The human side of geoscientists: comparing geoscientists' and non-geoscientists' cognitive and affective responses to geology

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Abstract

Geoscientists and non-geoscientists often struggle to communicate with each other. In this paper we aim to understand how geoscientists and non-geoscientists perceive geological concepts and activities, that is, how they think (cognitive responses) and feel (affective responses) about them. To this effect, using a mixed-methods approach, we compare mental models – people's representation of a phenomenon - of the subsurface, mining/quarrying, and drilling, between geoscientists (n=24) and non-geoscientists (n=38) recruited in Ireland. We identify four dominant themes which underlie their mental models: (1) degree of knowledge and familiarity, (2) presence of humans, (3) affective beliefs, and (4) beliefs about perceived impact of the activities. While the mental models of the non-geoscientists focused more on the perceived negative environmental and economic impacts of geoscience, as well as providing evidence of lay

expertise, those of the geoscientists focused more on human interactions. We argue that mental models of geoscientists and non-geoscientists are the result of beliefs, including both cognitive and affective components, and that both components need to be acknowledged for effective dialogue between the two groups to take place.

Introduction

Geoscience activities such as mining, quarrying, hazard risk management and landscape management are an integral part of society, affecting local communities, citizens and scientists. In their work, geoscientists must engage and work with people from other backgrounds and disciplines (Barthel & Seidi, 2017), as their work often directly involves and impacts different publics (e.g. Juang *et al*., 2019). However, geoscientists often struggle to communicate with non-geoscientists, particularly around controversial topics such as resource extraction and risk communication. For instance, past studies have investigated public perception and risk communication in the case of fracking (e.g. Boudet *et al*., 2014; Thomas *et al.*, 2017), carbon capture and storage (Seigo *et al*., 2014) and earthquakes (e.g. Marincioni *et al*., 2012). Specifically, in the context of earthquake risk communication, Marincioni *et al.* (2012) studied the case of the 2009 earthquake in l'Aquila, Italy, as a result of which 308 people died: the authors identified a lack of clear communication from the risk management authorities to the public in relation to earthquake prediction and structural resistance of buildings. In the context of public perception of carbon capture and storage, Seigo *et al.* (2014) compared risk and benefit perceptions of the technology in different Canadian regions, and found that predictors of risk perceptions, such as sustainability concerns, did not vary across different regions and were unrelated to familiarity with the technology. The authors also point out that there is a need to address lay people's "misconceptions" related to carbon capture and storage, in order for informed decisions to take place. In the context of a public perceptions of fracking, Thomas *et al*., 2017, in a literature review, identified mixed levels of awareness of shale operations, as well as ethical issues and widespread distrust of responsible parties. Other studies concerning fracking, such as that by Boudet *et al.* (2014), which looked at public perceptions of fracking in the U.S., found differences in perception between different genders, socioeconomic backgrounds, income levels and level of education, and highlighted a need for “wide ranging and inclusive public dialogue” around the risks and benefits of fracking. For effective, dialogic communication (e.g. Davies and Horst, 2016; Wildson and Willis, 2004) between geoscientists and non-geoscientists to take place, both groups must understand one another, i.e., the audience they are engaging with (Pidgeon and Fischoff, 2011).

A starting point from which to understand each other is to investigate the differences between geoscientists, defined as anyone with at least a university degree in geology or geoscience, and non-geoscientists, defined as those without such a degree. While acknowledging that those without a degree in geoscience may well possess expert knowledge relating to geoscience, we choose to adopt these definitions as indicators of expertise, and as useful starting points from which to discuss differences and similarities. Specifically, we investigate these differences by adopting the concept of mental models, which are defined for our purposes as an individual’s internal representation of a phenomenon, or a way for people to interpret and navigate the world (Johnson-Laird, 1983, 2010, 2013; Libarkin *et al.,* 2003).

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In the context of science education, Libarkin *et al.* (2003) recognise four categories of cognitive (mental) models: “conceptual models” which are precise, highly-stable representations of the world used by geoscientists (for instance, aquifer models); “conceptual frameworks”, organised and stable models of the world used by geoscientists (for instance, the notion of gravity); “naïve mental models”, intuitive models of the world that so-called ‘novices’ fill with fragmented and unconnected knowledge (for instance, the notion that the Earth is flat); and “unstable mental models”, unstable, incomplete and inexact mental models which are used by novices and easily modified (for instance, the idea that the Earth is spherical, but with flattened portions where humans live). “Conceptual mental models” are the result of cognitive change, often due to repeated cognitive engagement with the same problems and phenomena, and thus we envisaged that geoscientists’ mental models should conform to these, and non-geoscientists’ mental models should conform to Libarkin’s “naïve mental models” or "unstable mental models", as they are typically based on intuition and local knowledge.

Mental models have previously been used to understand non-experts’ perceptions of geoscience-related topics. For instance, Bostrom *et al.* (1994) investigated non-experts’ mental models of climate change, and found that global warming was regarded as “both bad and highly likely”. Zaunbrecher *et al*., (2018), investigating non-experts’ mental models of geothermal energy, identified varying attitudes and knowledge levels among participants, with negative emotions being evoked by the concepts of drilling and power stations. These studies also stress that there are emotional or affective components underlying the mental models of non-experts.

However, most mental models studies focus merely on cognitive components (e.g. Gibson *et al.,* 2016; Goel, 2007; Johnson-Laird, 2010, 2013; Shipton *et al.,* 2019) or on the cognitive superiority of geoscientists over non-geoscientists (Libarkin *et al.,* 2003; Vosniadou and Brewer, 1992). Here, we argue that mental models should also incorporate subjective and affective representations of a phenomenon, for both geoscientist and non-geoscientists.

Affect is a general positive or negative feeling that people may experience about an event, a situation, a technology or a process (Finucane *et al*., 2000). An affective response is thus the response to such an event, situation, technology or process, based on positive or negative feelings. Misperceptions of geological activities among the public are often attributed to affective and emotional processes (Devine-Wright, 2005; Finucane et al., 2000; Loewenstein et al., 2001). The role of emotions in risk perception and communication around nuclear waste has been investigated by Sjöberg (2007), who argued that emotions such as interest play an important role in risk perception and attitude. In Zaunbrecher *et al.'s* (2018) study of public perception of geothermal energy, an association between positive emotions and the acceptance of geothermal energy was identified. Similarly, Thomas *et al*. (2015) identified negative emotions in the mental models of non-experts when considering sea level change. While these studies recognise emotions as a component of the mental models of non-geoscientists, far less is known about the affective responses of geoscientists, and how they influence their mental models, as well as how they compare with those of non-geoscientists.

Compared with the number of studies focusing on non-experts or publics, fewer studies have used mental models to compare experts' and non-experts' perceptions. For example, Gibson *et al*. (2016) identified mismatches in perceptions of subsurface hydrology and geohazards between experts and non-experts. In a study comparing experts' and non-experts' mental models of nuclear waste, Skarlatidou *et al.* (2012) described non-experts' negative perceptions of nuclear waste as co-existing with a positive attitude towards nuclear energy, as well as lack of knowledge and familiarity, and discussed implications for risk communication. In the context of sea-level change, Thomas *et al.* (2015) identified both consistencies between the mental models of experts and non-experts, and barriers to publics engaging with the issue, and argued that factors other than knowledge bear an influence on the mental models of non-experts. These factors include "levels of concern, perceptions of self-efficacy and responsibility, trust and ways of actively engaging with or avoiding the issue" (Thomas *et al*., 2015, p.78).

The main goal of the present paper is to investigate how evaluation of both cognitive and affective beliefs underlie the mental models of geoscientists and non-geoscientists. We define beliefs as ”psychologically-held understandings, premises or propositions about the world that are felt to be true” (Richardson, 1996, p. 103).

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To this end, we used a mixed-method approach and identified the cognitive and affective underlying beliefs of geoscientists’ and non-geoscientists’ mental models. We chose to recruit participants from a rural community in Ireland where geologists typically conduct fieldwork (Martinsen *et al*., 2017) because the area’s spectacular Carboniferous geology lends itself to public engagement events. Better understanding the community will allow geoscientists and public engagement practitioners to develop such public engagement activities. While our sample of geoscientists (n=24) working across Ireland and non-geoscientists (n=38) recruited in a rural community in Ireland is not representative of all geoscientists and non-geoscientists in all settings, we suggest that understanding differences and resemblances of both the cognitive and affective components of mental models of geoscientists and non-geoscientists can help to improve two-way communication between them about often-contested areas of the geosciences.

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Materials and methods

The aim of this paper was to investigate the beliefs underlying the mental models of Irish geoscientists vs non-geoscientists around geological concepts and activities and use this to build future communication strategies.

To that end, a face-to-face survey was conducted with geoscientists (n=24, recruited across Ireland) and non-geoscientists (n= 38, recruited in a rural community in Ireland) to compare their mental models and underlying beliefs about the subsurface of the

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Earth, applied-geoscience activities (mining/quarrying and drilling), and geohazards (flooding). To establish their mental models, respondents were asked to sketch the activities, geohazard, and the subsurface to any depth they wished. Follow up questions about respondents' emotions and perceived outcomes of the activities and hazard were also included in a short survey.

In our analyses, we used a mixed experimental set-up of between-subjects design (to compare geoscientists vs non-geoscientists) and within-subjects design (to investigate sketches of subsurface, drilling, mining/quarrying, flooding within our sample group of geoscientists or non-geoscientists). Moreover, a mixed methods approach was used (i.e., a mixture of qualitative and quantitative methods) to investigate their beliefs about the subsurface and geological activities. Analyses of the qualitative results were done through qualitative thematic analysis (Boyatzis, 1998; Marshall and Rossman, 1999) and quantitative data were tested on statistical significance using the IBM SPSS Statistics 24 software package.

Procedure

Face-to-face surveys were conducted among 24 geoscientist and 38 non-geoscientist participants as detailed below. A summary of the socio-demographics of both is presented in Table 1. The geoscientists who took part in the study ranged in age from 21 to 59, with most identifying as male (58%), aged 21-29, and educated to degree level. The higher number of males is consistent with underrepresentation of females in geoscience (Dutt *et al.*, 2016). Most non-geoscientists identified as female (63%), aged 60 or older and educated to less than degree level and their age ranged from 16 to 60 or over. For a discussion of the limitations associated with our sample, see Limitations.

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Table 1. Sociodemographic details across all study participants.

	Geoscientists (n)	Non-geoscientists (n)
Female/ Male	42% females/ 58% males	63% females/37% males
Age		
16-21	0	1
21-29	14	7
30-39	8	3
40-49	1	8
50-59	1	5
60 or older	0	13
Declined to answer	0	1
Educational level		
less than degree level	0	18
to degree level	14	16
Other (higher than degree level)	10	4

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Non-geoscientists were recruited on several locations in County Clare, western Ireland, between August 2017 and February 2018 (see Table 1 for socio-demographic details). County Clare was chosen because it is a popular destination for geoscientists from academia and industry in the Republic of Ireland (e.g. see Martinsen *et al.,* 2017). It is an excellent setting for non-geologists to learn about geology, as well as one of the top tourist destinations in Ireland. Given the popularity of the area with geologists, we also anticipated that non-geoscientists living in the area may have a relatively high level of familiarity with geology or with groups of geologists, thus potentially providing useful insights for dialogue in this community.

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Invitation letters were posted to 50 addresses selected randomly using the online (Eir) phonebook and follow-up telephone calls were made to schedule a time for the survey to take place. In the invitation letters, participants were asked to take part in a study investigating public perception of geology, including knowledge about the geology of Co. Clare and the subsurface. No specific information on the aims of our study was provided in order to minimise response bias. This method was supplemented by convenience sampling in local businesses in Co. Clare. Details of those who did not wish to participate were immediately destroyed. Before commencing any interviews, following University College Dublin's ethical guidelines, all interviewees provided informed consent.

No incentives were offered for participation. The survey was administered in person by the lead author. Each survey took approximately 20-30 min to complete. Relevant spoken quotes by respondents during survey completion were written down by the lead author as support information and were included in the analysis.

Geoscientists were defined as people with a degree in geoscience, either working or doing research in the geosciences. They were recruited using convenience sampling techniques and ranged from MSc students (n=1), PhD students (n=11), and postdoctoral researchers (n=7), to professional geoscientists working in geoscience industry and academia (n=4) or education centres (n=1).

All participants were offered the opportunity to have the results of the research sent to them by sharing their contact details. Contact details were immediately separated from the data to guarantee anonymity.

Face-to-face survey

The survey was aimed at qualitatively assessing underlying beliefs of respondents' mental models of the subsurface, drilling, mining/quarrying, and flooding. This qualitative analysis was supplemented by quantitative analysis of survey responses.

First, respondents were asked: 'please sketch the ground under your feet starting from the surface of the earth down to any depth'. They were then asked to make sketches of drilling, mining/quarrying and flooding, a common way of measuring mental models (e.g. Gibson *et al*., 2016).

For drilling, mining/quarrying, and flooding, there were follow-up quantitative questions on the environmental and economic impacts, and the emotions associated with the activities and hazard. Flooding did not yield reliable scales for affective responses or significant results for perceived impact, hence it was excluded from further analyses and from the rest of the results.

Perceived environmental and economic impact of the activities were measured on a 5-point Likert scales ranging from totally disagree (1) to totally agree (5). To measure the perceived economic impact, after each sketch (of drilling and mining/quarrying) respondents were asked whether drilling or mining/quarrying *will improve the local* *economy*. Perceived environmental impact was measured by asking whether drilling or mining/quarrying *will have a negative impact on the local natural environment.*

Next, respondents were asked to rate how well a given emotion described their feelings towards drilling and mining/quarrying, respectively. They indicated which feeling they identified with from a list of 16 different feelings on 5-point bipolar scales, of which 8 were negative emotions (i.e., irritated, angry, hostile, frightened, frustrated, upset, concerned, deceived) and 8 positive emotions (i.e., optimistic, satisfied, inspired, enthusiastic, relaxed, excited, safe and interested). The measures were based on scales previously used by Sjöberg (2007), Roderiquez *et al*., (2018), and Visschers and Siegrist (2014). The negative and positive affective responses both formed reliable scales (Table 2), which is indicated by scores of Cronbach's alpha of 0.70 or higher (Peterson, 1994), and the mean scores on negative and positive affective responses were computed and used in further analysis.

Table 2. Reliability, mean (M) and standard Deviations (SD) of scales of affective responses and perceived impact.

	Geoscientists			**Non-geoscientists**		
	Cronbach's Alpha	**M**	**SD**	**Cronbach's Alpha**	**M**	**SD**
Affective responses						

Negative affect drilling	0.881	1.49	0.61	0.918	2.32	1.02
Positive affect drilling	0.944	3.19	1.12	0.953	2.40	1.09
Negative affect mining/quarrying	0.853	1.42	0.53	0.886	2.28	0.97
Positive affect mining/quarrying	0.958	3.02	1.22	0.835	2.22	0.87
Perceived impact						
Economic impact drilling	N/A	3.40	1.27	N/A	2.62	1.08
Economic impact mining/quarrying	N/A	4.05	1.39	N/A	2.94	1.35
Environmental impact drilling	N/A	2.16	0.92	N/A	3.48	1.39
Environmental impact mining/quarrying	N/A	3.05	0.80	N/A	3.74	1.22

Note: Whenever Cronbach's Alpha was not relevant (i.e., for single items) N/A is written in the table.

Analysis strategy

Analysis of the sketches

The first and second authors examined the sketches using a grounded theory approach taken as "the progressive identification and integration of categories of meaning from

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data" (Willig, 2008, p.35). This allowed the identification of six indicators of knowledge and familiarity in the sketches, namely: amount of *technical jargon*, defined as the presence of technical and subject-specific vocabulary in the labels of sketches, *sense of scale,* which refers to an indication of the awareness of the size of different elements included in the sketches (usually provided by a point of reference such as a scale bar); *number of layers,* the number of layers of rock or other material in the sketches; *number of labels,* the number of labels included in the sketches; *depth*, which refers to the depth to which they sketched the subsurface, ranging from the ground surface (coded as 1) to the core (5); and *human interactions*. The authors scored the sketches independently based on this. Pearson's correlation was used to determine the inter-rater reliability, which was deemed acceptable (Pearson's $r \geq 0.7$, $p \leq 0.001$).

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To test the differences between geoscientists and non-geoscientists on the six pre-defined indicators, Independent Sample T-tests and ANOVA Repeated Measures analyses were conducted using the IBM SPSS Statistics 24 software package.

These results informed our qualitative analysis of the sketches, whereby the sketches were subsequently analysed by means of thematic analysis to identify themes that were common to some or all of the sketches (Boyatzis, 1998; Marshall and Rossman, 1999). Thematic analyses were conducted manually by the first author.

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Analyses of perceived impact and affective responses

As we had a mixed design of between-subjects (geoscientists vs non-geoscientists) and within-subjects (drilling and mining/quarrying), we conducted two ANOVA Repeated Measures with geoscientists and non-geoscientists as between-subjects variables and perceived impact and affective response as dependent variables, respectively. Posthoc t-tests as part of the ANOVA Repeated Measures were run to compare in detail the cognitive and affective responses of geoscientists and non-geoscientists.

Results

Thematic analysis was used to analyse all sketches and written comments on the survey. We identified four common themes: (1) knowledge and expertise relative to the topics, (2) beliefs about human interactions (presence of humans in the sketches), (3) affective beliefs, and (4) beliefs about the impact on the economy or environment.

Knowledge and expertise

Technical knowledge and familiarity

The mental models of geoscientists contained indicators of detailed, technical knowledge and familiarity with geoscience content stemming from years of training and from professional expertise (e.g., see Cronin *et al.,* 2004). Specifically, the sketches made by geoscientists extended down to a greater *depth*, included more *technical jargon* related to geoscience, more *labels*, more *layers* within the Earth's interior, and a greater *sense of scale*, compared to those of non-geoscientists (Fig. 1). For instance, it was common for geoscientists to extend their sketches down to the mantle and/or core.

It is not surprising that geoscientists included these indicators of technical knowledge in their sketches given that drawing and sketching the landscape and the Earth's interior are skills typically acquired during geoscience undergraduate education (Johnson & Reynolds, 2006) and given the importance of spatial visualisation as a geoscience skill (Titus & Horsman, 2009). Without being prompted to do so, some geoscientists also included colours and colour-coding in their sketches, which is another habit likely to have been acquired during undergraduate geoscience training and thus linked to technical knowledge. Geoscientists may also have enjoyed the task of sketching to a greater extent, wanting to provide as much information as possible: for instance, a sense of enjoyment was reflected in the inclusion of smiles on the faces of stick figures in one geoscientist's sketch, which also included different types of fossils and crystal shapes (Fig. 1g). It was not uncommon for geoscientists to include exclamation marks in their labels, such as "*Hawaii!*", indicating engagement with the process of sketching and enjoyment. A greater degree of technical knowledge and familiarity with geoscience in the sketches of geoscientists is consistent with the assumption that geoscientists have "conceptual mental models", which are developed based on their expertise and training in geoscience.

Conversely, the lower levels of detail and technical knowledge in the sketches of non-geoscientists may reflect lack of knowledge but may also be linked to a lack of interest in the topics or a perception of science as inaccessible and exclusive. The notion that science can be viewed as a distant and inaccessible entity by non-scientists was identified in previous studies of public perception of risks (Bickerstaff *et al.*, 2006; Michael, 1992).

Furthermore, geoscientists' comments and sketches sometimes included knowledge that went beyond technical geoscience-related concepts, and incorporated elements of philosophy of science. For instance, one geoscientist labelled the different layers of the subsurface from an anthropocentric point of view as "*what we know*" (upper crust), "*what we think we know*" (lower crust), "*where we can make an educated guess*" (mantle), and "*anything goes*" (core). This indicates that geoscientists do not limit themselves to technical knowledge, but also tap into other types of knowledge in constructing their mental models. Religious belief systems also surfaced among participants, with one non-geoscientist stating: "[…] *we disagree on that [that ammonoid fossils are much older than humans]. I believe in the genesis and that humans arrived at the same time as animals*." In this case, these beliefs were deemed by the participant to be in opposition to the science and specifically to the geoscience concept of geological time which the survey brought to the fore.

Lay expertise

The non-geoscientists' sketches contained indicators of local knowledge about their own area (Fig. 1b), which we interpret as lay expertise (e.g., Cronin *et al.* 2004; Wynne, 1996). Lay expertise is here taken as a form of knowledge that is relevant to and can contribute to the scientific discourse (see Collins and Evans, 2002). For example, one non-geoscientist's sketch (Fig. 1h) of mining/quarrying included historical details, such as the historical ownership of mines by "*Judge Comyn*" and the "*government*", as well as the location of historical phosphate mines and the past site of "*surface mining and blasting*". Another non-geoscientist noted the presence of a "*water reservoir on top of Black Head*" in a comment written on the sketch, while also adding at the end of the survey: "*Having lived in Meath for 20 years, I was aware of mining in Tara Mines and the creation of Newgrange Visitor Centre*." In addition, a non-geoscientist included the subsurface depth beneath which water could be found in their local area, alongside the label: "*Drilling for water around Kilkee area. Good supply found*".

Such lay knowledge co-occurred with indications of low levels of familiarity and technical knowledge relating to geological concepts and activities. For instance, when asked to sketch the ground under their feet, one non-geoscientist included thickness of layers at millimetre scale and labelled the layers using specific terms such as "*ceramictite*" and "*concrete*" - indicating local knowledge - but did not know what was below the layer labelled "*stone, rock, clay 2m*", as is evinced from the "*? ? ? ?*" label (Fig.

1b), indicating uncertainty or unfamiliarity. Uncertainty was similarly expressed through written notes accompanying the sketches such as “*not sure*”, “*Cannot envisage this enough to draw. Sorry.*” or “*no idea how far down that goes*”. This sense of uncertainty may also be linked to the sense of distance from science viewed as exclusive and inaccessible already described.

Concluding remarks

In conclusion, even though the mental models of non-geoscientists contain few indicators of technical knowledge and familiarity, they possess lay knowledge, which is valuable for geoscientists and is for example recognised in citizen science projects that include the non-geoscientists in research projects (e.g., Nature, 2018; Skarlatidou *et al.,* 2012; Vera, 2018).

Therefore, while at first glance it appears that geoscientists possess conceptual mental models and non-geoscientists possess naïve mental models, given that geoscientists have more familiarity and technical knowledge related to geoscience, we find that underlying this, the mental models of both geoscientists and non-geoscientists are complex and reflect different knowledge in both groups.

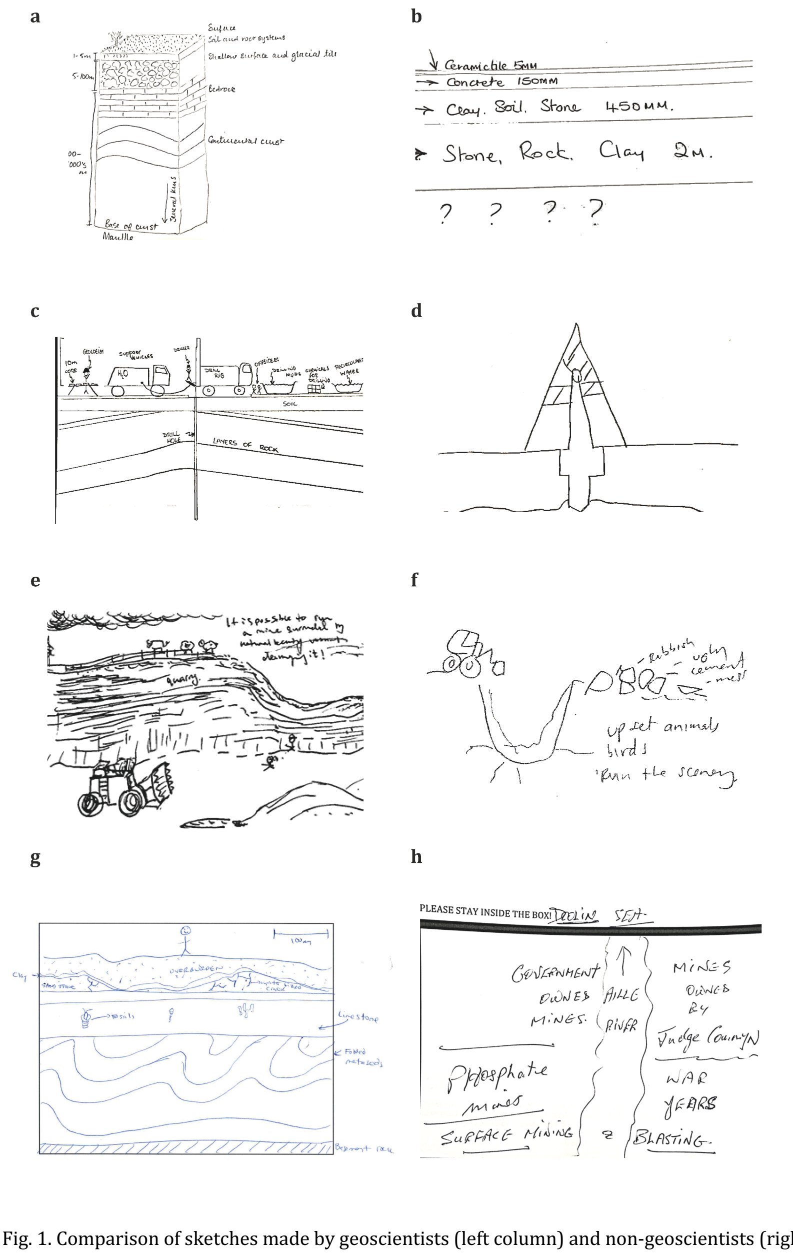

Fig. 1. Comparison of sketches made by geoscientists (left column) and non-geoscientists (right column). The sketches are of: **a,b**, the subsurface; **c,d** drilling; **e,f**, mining/quarrying; and **g,h,** subsurface (left), and mining/quarrying (right).

Beliefs about human interactions

A second theme that emerged from the sketches was the number of human interactions, defined as the presence of humans or human-operated machines in the sketches, comments or labels, including human-built structures such as a field, road or house. Geoscientists' sketches typically included human interactions. In particular, mining/quarrying activities were sketched from a very human lens by geoscientists, who highlighted details of people working in a lab or processing plant, or people using instruments such as microscopes (Fig 1c). Geoscientists also included details of labour division, showing people with tools performing different functions, or stick figures with hammers or helmets doing different types of work (Fig. 1c,e).

Non-geoscientists included fewer human interactions in their sketches, but contributed to the human interaction theme in their written comments in a different way. For instance, one non-geoscientist wrote: *"People are not interested in geology*". These results contrast with earlier reports of an anthropocentric view of the subsurface on the part of non-geoscientists, with geoscientists focusing on technical geoscience concepts rather than on human elements (e.g., Gibson *et al.,* 2016). A possible explanation is that mining/quarrying and drilling are tied to geoscientists' jobs and therefore including humans in the sketches may be geoscientists' way of highlighting the social process of science and their work.

These findings on human interactions are confirmed by Independent Sample T-tests, which indicate that geoscientists included more human interactions than non-geoscientists when sketching drilling, [$t(56) = 3.77$, $p \leq 0.001$] and mining/quarrying, [$t(56) = 3.14$, $p = 0.003$] . It is worth noting that, for the purposes of this analysis, a group of humans close together in the sketch was counted as one human interaction.

Affective beliefs

Drilling and mining/quarrying are highly controversial geological activities, and therefore we asked geoscientists and non-geoscientists to indicate their affective responses to them (see method), which refers to a general positive to negative feeling about these geological activities (Visschers and Siegrist, 2008). An ANOVA repeated measures analysis revealed a significant interaction effect, (Wilks' $\lambda = 0.76$); [$F(3,57)= 5.977$, $p \leq 0.001$], indicating that geoscientists and non-geoscientists have different affective responses to drilling and mining/quarrying.

As illustrated in Fig. 2, the posthoc tests effect revealed that non-geoscientists had more negative affective responses to mining/quarrying, [$t(59) = -3.96$, $p \leq 0.001$], and drilling, [$t(60) = -3.69$, $p \leq 0.001$], compared to geoscientists. Instead, geoscientists had more positive affective responses to mining/quarrying [$t(59) = 2.94$, $p = 0.004$], and drilling, [$t(60) = 2.85$, $p = 0.005$], compared to non-geoscientists. Geoscientists had far more positive than negative affective responses to both drilling and mining/quarrying, whereas non-geoscientists' strength of positive and negative affective responses did not statistically differ.

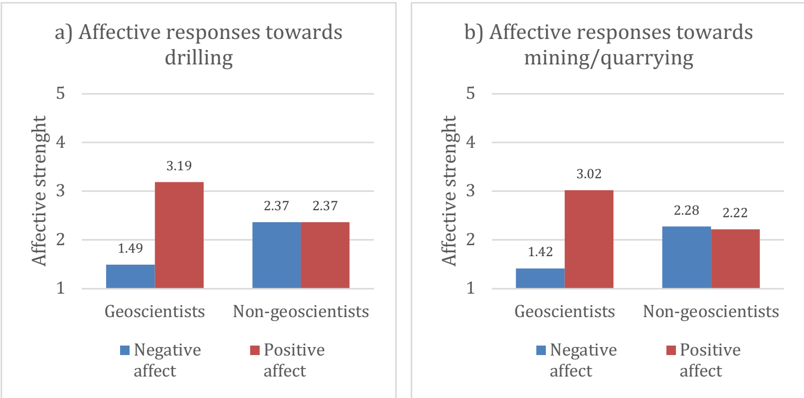

Fig. 2. a,b Affective responses towards drilling and mining/quarrying. Mean values of positive and negative affect responses are compared between geoscientists and non-geoscientists for different activities, namely (a) drilling and (b) mining/quarrying; measurements are on a scale from 1 (weak affective strength) to 5 (strong affective strength).

It should be pointed out that many of the geoscientists in our sample worked in research in geoscience activities (though area of research was not formally gathered), which could have resulted in more positive affective associations with their field of research, such as feelings of safety (cf. Mearns and Flin, 1995).

Beliefs about environmental and economic impact

An environmental or economic impact theme emerged from thematic analysis of the sketches. Non-geoscientists' sketches often highlighted environmental effects of drilling and mining/quarrying activities (e.g., noise from drilling, environmental degradation or pollution) through labels (Fig 1f), indicating that negative environmental impacts were at the forefront of their mind. For instance, this was illustrated by labels such as *"Grassy bank 3-4m high to screen activity from the outside world as process is unsightly"*. The theme was also present in written comments by non-geoscientists, such as: *"I live on the*

River Shannon where we have a large colony of dolphins. Several years ago a company wanted to open a quarry that requires blasting up to 3-6 times a week. Locals objected to this blasting as we believed that the blasting would affect the dolphins by way of seismic waves travelling through the ground and out to the Shannon. WE WON!" Another non-geoscientist, when sketching rock drilling, wrote "*causing underground problems, release of gas, etc., poisoning wells etc*." In general, it was clear that the non-geoscientists tended to associate negative emotions with the negative impact of geoscience on the environment, such as in the label "*ruin the scenery, upset animals, birds*" (Fig. 1f).

Through their labels, non-geoscientists also reported concern about the negative effects of geoscience on the economy (e.g., loss of tourism), as for example evinced by the label "*Road networks e.g. quarries, need to be in the Shannon [area] – this is a tourist area, not here"*. One label by a non-geoscientist is taken to imply a lack of trust in how geoscience operates: *"I think it is unfortunate that most geological studies are funded by large industry*". Lack of trust in industry and government has previously been identified as a dominant theme in a review of public perceptions of hydraulic fracturing for shale gas and oil (Thomas *et al*., 2017).

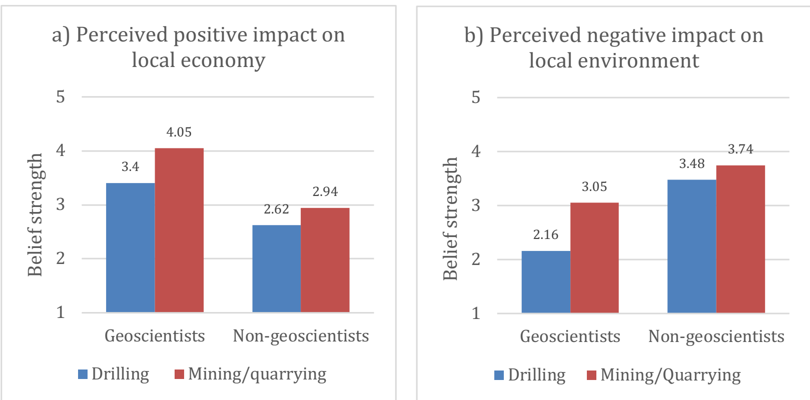

Fig. 3. Perceived economic and environmental impact. (a) Mean scores in answer to beliefs on the extent to which they agreed that drilling and mining/quarrying would improve the local economy; (b) Mean scores in answer to beliefs on the extent to which they agreed that drilling and mining/quarrying would have a negative impact on the local natural environment; measurements are on a scale from 1 (totally disagree) to 5 (totally agree).

These conclusions were confirmed in additional survey questions about the effects of drilling and mining/quarrying on the local economy and environment (see method). An ANOVA repeated measures analysis showed a significant interaction effect: geoscientists and non-geoscientists differed in their beliefs about impact across the geological activities of drilling and mining/quarrying, (Wilks' $\lambda = 0.773$); [$F(3, 57) = 5.578$, $p = 0.002$]. Specifically, non-geoscientists perceived greater negative impacts on the local environment for drilling, [$t(49) = -3.59$, $p = 0.02$], and mining/quarrying, [$t(51) = -2.15$, $p = 0.036$], compared to geoscientists. In contrast, geoscientists perceived greater positive impacts on the local economy from drilling, [$t(55) = 2.43$, $p = 0.019$], and mining/quarrying, [$t(56) = 2.92$, $p = 0.005$], compared to non-geoscientists (Fig. 3).

In line with previous studies of perceptions of the underground (Partridge *et al*., 2019), we recognised tensions between economic values and environmental values in comments written on the survey, such as "*Drilling for a well for water is ok. Drilling for oil or gas is not necessary. Invest in solar and wind energy alternatives. Fracking is just idiotic*." Such comments tended to equate fracking with a threat, associated with fear. Another participant wrote: "*Concerned about fracking if not properly supervised*". This tension may be linked to a desire for control (cf. Hooks *et al*. 2019) and regulation of geoscience activities and technologies (e.g., GSI, 2016), as typified by comments such as "*Concerned about fracking if not properly supervised*" or "*Groundwater pollution with farming practices, I would like it to be more controlled*."

Geoscientists, while indicating an awareness of the negative effects of geoscience on the environment in written comments on the survey, generally downplayed the negative effects and were sometimes defensive in tone. For example, one geoscientist while answering that mining/quarrying would lead to an increase in numbers of visitors and tourists to the area, wrote: "*Giving you an example, in North Yorkshire* [UK]*, there is a salt mine near Staithes where tourists are attracted by its geology and natural beauty. The mine is not necessarily degrading the importance of the land as a long as [there is] a good system keeping it in place.*" Another label written by a geoscientist illustrates a defensive tone: "*It is possible to run a mine surrounded by natural beauty without damaging it!*" (Fig. 1g).

In conclusion, beliefs about the environmental or economic impact underlie the mental models of both geoscientists and non-geoscientists, which suggests that they both are concerned about how geoscience activities impact the environment and economy. However, while geoscientists tended to highlight the positive impacts, often in a defensive tone, non-geoscientists tended to dwell on the negative ones.

Discussion

We have highlighted the differences in mental models between a sample of Irish geoscientists and non-geoscientists and their underlying beliefs when considering geoscience activities and concepts. We found support for our assumption that, for both geoscientists and non-geoscientists, mental models include cognitive (based on rational thoughts) and affective (based on feelings and emotions) components, and are therefore not consistent with the existence of rigidly defined categories of mental models which focus merely on cognitive components (e.g. Gibson *et al.,* 2016; Goel, 2007; Johnson-Laird, 2010, 2013) or on the cognitive superiority of geoscientists over non-geoscientists (Libarkin *et al.,* 2003; Vosniadou and Brewer, 1992). Indeed, we find that the mental models of both groups are complex reflections of different knowledge, beliefs and affect. Hence, we argue that mental models should be redefined as *the cognitive and affective representation of a phenomenon*.

The presence of strong positive affective responses and human interaction in the mental models of geoscientists contrasts with the myth of the scientist (Barthes, 1974) as an impartial, detached observer of reality (Mitroff, 1974), and dissents with the rhetoric of fact-based knowledge. In other words, geoscientists are first and foremost human. The results contribute to the erosion of the ideal of the objective scientist, focused solely on facts, helping to deconstruct the myth of science that sees scientists as impartial and detached. Whilst the notion that all experts are affected by biases when making judgements under uncertainty has been known by scholars at least since the work of Tversky & Kahneman (1974), this is not commonly recognised within the geoscientific community (e.g., see Curtis, 2012). We have shown that geoscientists and non-geoscientists alike go beyond facts into emotional territory when constructing their mental models.

Understanding differences and resemblances of both the cognitive and affective components of mental models of geoscientists and non-geoscientists is an important step in improving the communication between them, for instance when discussing often-contested areas of the geosciences such as resource extraction (see Stewart and Lewis, 2017). As a practical step, in communicating with each other, geoscientists and non-geoscientists may wish to acknowledge their differences and focus on commonalities in order to find common ground. For instance, given that both geoscientists and non-geoscientists are concerned with the impacts of geoscience on the economy and the environment and given that both groups incorporate affect in their mental models of geoscience concepts and activities, geoscientists may be able to reach wider audiences by acknowledging these concerns and affective components, and including feelings and affect in their chosen form of communication (e.g., personal motivations for their research). In addition, geoscientists may benefit from using storytelling and narrative, which typically include both affective and cognitive components, as their chosen modes of communication, a recommendation consistent with previous science communication research (Dahlstrom, 2015). If geoscientists acknowledge the emotional component of their mental models, this may also lead them to reflect on the meaning of scientific knowledge and to change their view of themselves as keepers of knowledge. On one hand, this could influence how they communicate their work and activities to geoscientists and non-geoscientists, but it could also lead to a broader understanding of epistemology and the social component of geoscience on the part of geoscientists (see Stewart, 2016). While it is useful for geoscientists to acknowledge or reflect on the affective components of their mental models, whether it is always appropriate to incorporate emotions in communication efforts is a complex matter that is likely to depend on the mode of communication (e.g., in person workshops versus an explainer video on social media). There may well be occasions when the purpose of a science communication or public engagement activity is limited to information sharing. We suggest that, in these cases, the self-reflection brought about by the internal acknowledgement of affective components will still be of benefit to the geoscientists engaging in these activities.

Given that non-geoscientists often incorporate lay expertise in their mental models, in order to build trust and common ground, geoscientists may also wish to acknowledge and tap into local knowledge held by non-geoscientists, for example simply by asking non-geoscientists questions about their local area. At the same time, by recognising that geoscientists' mental models are based on emotions too, non-geoscientists may be better able to engage with them. Overall, showcasing geoscience as a human activity ought to help improve dialogue between the two groups. The above recommendations are also very relevant to public engagement and science communication practitioners who not only will be trained in how to engage with communities and publics, but are also less likely to be seen as having an agenda (for instance motivated by economic interests or links to industry) by the non-geoscientists they are engaging with.

Limitations

While this mixed-method study highlights differences and similarities between the mental models of geoscientists and non-geoscientists, it should be noted that the sample size is small, and thus our results need to be interpreted with care. Future research is needed to validate our conclusions. It should further be noted that the geoscientists who took part in this study were primarily highly-educated males working in applied geoscience research at the time the survey took place (only 2 worked outside of research), and they were younger compared to the non-geoscientists who took part (for details, see Materials and Methods). The latter is fairly representative for geoscientists (e.g., Dutt *et al.*, 2016), however, we cannot say with certainty that these differences in socio-demographics play a role in the differences we find. For example, female and younger geoscientists may hold different perceptions of geoscience activities and their impacts (cf. Seigo *et al.*, 2014). However, this does not influence our main conclusion that geoscientists' mental models are influenced by both cognitive and affective responses.

Concluding remarks: the human side of geoscientists

Our finding that geoscientists stray beyond facts into the realm of emotions and beliefs in constructing their mental models of geoscience concepts and activities is a key realisation for geoscience communication practitioners. We have argued that putting the human element at the centre of communication strategies will help achieve meaningful dialogue between geoscientists and non-geoscientists.

Geoscientists, specifically those who conduct research on resources, energy, earth and environmental science, are increasingly required to wear multiple hats in engaging with non-geoscientists in order to tackle societal challenges around energy and resources. Therefore, an increased mutual understanding of the thoughts and feelings of geoscientists and non-geoscientists will help facilitate dialogue between the two groups.

Acknowledgements

Ethical approval for the study was obtained from University College Dublin (Ethical Exemption Reference Number HS-E-17-84-Lacchia-Haughton). We are very grateful to the survey respondents who kindly gave their time to assist this research. We wish to thank three Anonymous Referees and our editor, Beth Bartel, for their valuable comments which much improved this manuscript.

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Supporting information

1 Images of sketches

Data availability

All data underlying the results is available in the manuscript and supporting information. Additional data around this project is available from the corresponding author.

Funding

This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092 and co-funded under the European Regional Development Fund and by PIPCO RSG and its member companies.

Competing interests.

The authors declare no competing financial interests.

Author contributions.

All authors conceived and planned the study; A.L. conducted the data collection; A.L. and G.S. analysed and interpreted the data; all authors helped to draft the manuscript.

Author response to Reviewer #3

Overall I really enjoyed this paper and it utilised a slightly different approach to its analysis than a traditional mental models paper, many of which use interview data alongside textual/pictorial analyses. The sketches were really interesting with fascinating analysis and they incorporated an affective component of geoscientists, something that is not usually done for m.m approach but provides a worthy discussion point. There are a few clarifications and changes that I feel would improve this paper.

We wish to thank the referee for their positive comments and constructive review. We have enjoyed and benefited from reading the reviewer comments and the references therein. We have made all the changes recommended and think the paper has benefited from the review. Please find replies to each comment below in blue.

24 Not clear what 'beliefs' are just that they are composed of cognitive and affective components. A sentence defining how the authors want to contextualise 'beliefs' would be useful somewhere in the introduction

We have added the following sentence to the introduction (lines 134-135), explaining what we take beliefs to mean (based on a definition that is used in science education):

"We define beliefs as "psychologically-held understandings, premises or propositions about the world that are felt to be true" (Richardson, 1996, p. 103)."

We have also added a reference to the study cited in the reference list.

59 – 61 A couple of lines acknowledging that non-geoscientists may actually be very knowledgeable from a different perspective (as the paper does end up doing later on) should be included. There are clearly those without a degree who will be at an 'expert' level for example. How one defines a nonexpert and expert can be quite tricky!

We completely agree that these definitions are tricky and that those who may not be defined formally as 'experts' may possess expert knowledge (and indeed find this to be the case in our results). We have rephrased as follows (lines 59-65):

"A starting point from which to understand each other is to investigate the differences between geoscientists, defined as anyone with at least a university degree in geology or geoscience, and non-geoscientists, defined as those without such a degree. While acknowledging that those without a degree in geoscience may well possess expert knowledge relating to geoscience, we choose to adopt these definitions as indicators of expertise, and as useful starting points from which to discuss differences and similarities."

108 Is there any work that has explored affective responses of experts more generally even? This is something that seems to be lacking in the literature more generally. And is there a reason that research focuses on simply the knowledge aspect of how this group understand a risk issue? (I mean generally, not this specific paper as it is a departure from the norm for m.m)

We agree that, while there is plenty of psychological research on risk perception that highlights the importance of both emotions and cognitive components (e.g., Sjöberg 2007, Slovic *et al* 2004), studies exploring affective responses of experts seem to be lacking from the literature. Apart from one study about climate change (Lowe & Lorenzoni, 2007) which recognises experts' affective components in risk perception, to our knowledge the mental models literature tends to focus on cognitive components when looking at experts. Perhaps this focus on knowledge for experts is related to the highly-pervasive notion that experts are objective and somehow devoid of emotion, which leads researchers (often from the natural sciences) to view other experts as objective (we touch on this in lines 539-540 of the paper). We hope that future work will explore this interesting avenue of research.

Reference mentioned above:

Lowe, T.D. and Lorenzoni, I. Danger is all around: Eliciting expert perceptions for managing climate change through a mental models approach. *Global Environmental Change*, 17, 1. 131-146, 2007.

158 Switch non-geoscientists and scientists (number of) for consistency as you report recruitment of geoscientists and then non-geoscientists over the page (139-140), just to ease reading

We have changed to ‘24 geoscientist and 38 non-geoscientist participants’ (line 174).

167 Table 1 does not add up, numbers reported in all sociodemographic categories (age and educational level) for both groups do not come to the total recruited. Please fix.

Thank you for noticing this error. We have fixed this and added a row with the number of respondents who declined to disclose their age (n=1). All counts add up now.

176 I was curious why you chose to recruit from an area where you anticipated knowledge levels about the topic to be higher, was this a conscious decision? The aim of the research and purpose for creating the mental models could be clearer. You do mention in your final paragraph of the introduction (124 – 133) that you use a rural community but give the impression that the sample is typical, not one with potentially strong links to this topic. Make this a little clearer ie. that you used this sample specifically because they lived in this area and therefore would be more aware of possible issues or raise things geoscientists may not have considered for example and therefore future dialogue with such a community should consider x, y, z (if this was your intention)

This is a good point. We chose this area because it is the current focus of public engagement activities by geoscientists working in iCRAG (Irish Centre for Research in Applied Geoscience) and we wished to better understand the audience for these activities.

We have added the following to the introduction (137-142):

“We chose to recruit participants from a rural community in Ireland where geologists typically conduct fieldwork (Martinsen *et al*., 2017) because the area’s spectacular Carboniferous geology lends itself to public engagement events. Better understanding the community will allow geoscientists and public engagement practitioners to develop such public engagement activities.”

And rephrased the following sentence in the Materials & Methods (lines 196-199):

“Given the popularity of the area with geologists, we also anticipated that non-geoscientists living in the area may have a relatively high level of familiarity with geology or with groups of geologists, thus potentially providing useful insights for dialogue in this community.”

178 Please include a sentence on what information respondents were given in their recruitment letter, was it topic blind or not? (To make it clear if this would bias response)

We have added (lines 202-205): “In the invitation letters, participants were asked to take part in a study investigating public perception of geology, including knowledge about the geology of Co. Clare and the subsurface. No specific information on the aims of our study was provided in order to minimise response bias.”

237 The authors state that they pre-defined six indicators, on what basis was this done? Was this prior to the thematic analysis or from the TA? Not clear, particularly as late on (263) they mention there being four themes. Were the initial six themes deductive and latter inductive utilising grounded theory? (e.g. see Glaser and Strauss (1967) or Pidgeon and Henwood (1997))

Thank you for pointing out that this was unclear. The pre-defined six indicators were developed first, and the thematic analysis (from which resulted four themes) was conducted afterwards, and informed by the indicator analysis. Both types of analysis were done using an inductive grounded theory approach. We have rephrased as follows to better explain our methodology (lines 260-285):

“The first and second authors examined the sketches using a grounded theory approach taken as “the progressive identification and integration of categories of meaning from data” (Willig, 2008, p.35). This allowed the identification of six indicators of knowledge and familiarity in the sketches, namely: amount of *technical jargon*, defined as the presence of technical and subject-specific vocabulary in the labels of sketches, s*ense of scale,* which refers to an indication of the awareness of the size of different elements included in the sketches (usually provided by a point of reference such as a scale bar); *number of layers,* the number of layers of rock or other material in the sketches; *number* *of labels,* the number of labels included in the sketches; *depth*, which refers to the depth to which they sketched the subsurface, ranging from the ground surface (coded as 1) to the core (5); and *human interactions*. The authors scored the sketches independently based on this. Pearson's correlation was used to determine the inter-rater reliability, which was deemed acceptable (Pearson's $r \geq 0.7$, $p \leq 0.001$).

To test the differences between geoscientists and non-geoscientists on the six pre-defined indicators, Independent Sample T-tests and ANOVA Repeated Measures analyses were conducted using the IBM SPSS Statistics 24 software package.

These results informed our qualitative analysis of the sketches, whereby the sketches were subsequently analysed by means of thematic analysis to identify themes that were common to some or all of the sketches (Boyatzis, 1998; Marshall and Rossman, 1999). Thematic analyses were conducted manually by the first author."

We added this reference to the reference list:

Willig, C. Grounded theory. In: Willig, C. (Eds.), *Introducing qualitative research in psychology – adventures in theory and method*. Maidenhead: Open University Press – McGraw Hill Education, 34-51, 2008.

342 Check Nature reference, e.g. title?

We have added the title of this *Nature* editorial (The best research is produced when researchers and communities work together) in the references (line 700).

485, 503, 517 I would argue that the definition of mental models are conceptual or knowledge based but as you correctly say, of course this is not the way humans think and there is research that supports that particularly in non-experts/publics conceptualisation of risk even where it is unfamiliar to them. This is where your paper is more unique as experts are not traditionally asked about their affective response in this methodology but you have done just that. My main thought throughout this paper has been blurring of this line of whether mental models are used as a tool for experts to only provide rational information or if they should be incorporating emotion (as you discuss later, you want them to include emotion). I think this discussion point is one that will be divisive. Clearly it has an impact on how an expert conceptualises a risk issue and is an important consideration. You state that perhaps they should provide motivations and affect in their dialogues in communication strategies, this might get tricky when it comes to impartiality or a reliance on expertise. I think this is a worthwhile discussion point and one that is quite difficult. I am thinking of deliberative work where people defer to the experts and the influence of affect and how this would interact. In summary, acknowledge the complexities that this may bring.

This is a very interesting point and indeed how this will work in practise, whether the communication is taking place in deliberative workshops or dilemma cafés, is complex and merits further research. We have added these lines (lines 564-572) to the discussion:

“While it is useful for geoscientists to acknowledge or reflect on the affective components of their mental models, whether it is always appropriate to incorporate emotions in communication efforts is a complex matter that is likely to depend on the mode of communication (e.g., in person workshops versus an explainer video on social media). There may well be occasions when the purpose of a science communication or public engagement activity is limited to information sharing. We suggest that, in these cases, the self-reflection brought about by the internal acknowledgement of affective components will still be of benefit to the geoscientists engaging in these activities."

533 Related to the previous point about communications, are geoscientists the group that should be doing this as they may be seen as having an agenda? So what is the purpose of the communications, make this a little clearer. Perhaps a more interdisciplinary approach including social scientists and comms specialists would be appropriate to eradicate the 'expert' on said topic and influence they have.

We completely agree that there is a key role here that can be played by science communication and public engagement specialists. We have added the following sentence (lines 579-583):

"The above recommendations are also very relevant to public engagement and science communication practitioners who not only will be trained in how to engage with communities and publics, but are also less likely to be seen as having an agenda (for instance motivated by economic interests or links to industry) by the non-geoscientists they are engaging with."