuals who have acquaintances who may have experienced health issues as a result of radon exposure more inclined to test/mitigate?

"Health effect perception" refers to individuals' personal beliefs about the health consequences of radon exposure. Duckworth (Duckworth et al., 2002) found that perception of radon as a health risk was correlated positively with planning to conduct further radon testing and mitigation. Additionally, Khan and Chreim (Khan et al., 2019a) reported that having knowledge of individuals within one's social network who had contracted lung cancer serves as a facilitator for taking radon protective measures. In our study, a majority of participants (84.2%) reported not personally knowing anyone who might have experienced health issues due to radon. Nevertheless, those who had such personal acquaintances were more likely to consider radon testing and mitigation measures (Fig. 5), confirming previous studies (Khan et al., 2019a) (Table 2).

4.9. Which radon management stakeholders are known to residents?

There are many different stakeholders in radon risk management. The study of Perko and Turcanu (Perko et al., 2020a) identified the following radon stakeholder groups: potentially affected radon stakeholders (e.g. residents, workers, schools), regulators and opinion makers (e.g. health specialist, authorities, politician) and radon mitigation stakeholders (e.g. professionals, radon services, builders, architects). Our study aimed to determine the level of awareness of stakeholders in radon-related issues among residents. The survey results showed that the radon mitigation stakeholders and authorities such as Jozef Stefan Institute, National Institute of Public Health, and Ministry of Health were the most well-known stakeholders in radon-related issues among respondents. However, contractors for remediation were more well-known than companies measuring radioactivity. This suggests that people may have more difficulties performing tests for radon concentrations in their homes than in mitigating their homes if concentrations exceeded legal norms, because they have less knowledge of the point of contact. These results align with findings from other countries, such as those observed in studies conducted by Hevey and others in Ireland, the UK, and Belgium (Hevey et al., 2023). Interestingly, the survey found that stakeholders working on radon-related issues are not significantly better known to residents living in high and medium risk radon areas compared to those living in low-risk areas. Lesser-known stakeholders should make more outreach efforts to increase public awareness and understanding of their roles in mitigating radon risks. Additionally, the study suggests that some stakeholders are better known than others, highlighting potential communicators for radon risk-related topics as suggested by Apers et al. (2023b).

4.10. Trust: confidence, truthfulness and competences of stakeholders

Trust is a multidimensional latent construct, meaning that it cannot be directly observed, but needs to be inferred from several observable indicators or dimensions, e.g. confidence, truthfulness and competences (Stephen Hunt et al., 1999). Poortinga et al. (2008) discovered that risk communication initiatives, which demonstrate the government's sincere commitment to addressing the health hazards associated with indoor radon gas, yield positive effects on trust in institutions responsible for risk management. Regrettably, in many countries authorities are not perceived as a reliable source of information regarding radon risk, for instance in Bulgaria (Djounova et al., 2023) or in the USA (deLemos et al., 2009). In our study, the trust construct is measured using three dimensions: confidence, trustworthiness, and competence.

As the authorities are entrusted with the responsibility of formulating and executing the national RAP, it becomes essential to assess the level of confidence that residents place in these governing bodies (Perko et al., 2023). Confidence in authorities was measured with regards to the actions undertaken by authorities to protect the population against nine

different risks, including radon.

Results show rather low confidence in authorities to protect the population against indoor air pollution due to radon, (49% have no or (very) little confidence), and the presence of the naturally radioactive gas radon indoors (47% have no or (very) little confidence).

The relationship between trust in authorities to effectively handle radon risks and intention to test and mitigate was not statistically significant (Table 2).

In terms of truthfulness (telling the truth about radon) and competence in managing radon risks, the survey findings indicate that the Jozef Stefan Institute stands out as the most trusted stakeholder, both in terms of truthfulness and technical competences. The results also showed that although health authorities are well-known, many respondents do not consider them a competent or trustworthy stakeholder regarding radon risks. In contrast, scientists from universities and the Radiation Protection Administration are relatively well-known, and their competences and trustworthiness are in general recognized. The lowest level of trust was placed in contractors for remediation, such as builders and companies measuring radioactivity. Additional analysis revealed that trust in mitigation contractors (within the building industry) and trust in radon measurement companies were significantly associated with the intention to test and mitigate (Table 2). However, trust in authorities and trust in the scientific organization, the Jozef Stefan Institute, did not have a statistically significant association with behavioural intention (Table 2).

4.11. Response efficacy: do individuals believe dwelling remediation is effective in reducing radon concentration?

An individual is more likely to intend to perform a behaviour, such as testing or mitigating for radon, only if they are convinced that it will lead to the desired outcome (Weinstein et al., 1990), (Weinstein et al., 1992b) and (Witte et al., 1998b) and (Dragojevic et al., 2014). Coping appraisal plays a crucial role in adopting or maintaining a health protection behaviour and helps overcome fears and mental blocks. Coping appraisal comprises three elements: response efficacy, self-efficacy and response costs (Hahn et al., 2019), (Rhodes et al., 2006), (Weinstein et al., 1998b, 1999). While most respondents agreed or strongly agreed that home remediation and special installations offer effective protection against radon hazards, some respondents expressed disagreement and uncertainty regarding the ability of special installations to reduce radon levels to a safe level. A test conducted to compare response efficacy scores between the participants who watched the video and those who showed no significant statistical differences. This suggests that exposure to a video may not have a significant impact on an individual's perception of the effectiveness of recommended behaviours. Another test was conducted to compare response efficacy scores between participants from high and medium risk areas and those from low radon risk areas, and the results were not statistically significant. Finally, a correlation analysis was conducted to examine the relationship between response efficacy scores and participants' intention to test and mitigate radon exposure, and the results showed a positive moderate relationship (Fig. 5). Participants who perceived the recommended behaviours as more effective were more likely to express the intention to test and mitigate radon exposure (Table 2). These findings highlight the importance of promoting accurate and effective information about radon mitigation to improve individuals' perception of the effectiveness of recommended behaviours and increase their intention to take action to protect themselves and others from the harmful effects of radon exposure.

4.12. Do residents have confidence in their ability to conduct radon testing and mitigation effectively?

Self-efficacy refers to the belief in one's own competence to perform a behaviour even in the face of barriers (Rhodes et al., 2006), (Weinstein

et al., 1998b, 1999). Higher levels of self-efficacy are associated with increased radon protection (Davis et al., 2018). Our study also revealed a moderate association between self-efficacy and intention to test and mitigate (Fig. 5 and Table 2). In addition, the results indicate that over 75% of individuals lack confidence in their ability to effectively remediate their homes. However, more than 63% express confidence in their capacity to hire a contractor to reduce indoor radon levels. Additionally, over 30% of respondents lack confidence in their ability to find the necessary information to protect themselves in the case of high radon levels in their homes. Around 33% remain neutral on the matter, while nearly 35% feel confident in their ability to access the required information to safeguard themselves against radon exposure. There is no notable variance in self-efficacy levels between individuals residing in high radon risk areas and those in low radon risk areas.

4.13. Financial burden, other burdens and ease: is radon testing and mitigation perceived as a financial or other burden?

Perceived behavioural control encompasses the assessment of financial resources, the ease of conducting radon testing and remediation, and the burden these measures may place on individuals, as highlighted in various studies (Weinstein et al., 1998c), (Weinstein et al., 1990), (Weinstein et al., 1992b) and (Witte et al., 1998b) and (Dragojevic et al., 2014). The study by Hevey et al. (2023) acknowledges that the costs of mitigation and the (lack of) availability of financial support have been recognized as significant burdens for radon mitigation by authorities, contractors, and residents. When the act of radon protection is perceived as burdensome, it can lead to low intentions to engage in protective measures (Weinstein et al., 1999). Moreover, it has been found that a low-effort intervention proved relatively more effective in getting decided-to-act people to order tests than in getting undecided people to decide to test (Weinstein et al., 1998a). Furthermore, Irvine et al. found that “among people finding high radon, 38% mitigated quickly, 29% reported economic impediments, and 33% displayed delaying behaviours. Economic barriers and delaying behaviours resulted in 8.4 mSv/year or 10.3 mSv/year long term excess exposure, respectively, increasing lifetime risk of lung cancer by ~30–40%” (Irvine et al., 2022) p.15471.

The findings reveal that approximately 48% of respondents feel confident in their ability to afford a radon test costing 50 euros, while 36.6% remain neutral, and 15.4% stated that they cannot afford it. Similarly, over 48% of people indicated their capacity to afford 1000 euros for radon mitigation, with 22% expressing neutrality and 14.6% were unable to cover the cost. In terms of financial burden, 48.8% of respondents agree or strongly agree that reducing radon in their homes would require more resources than they possess, while 35.5% disagree or strongly disagree with this statement. Overall, 65.6% of respondents believe that remediating their dwellings to reduce radon would be burdensome. Additionally, a significant majority (72.9%) perceive the procedure for remediating their homes due to radon as difficult. However, 58.6% believe that testing their dwellings for radon is relatively easy. No statistical differences were observed in terms of perceived behavioural control, burden, and ease between areas with high radon risk and areas with low radon risk. The findings indicate that individuals who lack confidence in their ability to procure 50 euros for radon testing tend to exhibit minimal or low intentions to take protective measures against radon exposure (Fig. 5 and Table 2).

4.14. Aesthetic impact: do residents believe that radon mitigation would visually harm their homes?

Turcanu and colleagues (Turcanu et al., 2020) revealed that homeowners may have concerns about mitigation measures visually impacting the aesthetics of their homes. Opposite to this, our analysis shows that a majority of people living in Slovenia do not believe that mitigation of a dwelling due to radon would visually harm their home, with a

smaller percentage perceiving a significant visual impact. A significant portion of respondents expressed uncertainty or ambivalence about the aesthetic consequences of radon mitigation. Overall, there was no association found between aesthetic impact and behavioural intention (Table 2).

4.15. Does a radon problem in a building negatively impact its financial value?

The study assessed the economic impact of radon on property value using a single-item measurement. A majority of respondents (64.7%) agreed or strongly agreed that radon problems can indeed influence a property's value, thus recognizing the potential economic impact associated with radon issues. Approximately 24.2% of respondents neither agreed nor disagreed, suggesting some level of uncertainty or lack of opinion on the matter. Conversely, 11% of respondents disagreed or strongly disagreed with the statement, indicating a perception that radon problems have minimal influence on property value.

These findings provide valuable insights into participants' perspectives on the economic implications of radon on property value. They highlight that a significant portion of respondents acknowledge the potential impact, while a smaller proportion expresses scepticism or lack of concern regarding this matter. However, the relationship between the impact of radon on a property's financial value and behavioural intention was found to exhibit a very weak level of association (Fig. 5) (Table 2).

4.16. Subjective norms: do family members and friends of respondents care about radon-related issues?

Subjective norms refer to the belief that an important person or group of people will approve and support a particular behaviour, for instance, protecting oneself against radon (test and/or mitigate). Subjective norms provide valuable insights into participants' perceptions of the support and approval they receive from important individuals regarding radon-related behaviours (Clifford et al., 2012) and (Park et al., 2001), (Turcanu et al., 2014). They were identified as playing a significant role in influencing one's intention to measure their home for radon. This finding can be strategically leveraged to promote greater adoption of radon measurement in the future, as demonstrated in the study by Clifford et al. (2012). Furthermore, our study confirms the findings of previous research; it reveals a moderate association between subjective norms and the intention to test and mitigate (Fig. 6) (Table 2). Nevertheless, our study's findings point to a wide array of perspectives among participants, with many individuals expressing challenges in gauging the attitudes of their family and friends towards radon mitigation. Regarding radon testing, nearly half of the participants (47.7%) perceive that the important people in their lives are either neutral or unsupportive of them testing for indoor radon. However, an equal percentage (47.7%) believes that the important individuals in their lives are in favour of radon testing.

In terms of radon remediation, a significant proportion of participants (49.4%) believe that the important people in their lives are not supportive of remediating their homes for radon if necessary. On the other hand, 17.9% perceive support from important individuals for radon remediation.

When it comes to being informed about radon, a considerable portion of participants (45.8%) believe that the important people in their lives value their knowledge and awareness about radon. However, 15.6% perceive that these important individuals may not prioritize being informed about radon.

In terms of the care shown by significant individuals in their lives regarding radon-related actions, a majority of participants (54.1%) believe that these individuals do care about their actions related to radon in their homes. Conversely, a small percentage (12%) perceive that these individuals do not place importance on their radon-related

actions.

Overall, these findings highlight the varying perspectives participants have regarding the support and approval they receive from important individuals for radon-related behaviours. It emphasizes the importance of understanding the social context surrounding radon testing, radon mitigation, and being informed about radon-related issues.

4.17. Descriptive norms: is radon testing and mitigation a common practice within social groups?

Descriptive norms refer to the perception of what is considered typical or normal behaviour within a group. It involves understanding what most people in a specific context think, feel, or do (Cialdini et al., 1990). In the context of radon, descriptive norms pertain to individuals' perceptions of others' behaviour regarding testing for radon and mitigating their homes. The Potsdam Radon Communication Manifesto explicitly underscores that descriptive norms could potentially be one of the most influential factors shaping radon protection behaviour (Bouder et al., 2021).

The results revealed that there is a significant belief among participants that most people in their neighbourhood have tested their houses for indoor radon. However, participants expressed a prevailing perception that the people they know, including their friends, do not engage in activities related to indoor radon. Additionally, participants perceived that remediation of houses for radon, when levels exceed the limits, is not a common practice in their neighbourhood. Furthermore, we examined whether descriptive norms could predict the intention to safeguard against radon: individuals are more inclined to partake in radon testing and mitigation measures when they perceive these actions as customary or typical within their social circles. This finding, as depicted in Fig. 6, substantiates previous assumptions by Bouder et al. (2021). Further analysis revealed no statistically significant difference in descriptive norms between areas with medium/high radon risk and areas with low radon risk (Fig. 6 and Table 2).

4.18. Stigma: is there a risk of stigma associated with radon in dwellings?

Stigma is a social phenomenon characterized by the disapproval or negative judgment associated with a particular circumstance, attribute, or individual. Participants in the study by Khan and Chreim (Khan et al., 2019a) cited stigma as a significant barrier to domestic radon testing and mitigation. Our study explored participants' attitudes towards the handling of radon-related issues, with a focus on the potential stigma associated with them. Interestingly, the results indicate that a majority of participants are quite open to discussing radon matters, as 69.1% disagreed with the notion of keeping a radon problem secret, and 80.4% disagreed with the idea of being cautious about sharing radon-related information. However, the association between stigma and behavioural intention is negligible (Table 2 and Fig. 3).

4.19. Is there enough radon information readily accessible?

Numerous studies have been conducted in the field of radon information. For a systematic overview of such studies, refer to Apers et al. (2023a). A study by Perko and Turcanu conducted in 2017 (Perko et al., 2020a) shows that the availability of radon information on the internet in radon prone areas is often limited, that radon websites should be improved with consistent information supported by engaging stories, provide for personalized features, support stakeholder feedback and dialogue, and include the use of social media. In our study, the information comprehensiveness measures the extent to which respondents have sufficient information concerning radon and performing radon tests at home. In our study, 38.3% of the respondents feel well informed about which actions are needed related to indoor radon levels. Approximately 33% of the answers indicated neither agreement nor

disagreement. The remaining respondents (27.8%) consider their knowledge rather limited to estimate the needed actions. In addition, the majority of the respondents (68.8%) feel well informed about whether or not to test for radon indoors. Just under 10% do not concur with this opinion and indicate they (strongly) disagree. Furthermore, about 20% of the respondents appear to be indifferent. These findings suggest that while a significant number of respondents feel that there is enough information available for them to decide performing a radon test at home, there is still a considerable proportion of individuals who are uncertain or feel uninformed about this matter. However, information comprehensiveness and behavioural intention are not statistically significantly associated (Table 2).

4.20. Is there too much uncertainty to make informed decisions related to radon?

In radiation protection, it is advised to openly and transparently communicate about uncertainties (Hoti et al., 2020). Greater uncertainty necessitates increased communication (Perko et al., 2020b). Uncertainty communication related to radiological risks influence emotional arousal, but it does not generate negative feelings such as anger or fear (Hoti, 2023) and it does not cause panic (Perko et al., 2020b). In our study, participants were asked to rate their level of agreement with the following statement: "Information about the health effect of radon is still too uncertain to take actions based on it." A significant portion of the respondents (40.6%) holds a neutral stance toward the statement, while 32.9% of respondents either agree or strongly agree with it. In contrast, 26.5% of respondents disagree or strongly disagree with the statement. As expected, uncertain information related to radon was found to have no significant association with behavioural intention (Table 2).

4.21. Affective response to information: does information related to radon elicit negative emotions?

The term "affective response to information" refers to the emotional or feeling-based reactions and attitudes that individuals experience when they receive and process information through various communication channels (Renn, 1992). This concept acknowledges that radon communication is not solely about the transmission of facts and data, but also involves the elicitation of emotional reactions in the audience.

Our findings suggest that information related to radon, whether acquired before the survey or through the video presented during the survey, does not trigger substantial emotional reactions among the respondents. The majority of individuals tend to remain neutral when it comes to feelings of concern or nervousness regarding the potential impact of radon-related information.

However, the results demonstrate a clear relationship between emotional responses to radon-related information and the intention to take protective measures (Fig. 6). A stronger emotional reaction to information about radon corresponds to a higher likelihood that respondents express the intention to conduct radon testing or engage in mitigation efforts (Table 2). This discovery aligns with previous research on radon risk communication, where scholars have recommended incorporating emotional appeals into radon risk communication as a means to motivate individuals to engage in testing and mitigation measures, e.g. (Apers et al., 2023b), (Khan et al., 2019a), (Alsop, 2001).

4.22. Which communication channels are recommended for radon-related communication?

As anticipated, the majority of respondents (61.2%) have shown limited interest in further information concerning radon. However, among those who express a willingness to receive additional radon-related information, the preferred communication channels are television (35.9%), radio (35.3%) and newspaper (33.3%). Other options that

are also preferred are leaflet (31.8%) and personalized information letter (31%). 17.6% of the respondents would like to be informed through information from the school, while 16% prefers social media as a communication channel. Only a small fraction indicated a meeting with the local community (11.2%), info via phone (7.7%) or email (6.4%). The preferred sequence of communication channels validated in this study corroborates the results from radon communication workshops conducted in Slovenia by [Apers et al. \(2023b\)](#).

5. Study applications and limitations

Though the development and testing of scales measuring a wide range of concepts, this study provides researchers, authorities and practitioners with a useful and multipurpose survey tool to study the complexity of human behaviour in the context of radon.

By highlighting factors that influence people's testing and mitigation behaviour it also supports authorities' efforts to improve the number of radon mitigations in dwellings. For instance, the Slovenian case study revealed that potential for affective response (emotions) and perceived susceptibility had the strongest positive correlations with the intention to protect from radon risk. This underscores the key role of emotions such as affective responses, worry, and potential fear in driving residents' intentions to adopt radon protection measures. Alongside the positive association between intention to engage in protective behaviours and perceived severity, it also shows the importance of including personal testimonials in communicating about radon risks. Positive correlations were also observed between behavioural intentions and subjective and descriptive norms, showing that risk communication interventions should not only focus on the individual but also their social context and the knowledge sharing practices in the community. In contrast, the correlation between concepts like radon awareness and radon knowledge and the inclination to adopt radon protection behaviours appears less robust. This suggests that national RAPs should not solely emphasize raising awareness and knowledge but should also consider other critical aspects. Additional research in this area is however essential, since correlation implies that the variables tend to change together in a linear fashion, but it does not necessarily indicate that changes in one variable directly lead to changes in the other.

The surprising result revealed that there were almost no differences found in the measured concepts between medium/high radon risk areas and low-risk areas. This lack of distinction was evident even in terms of the intention to protect oneself, susceptibility, or the knowledge of stakeholders involved in radon-related issues. This demonstrates that the outreach and engagement efforts conducted so far were not well-targeted to specific population groups.

Due to the low number of people familiar with radon, we decided to share basic information about radon with the survey respondents in order to enable all respondents in this survey to respond to the socio-psychological radon related questions and statements. We did this in the form of a video in order to bring some dynamic in a long questionnaire. Differences between respondents exposed to the video and those who were not exposed were controlled for and in few cases these differences were statistically significant. More research is needed to study the effect of such a communication embedded in a survey and understand whether the difference was caused by the communication itself or by differences in familiarity with radon.

A key limitation of this study pertains to the primary focus on the intention to test and mitigate radon, which does not necessarily translate into actual behaviour. In radon-related research, intention is commonly measured as a vital predictor of whether individuals will take steps to test for and mitigate exceeded radon levels in their homes. However, it's essential to acknowledge that while intention can be a valuable predictor of behaviour, there are instances where individuals express a strong intention to test and mitigate radon levels but may not follow through due to various reasons. Conversely, some may have low intentions but proceed with testing and mitigation, influenced by external

factors such as government regulations or public health campaigns ([Hevey et al., 2023](#)). A comprehensive approach is imperative, encompassing the examination of both intention and actual behaviour, as well as the multifaceted factors that impact them directly or indirectly.

6. Conclusions

Public opinion surveys have become the instrument of choice for authorities to inform national RAPs in terms of actions aimed at increasing the mitigation of indoor radon exposure in dwellings. This study has developed, validated and analysed survey items and scales, pertaining to key theory-driven socio-psychological concepts relevant in the context of radon risk management. These tools offer a reliable foundation for assessing gaps and strategies to increase testing and remediation of homes. They support RAP owners and researchers of societal aspects of radon management to design focused, validated and reliable surveys that provide the scientific evidence basis for improved radon policies. Radon authorities can then utilize these insights to fine-tune their communication and engagement strategies in the realm of radon management.

Additionally, this research has shed light on the concepts closely intertwined with radon testing and mitigation. As a result, future questionnaires can be more focused on these critical aspects. Further research should investigate whether the strength of such associations differs depending on the cultural context and to what extent they can be linked to causal relationships.

Given that radon management involves complexities across various levels—individual, interpersonal, organizational, community, and societal—a comprehensive questionnaire should assess respondents' attitudes and experiences across all these dimensions. Embracing this holistic approach to surveys allows researchers and policymakers to attain a more nuanced understanding of the varying factors that prompt certain individuals to test for and mitigate radon levels, ultimately facilitating the development of more effective strategies to encourage these behaviours.

This questionnaire has provided invaluable insights for enhancing communication interventions in radon priority areas. Despite authorities implementing various communication strategies, a considerable lack of interest in radon testing prevails amongst the general population, alongside notably low compliance among residents regarding radon mitigation in dwellings. The findings underscore the necessity for communication interventions to be more precisely tailored towards specific population groups rather than employing generalized approaches. Furthermore, the study makes it evident that simply enhancing awareness and knowledge about radon is insufficient to increase the testing and mitigation of dwellings. Effective communication interventions must pivot towards eliciting emotions, leveraging narrative stories, highlighting successful mitigation cases, and utilizing personal testimonies from individuals affected by lung cancer. Focusing on these factors and integrating positive social norms, such as "*an increasing number of people in the radon priority areas have already tested and mitigated their homes*," is crucial to inspire more individuals to engage in testing and mitigation measures.

CRedit authorship contribution statement

Tanja Perko: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing. **Peter Thijssen:** Conceptualization, Methodology, Supervision, Visualization. **David Hevey:** Conceptualization, Methodology, Supervision. **Catrinel Turcanu:** Conceptualization, Methodology, Supervision, Validation. **Melisa Muric:** Data curation, Formal analysis, Methodology, Software, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tanja Perko reports financial support was provided by the Euratom research and training programme 2019–2020 under grant agreement No 900009. The field study was funded by SRPA, Slovenia. Tanja Perko reports a relationship with Euratom research and training programme 2019–2020 under grant agreement No 900009 that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Annex

Table A

Constructs, items and reflective scale attributes

Construct	Items	Factor loading Principal axis or correlation between two items	Cronbach's Alpha or Spearman-Brown statistics for two items N out of 2012(%)
Intention to protect from radon	RA5_1 I intend to test radon concentrations in my home if advised.	0.94	0.92 N = 1691 (84 %)
	RA5_2 I intend to measure radon in my home as a precaution.	0.91	
	RA5_3 I intend to start the remediation of my home if advised.	0.82	
Severity	RA12 Not acting when there is a high radon concentration in my house would be a severe threat to my health.	0.81	0.91 N = 1812 (90.1%)
	RA12_1 Not undertaking any action against high radon concentration in my house would be life-threatening for me.	0.84	
	RA12_2 If my neighbours had high radon concentrations and don't remediate their health would be in severe danger.	0.9	
Susceptibility	RA12_3 If people in my community address the radon risk, then they can avoid serious health issues due to radon.	0.83	0.85 N = 387 (85.4%)
	RA13 I believe that I can develop lung cancer due to radon if I don't tackle high concentration in my home.	0.85	
	RA14 How likely do you think it is that you will get sick if you don't remediate high radon concentrations?	0.88	
Self-efficacy	RA14_1 I will remain healthy although I don't remediate high radon concentrations in my home	Excluded	0.69 N = 1845 (91.7%)
	RA15 How likely do you think people in your neighbourhood will get sick if they don't remediate high radon concentrations?	0.7	
	RA21_b I am NOT confident that I will be able to effectively remediate my home if I wanted to.	excluded	
Perceived behavioural control	RA22 I am confident I would be able to hire a contractor to decrease the indoor radon concentration if I wanted to.	0.73	0.72 N = 1907 (94.8%)
	RA33 I am confident that in the case of high levels of radon in my home, I will find the information needed to protect myself.	0.73	
	RA22_a I am confident that I could obtain 50 euros to test for radon if needed.	0.76	
Perceived burden	RA22_b I am confident that I could obtain 1000 euros to remediate for radon if needed.	0.76	0.82 N = 1738 (86.4%)
	RA23_1 I believe reducing radon in my home would require more resources than I have.	0.84	
Subjective norms	RA23_2 I believe reducing radon would be burdensome for me.	0.84	0.7 N = 1230 (61.1%)
	RA34 Most people who are important to me are NOT in favour of me testing for indoor radon.	-0.46	
	RA34_b Most people who are important to me are in favour of me remediating my home for radon if needed.	0.77	
Descriptive norms	RA34_1 In general, people who are important to me would like me to be informed about radon.	0.7	0.8 N = 1402(69.7%)
	RA34_2 People who are significant in my life don't care about my actions related to radon in my home.	-0.51	
	RA35 I believe most people in my neighbourhood tested their houses for indoor radon.	0.80	
Stigma	RA35a I believe most people that I know does something related to indoor radon.	0.71	0.76 N = 1915(95.2%)
	RA36 I believe most people in my neighbourhood remediated their houses when indoor radon levels exceeded the limits.	0.75	
	RA37 As far as I know, most of my friends living in the same neighbourhood did NOT test their houses.	excluded	
Affective response to information	ST2 I would work hard to keep a radon problem a secret.	0.79	0.81 N = 1910 (94.9%)
	ST4 I would be very careful whom I tell I radon problem in my home.	0.79	
	RA10 Information about radon makes me worry.	0.82	
	RA11 Information about radon makes me nervous.	0.82	

* Principal axis factoring analysis without rotation.

Table B
Response efficacy items correlation

Response efficacy	RA17	RA18_1	RA19	RA19_1
RA17 Home remediation, if needed, offers effective protection against radon hazards.	1			
RA18_1 Home remediation, if needed, will fail to protect from high radon concentrations.	-0.08 p=<0.001	1		
RA19 A special installation would eliminate the radon hazard if needed.	0.5 p=<0.001	0.04 p = 0.04	1	
RA19_1 A special installation can NOT reduce radon to a safe level in homes that have a radon problem.	-0.08 p=<0.001	0.32 p ≤ 0.0001	-0.16 p < 0.0001	1

Table C
Items for perceived ease, visual & economic impact and information comprehensiveness

(Multidimensional) constructs and one item measurements	Items	N (out of 2012)	Mean (min = 1, max = 5)	Std. Deviation
Perceived ease	RA24 I believe the procedure for radon testing my home is easy.	1579	3.39	0.93
	RA25 I believe the procedure for remediating my home due to radon is difficult.	1537	3.41	0.95
Aesthetic impact	RA51 Remediation due to exceeded levels of radon would visually destroy my home.	1535	2.46	0.88
Economic impact	RA51_b A radon problem can influence the value of property.	1829	3.69	0.97
	RA30 I don't feel well informed about which actions are needed related to indoor radon levels.	1953	3.79	0.94
Information comprehensiveness	RA31 There is enough information for me to decide whether I should perform a radon test at home.	1866	2.82	1.04

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