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The effect of frames on engagement with quantum technology

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Abstract

Engaging a larger, non-specialist audience with quantum technology poses challenges as the theory underlying quantum technology is very different to what we experience in our everyday lives. Quantum technology is predicted to have a significant impact on society once it matures. This study ($n = 637$ adults representative of the Dutch population) examined the effect of different frames on engagement – specifically, information seeking, internal efficacy, general interest and perceived knowledge – with quantum technology. The different frames were: enigmatic, explaining quantum physics, benefit, risk and balanced. Results indicated that framing quantum as enigmatic does not affect engagement, while explaining quantum physics positively influences general interest. Furthermore, emphasising a benefit of quantum technology increases participants' internal efficacy, whereas highlighting both a benefit and a risk of quantum technology decreases perceived knowledge. Based on these findings, we offer practical advice for science communicators in the field and suggest further research.

Keywords: Quantum science; Quantum technology; Public engagement; Science communication; Framing

1 Introduction

Quantum technologies are envisioned to have significant implications on society – both positively as well as negatively. Positive implications include, for instance, saving or extending lives through drug discovery [1, 2], providing secure communication as a defence against hacking threats [3, 4], and identifying risks to ground conditions through accurate sensing [5]. Examples of negative effects include concerns about how criminal organisations may use this technology [1, 3], as well as unequal access to the technology depending on where you live [6]. It has been argued that simply allowing China, the West, and the wealthy to control quantum technology will likely worsen existing inequalities, and consequently deny populations access to the benefits that the technology can provide [6].

To maximise the positive and minimise the negative impacts of quantum technology on society, it is important to connect to society in an early phase of the technology's development [7]. Allowing for citizens to participate in societal dialogues could give technology developers and policy makers a better understanding of how quantum technology affects different groups of people [8], and it could also lead to more public support and less public opposition [8–10]. Moreover, citizens should be given the opportunity to participate from a democratic perspective, as this technology can significantly affect citizens' lives [11].

Engaging a larger, non-specialist audience with quantum technology poses challenges as the theory underlying quantum technology is very different to what we experience in our everyday lives. Societal actors could feel unqualified to participate in a dialogue about such a technology. Referring to quantum theory in certain ways, such as calling it enigmatic, potentially enhances this feeling even further [12, 13].

In this work, we examine three potential issues in the way quantum technologies are currently communicated to non-expert audiences, focusing on the *frames* used in such communication [14, 15]. These are: 1) the enigmatic frame; 2) the explanation frame; and 3) the benefit, risk and balanced frames. The goal of our study is to determine whether these potential issues are indeed problematic by testing the effects of these frames on participants' self-reported engagement. The next section covers the theoretical concepts on which our study is based in detail.

2 Theory

2.1 Scientific engagement

When we look at the history of science communication, there is a shift from focusing on public understanding of science to public engagement with science [9]. According to the historic overview provided in [9], governments tried to increase public acceptance of science and technology by educating the public through one-way communication models (i.e., referred to as the deficit model) starting from the 1980s. However, this approach did not always succeed in increasing public acceptance. Some groups became even more critical after obtaining additional information from experts, for example in the United Kingdom on genetically modified crops [11].

Science communication scholars have since advocated moving to public engagement models (also called "upstream" engagement [9, 10, 16, 17]), but this remains challenging. The domain of science and technology is alienating for some people [18, 19], which hinders engagement. For example, a qualitative thematic analysis on students' reflective writings found that a lot of the students thought science was inaccessible [18]. Also, many of them did not identify as scientists even while some of them had a scientific job themselves. Research into factors that could increase engagement with science therefore remains important.

Public engagement with science can be measured in a variety of ways, for instance through reflective writings (e.g., [18]), experimental surveys (e.g., [19]), and public dialogue exercises (e.g., [1]). In our study, we used an experimental design such that we could systematically manipulate the presence or absence of different frames and measure their effect on the various engagement dimensions. For the scientific engagement questions, we adopted the scientific engagement measure outlined in [20]. The authors found that avoiding jargon has a positive indirect effect on participant's self-reported scientific engagement, which they measured via four variables. They assessed (1) participants' intentions to seek additional information on the scientific technologies presented (self-driving cars, medical printers and robot surgeons), (2) their beliefs about their own ability to understand and engage with information about the scientific technologies, (3) their general interest in them, and (4) their confidence in their knowledge of the scientific technologies.

In this way, four different dimensions of scientific engagement were examined: (1) information seeking, (2) internal efficacy, (3) general interest and (4) perceived knowledge.

2.2 The effect of frames on engagement

In this work, we examined the effect of *frames* on quantum technology engagement. Framing refers to "select[ing] some aspects of a perceived reality and mak[ing] them more salient in a communicating context, in such a way to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation" [21, p. 52]. By emphasising only some aspects while ignoring other parts of certain information, frames can influence how audiences interpret and perceive that information [21].

Theoretical research has identified four main potential issues with the current communication about quantum science and technology to a broader audience. These are: 1) framing quantum science and technology as enigmatic [12, 13]; 2) not explaining the underlying quantum physics concepts when explaining quantum technology, thereby leaving the technology as a black box [22]; 3) communicating a "narrow public good frame", which means, among other things, that there is no broader reflection on the benefits *and* risks of quantum technology [8]; and 4) a strong focus on quantum computing at the expense of other quantum technologies [8]. The occurrence of these potential popularisation issues have been quantified in English TEDx talks [14] and Dutch newspaper articles [15], and it was found that all four issues are present to varying degrees in both datasets. Therefore, it is of great importance to investigate whether these potential issues genuinely hinder public engagement. To ensure a feasible design, the present study addresses only the first three potential issues, discussed in more detail below.

2.2.1 The enigmatic frame

The first frame we studied is the enigmatic frame. According to Vermaas, Coenen, and colleagues, the enigmatic frame could make the domain of quantum technology unapproachable for non-specialist audiences [12, 13]. If quantum experts highlight that they find quantum science and technology enigmatic, non-experts might consequently think that there is no chance that they will ever be able to acquire the knowledge needed to participate in a dialogue about the technology [12, 13]. Based on these two works [12, 13], the enigmatic frame is therefore considered to mainly affect the internal efficacy dimension of engagement (i.e., (2) their beliefs about their own ability to understand and engage with information about the scientific technologies).

If the enigmatic frame were hardly present in public communication, its potential to act as a barrier to engagement would be negligible and not worth investigating. However, the frame is clearly visible: in both English TEDx talks [14] and Dutch newspaper articles [15] with quantum science and technology content, the spooky and enigmatic frame appeared in almost a quarter of the content (23% in TEDx talks and 24% in newspaper articles). This underscores the importance of examining whether such a frame hinders engagement with quantum science and technology.

2.2.2 The explanation frame

Secondly, we examined the effect of the explanation frame on engagement with quantum technology. Grinbaum has argued that popular communication about quantum technology should include explanations of the "strange features of quantum theory" (p. 299), such as *superposition*, *entanglement* and *contextuality* [22]. *Superposition* refers to the fact that a particle following the laws of quantum mechanics can be in two states simultaneously (i.e., a particle in a superposition state is in a linear combination of states) [23, 24]. *Entanglement* means that particles share a state, making it no longer appropriate to refer to those particles as separate [23, 24]. Finally, *contextuality* addresses the idea that performing a measurement on a quantum state has an irreversible impact on that state (although there is more nuance to this, see [25]). According to Grinbaum, not explaining these features leads to several weaknesses [22]. One of these weaknesses is that without such explanation, the technology remains a black box to general non-expert audiences. Because its inner workings are not explained, it becomes difficult for people to actually understand how quantum technology works. Looking at the four engagement variables in this study [20], such a lack of transparency has the potential to negatively affect the perceived knowledge dimension of engagement (i.e., (4) people's confidence in their own knowledge of quantum technology).

In addition, there is some evidence that the explanation frame may increase engagement through increased interest in the technology (i.e., (3) people's general interest in quantum technology). Working on over a hundred outreach projects about quantum and solid-state physics, Bobroff observed that people are often fascinated by the underlying theory and not just by potential applications [26]. This suggests that the explanation frame could positively influence the general interest dimension of engagement. However, since this insight in [26] is based on personal observation rather than systematic study, it remains unclear whether this effect holds more broadly.

In contrast to the above, there are concerns that explaining quantum physics concepts may actually reduce engagement by lowering people's internal efficacy (i.e., (2) their beliefs about their own ability to understand and engage with information about quantum technology). As quantum physics concepts are counterintuitive to everyday experiences, such explanations may alienate people in a similar way as the enigmatic frame (see Sect. 2.2.1) [12, 13]. For example, performing a measurement on a quantum state does not appear in everyday experiences: for us, looking at an object does not all of a sudden change its properties, but by 'looking' at a quantum object you do change its properties. Van Wezel and colleagues described this as "genuine quantum weirdness" [27]. As a result, people may lose confidence in their own ability to understand and engage with information about a technology that operates according to such strange properties.

Just over half of the English TEDx talks (54%) and Dutch newspaper articles (51%) include explanations of quantum concepts such as superposition, entanglement, and contextuality [14, 15]. This makes it particularly relevant to investigate how the presence or absence of an explanation frame affects public engagement.

2.2.3 The benefit, risk and balanced frames

Thirdly, we investigated the benefit, risk and balanced frames on participants' engagement with quantum technology. The benefit, risk and balanced frames focus on discussing one of the potential benefits of quantum technology, one of its potential risks, or one of its potential benefits and risks at the same time. Roberson and colleagues have emphasized the need for widely reflecting on how quantum technology may impact society [8]. This includes critical reflection on both the potential benefits and potential risks of the technology, in order to facilitate public dialogues on a range of possible outcomes of the technology. This has as a goal to maximize the benefits of quantum technology while minimizing its risks on society. Currently, potential benefits of quantum technology seem to be communicated about six times more often than potential risks in communications about quantum technology [14, 15]. Since this contradicts what Roberson and colleagues argues for [8], it is important to examine what such skewed communication does to engagement.

Many experimental studies have already demonstrated that the benefit frame increases public support for emergent technology, while the risk frame tends to decrease it. This has been observed for various emergent technology, such as for genetically modified foods [19], carbon nanotubes [19], artificial intelligence [28], hydrogen technology [29], and nanotechnology [30]. While these studies primarily focus on how benefit and risk frames influence support for emergent technology, there is still little experimental research available on how benefit and risk frames affect the dimensions of public engagement in [20] with emergent technologies.

That said, some experimental studies on emergent technology have already explored the effect of benefit and risk frames on specific engagement dimensions, such as information seeking (i.e., (1) participants' intentions to seek additional information on quantum technology) and general interest (i.e., (3) participants' general interest in them). For instance, one study found that highlighting both the potential benefits and risks of nanotechnology increased participants' feelings that they needed more information before making decisions about nanotechnology [31]. While the authors interpreted this as an indication of future information seeking, the phrasing of their questions made it unclear whether participants actually intended to search for more information in the future. In addition, another study found that, in the context of nanotechnology, presenting both a potential benefit and risk increased interest in the technology among individuals who were open to new or inconsistent information [32].

Furthermore, qualitative evidence suggests that emphasizing the benefits of quantum technology can increase engagement, specifically through an increase in interest (i.e., (3) participants' general interest in quantum technology). For example, a public dialogue exercise in 2017 in the United Kingdom revealed that talking about potential benefits of quantum technology increased participants' engagement and excitement about the technology [1]. The authors observed that, at first, the participants who entered the dialogue found quantum science and technology difficult to understand and for experts only. The personal relevance of learning about quantum technology was not immediately clear. However, when the discussion shifted to talking about possible benefits, participants became more engaged and excited about quantum technology as they started to understand how quantum technology could be relevant to their own lives.

Finally, it may be that a risk frame does not affect engagement through information seeking (i.e., (1) participants' intentions to seek additional information on quantum technology). The question of what motivates people to seek information about risks has been widely studied through the so-called Risk Information Seeking and Processing Model (RISP) [33]. The theory states that motivation plays an important role in information seeking and processing, which can arise for two reasons: 1) that people will put effort into seeking information until they feel are satisfied with the amount of information they have on the risks, or 2) that people feel that others expect them to know something about the risks. In the case of quantum technology, people may feel that they have little personal control over the risks, which could potentially lead to avoidance as a way to counteract negative emotions. Additionally, because quantum technology is still in an early development phase and people are likely still unfamiliar with the technology, it is unlikely that widespread social expectations exist. Therefore, it may be that a risk frame does not encourage people to actively seek information about it.

2.3 Research questions

As introducing public engagement in an early phase of a technology's development is important [9, 10, 34], it is essential to investigate the incentives and barriers to engagement with quantum technology early on. Our goal is to examine the effect of different frames on engagement with quantum technology. We focus specifically on the Dutch context, given the Netherlands' role in quantum technology research and its explicit aim to connect quantum technology with society, as outlined in the National Agenda Quantum Technology [35]. Moreover, the Dutch public is likely to encounter the frames under investigation, as they already appear in varying degrees in their national newspapers [15].

Our study aims to answer the following research questions (RQs):

RQ1. Does the enigmatic frame influence the self-reported engagement with quantum technology?

RQ2. Does the explanation frame influence the self-reported engagement with quantum technology?

RQ3. Does the benefit, risk and balanced frames influence the self-reported engagement with quantum technology?

3 Method

Following our research questions, we used a survey design in which participants were randomly assigned in a 2 (enigmatic, not enigmatic) × 2 (explanation, no explanation) × 4 (none, benefit, risk, balanced) between-subjects design (i.e., each participant was exposed to only one experimental condition). We would like to refer the reader to the S1 Appendix for the reasons behind the 2 × 2 × 4 design. A total of $n = 649$ participants were recruited by KiesKompas (https://www.kieskompas.nl/en/), a Dutch survey company, to form a representative sample of Dutch adults in age, gender and education. Before the data collection, the study information, design plan, sampling plan, variables and analysis plan were preregistered on OSF Registries (view-only link: https://osf.io/h6b7s?view_only=6de271037d4f4e358118537926977e86). The Ethics Review Committee of the Faculty of Science of Leiden University gave ethical approval to conduct the study (2023 - 02).

3.1 Independent variables

The independent variables consisted of the enigmatic frame condition, the explanation frame condition and the benefit, risk and balanced frames conditions. The specific wordings per experimental condition can be found in S1 Table in the Appendix. Jargon terms such as superposition, entanglement and contextuality were avoided (as jargon has been found to hinder engagement [20]).

3.1.1 Enigmatic frame condition

In the enigmatic frame condition, participants viewed a statement in which quantum mechanics was referred to as enigmatic ("raadselachtig" in Dutch), while in the no enigmatic frame condition this adjective was left out.

3.1.2 Explanation frame condition

To obtain a more rigorous test of whether providing a quantum physics explanation affects engagement, we opted for a message sampling approach [36]. This approach means that, rather than a single message, various messages that all share the trait being studied are used as experimental stimuli to limit the effect of one specific message. In this way, we gained confidence in that we measured the effect of providing an explanation of a quantum physics concept on participants' engagement, rather than the effect of a certain concept or a certain type of explanation. We designed six different messages that explained a quantum physics concept: participants were randomly assigned to read an explanation about superposition, entanglement or contextuality in two different ways. These two different ways were chosen based on how physics concepts in major Dutch newspapers are often explained [37]. Afterwards, we collapsed the results.

3.1.3 Benefit, risk and balanced frames condition

In addition to both manipulations above, participants were also randomly assigned to view a benefit frame, a risk frame, both a benefit and risk frame (i.e., a balanced frame), or none of these frames. We designed a benefit frame around health and a risk frame around security (as these got the most reactions in the public dialogue exercise [1]).

3.2 Dependent variable

After reading the text associated with one of the 16 experimental conditions, participants were asked to self-report their engagement with quantum technology. We adapted the 4-variable engagement measure in [20] such that all of the statements referred to quantum technology instead of science and technology in general. Each variable was thereby measured using a multi-item scale, with responses recorded on a Likert scale with 5 options (ranging from strongly disagree – strongly agree). The multi-item scales can be found in S2 Table in the Appendix.

We assessed the reliability of the scales through Cronbach's alpha [38] a commonly used psychometric tool to measure the internal consistency of questionnaires. It measures the extent to which the items on a scale measure the same latent construct. The higher the value, the better the internal consistency, with values above 0.7 generally considered acceptable. When consistency is too low, a leave-one-out analysis is performed, in which Cronbach's alpha is computed for all combinations of the scale with one item removed. When this yields a considerably improved alpha, the scale is used with one item less.

The first scale assessed whether participants intended to seek out more information about quantum technology in the future (i.e., (1) information seeking), a 3-item scale, Cronbach's alpha = 0.94). The second scale assessed whether participants' believed that they can understand and engage with information about quantum technology (i.e., (2) internal efficacy), a 4-item scale, Cronbach's alpha = 0.859). The third scale was to assess participants' interest toward quantum technology (i.e., (3) general interest), a 6-item scale, Cronbach's alpha = 0.892). And fourthly, we were interested in the confidence that the participants have about their own quantum technology knowledge (i.e., (4) perceived knowledge). This scale originally had 4 items, with Cronbach's alpha = 0.446. A leave-one-out-analysis (cf. [39]) showed that the 3 item scale with items 1, 2 and 4, performed considerably better, Cronbach's alpha = 0.848, thus we work with these three items).

3.3 Analysis and statistical procedures

Data were analysed with R (version 4.2.2, RStudio Team [40]). To evaluate the effects of the different conditions, we conducted a multiple linear regression analysis with dummy variables. In line with our preregistration, we tested for main effects and did not analyse possible interactions. The model was run for each engagement variable: (1) information seeking, (2) internal efficacy, (3) general interest and (4) perceived knowledge. The sum score for each of the engagement variables was calculated by adding up the Likert scale questions associated with them. A condition was determined to be a significant contributor to the particular engagement variable if $p < 0.0125$. This threshold was derived by applying a Bonferroni correction, which is a statistical adjustment that divides the significance level – which is standard 0.05 – by the number of tests conducted, to reduce the risks of false positives.

While the four sets of linear regression examine the effect of the experimental conditions on each engagement variable individually, we additionally wanted to assess the effect of the conditions on a linear combination of these variables – treating this as an overall measure of public engagement with quantum technology. Therefore, we additionally conducted a multivariate analysis of variance (MANOVA, cf. [41]).

4 Results

4.1 Descriptives

The survey ran between May 16th and May 23rd 2023 and resulted in a total sample of $n = 649$ Dutch-speaking adults. Participants provided written consent to KiesKompas prior to the survey. Because KiesKompas fully anonymized the data before providing it to the authors, the participants' identities were never visible to them. The median time to complete the survey was 3 minutes and 18 seconds. As 12 participants finished the survey in 90 seconds or less, we assumed that they did not think their response through and we discarded them from the analysis. This resulted in a final sample of $n = 637$ participants (394 men, 243 women; $M_{age} = 57.53$ years, sd = 15.98 years; 110 participants (17.3%) reported having completed a low level of education, 260 (40.8%) reported an average level, 265 (41.3%) reported a high level of education, and 2 (0.3%) didn't specify.).

To approximate the population of the Netherlands, the data was weighted by post-stratification for gender, age and education. The weights were trimmed at 98th percentile, to lessen the effect of the highest-weight outliers. Table 1 shows the number of participants that were assigned to each condition in the 2 (enigmatic, not enigmatic) × 2 (underlying explanation, no underlying explanation) × 4 (none, benefit, risk, balanced) design for the unweighted and weighted data.

Table 1 Number of participants in each condition before and after weighting

	Unweighted		Weighted	
	Did not read frame	Read frame	Did not read frame	Read frame
Enigmatic frame	321	316	309	323
Explanation frame	319	318	318	314
Risk frame	309	328	295	337
Benefit frame	319	318	325	307
Balanced frame	480	157	473	159

Table 2 Multiple linear regression analysis of the experimental conditions per outcome variable. The first number in each cell represents the estimate (b), and the number in parentheses represents the standard error. *p*-Values in bold indicate significance at a level of <0.0125

Frame	Information seeking	Internal efficacy	General interest	Perceived knowledge
Intercept	7.62 (0.32), ***p* < 0.001**	8.53 (0.36), ***p* < 0.001**	17.67 (0.52), ***p* < 0.001**	6.00 (0.26), ***p* < 0.001**
Enigmatic	−0.41 (0.25), *p* = 0.101	−0.53 (0.28), *p* = 0.064	−0.77 (0.41), *p* = 0.059	−0.14 (0.20), *p* = 0.486
Explanation	0.26 (0.25), *p* = 0.305	0.31 (0.28), *p* = 0.276	1.17 (0.41), ***p* = 0.004**	-0.04 (0.20), *p* = 0.837
Risk	0.31 (0.35), *p* = 0.379	0.54 (0.40), *p* = 0.173	0.63 (0.57), *p* = 0.275	0.34 (0.29), *p* = 0.227
Benefit	0.70 (0.37), *p* = 0.058	1.06 (0.42), ***p* = 0.011**	0.92 (0.60), *p* = 0.127	0.67 (0.30), *p* = 0.024
Risk × Benefit	−0.85 (0.50), *p* = 0.092	−1.39 (0.57), ***p* = 0.015**	−1.13 (0.82), *p* = 0.168	−1.04 (0.41), ***p* = 0.011**

Note: Intercept is the expected sum score for the given variable for when none of the experimental conditions apply.

4.2 Significant contributors to the regression models

The results of the regression models for 1) information seeking, 2) internal efficacy, 3) general interest and 4) perceived knowledge are shown in Table 2. First of all, the results show that the enigmatic frame condition did not significantly contribute to any of the four models.

Secondly, the explanation condition was found to be a significant contributor for general interest ($b = 1.171$, $p = 0.004$). Participants that viewed a quantum physics explanation scored 1.171 points higher (on the five point scale) on general interest than the group of participants that had not viewed a quantum physics explanation. The explanation condition did not contribute significantly to the other models for information seeking, internal efficacy and perceived knowledge.

Thirdly, the benefit frame was found to be a significant contributor to the model for internal efficacy ($b = 1.060$, $p = 0.011$), while the risk frame did not significantly contribute to any of the four models. Furthermore, the score of the participants that received a balanced frame significantly dropped in comparison to participants that only read a risk or only read a benefit frame for perceived knowledge ($b = -1.040$, $p = 0.011$). None of the other engagement variables were significantly affected by the risk and/or benefit frames.

4.3 MANOVA

Finally, we tested whether the conditions correlated significantly with a linear combination of information seeking, internal efficacy, general interest and perceived knowledge, treated as a measure of public engagement. As shown in Table 3, the explanation condition correlated significantly (Pillai's trace = 0.028, $F(4, 626) = 4.491$, $p = 0.001$) whereas the other conditions did not.

5 Discussion

This study examined the effect of the enigmatic frame, the explanation frame, and the benefit, risk and balanced frames on the self-reported engagement with quantum technology. To the best of our knowledge, this is the first study that experimentally assessed the effect of these frames on quantum technology engagement.

Table 3 MANOVA model to test the effect of the conditions on a linear combination of the four engagement variables: information seeking, internal efficacy, general interest and perceived knowledge. *p*-Values in bold indicate significance at a level of <0.05

	Pillai	Approx. F	Num Df	Den Df	*p*-value
Enigmatic frame	0.010	1.622	4	626	0.167
Explanation frame	0.028	4.491	4	626	0.001
Risk frame	0.003	0.437	4	626	0.782
Benefit frame	0.003	0.477	4	626	0.753
Risk frame × Benefit frame	0.012	1.825	4	626	0.122

5.1 No effect of the enigmatic frame on engagement

First of all, we found that the enigmatic frame did not significantly affect any of the dimensions of engagement we studied. This is surprising, given that Vermaas, Coenen and colleagues argued that the frame would have negative implications for people's beliefs about their own ability to understand and engage with quantum technology [12, 13]. Apparently the frame is not as detrimental as expected for people's engagement with quantum technology. Our finding is encouraging, given the regular occurrence of the enigmatic frame in popular communication about quantum science and technology [14, 15].

It should be noted that participants in the enigmatic frame condition scored lower on all four dimensions of engagement than participants not in this condition, but these results are not statistically significant. As participants in the enigmatic frame condition were exposed to the frame only once, this raises questions about the possible effects of repeated exposure of the frame.

5.2 The explanation frame affects general interest

Secondly, we found that an explanation of a quantum physics concept increased participants' engagement and especially interest in quantum technology. Our finding is in line with the observation from Bobroff who noticed that people are fascinated by quantum physics concepts [26]. We conclude from this that the counter intuitiveness of these concepts do not have negative effects, but positively influence quantum technology engagement. Given that many experts [14] and journalists [15] explain at least one of the three concepts we included in our study – superposition, entanglement, and contextuality – in their popular communications, our finding is encouraging.

5.3 The benefit frame increases internal efficacy, whereas the balanced frame decreases perceived knowledge

Thirdly, the benefit frame had a positive effect on participants' internal efficacy. This result may align with the conclusion from the public dialogue exercise in the United Kingdon that discussing benefits raises participants' engagement and excitement about quantum technology as the personal relevance becomes clear [1]. Future research should investigate whether this is indeed the case and, if so, explore additional factors that help clarify the personal relevance of quantum technology.

We furthermore found that none of the engagement variables were significantly affected by the risk frame. This is similar to the findings from another study, where the risk frame did not significantly affect public engagement with nanotechnology [32]. Based on the RISP model [33], this may suggest that people do not perceive an information insufficiency regarding this topic, nor do they experience social pressure to learn more about quantum technology's risks. Future research could explore potential predictors underlying this finding (see [33]), such as individuals' perceived personal control and their affective responses to the risks.

Finally, considering the balanced frame, participants' perceived knowledge decreased significantly compared to participants exposed to either a benefit or a risk frame. The conflicting information provided may have created ambivalence about the societal impact of quantum technology, leading participants to doubt their own knowledge about this topic. In contrast to previous studies, the balanced frame did not increase information seeking [31] or interest in quantum technology [32]. However, the study in [32] noticed this slight positive effect in interest only for participants' who were open to considering new or inconsistent information. In our study, we did not look at effects from differences in personality traits, which may be a reason for this discrepancy. It would be interesting to explore the effects that factors other than frames, such as different personality traits, age, gender and science credibility, have on quantum technology engagement.

5.4 Limitations of this study

The lab setting of this study allowed us to accurately control the experiment. However, a translation of our experiment into a real-world setting would give better insights into real-life effects. Future studies could involve writing different news stories about quantum technology, each emphasizing a specific frame, and then tracking how readers respond to these articles. Another research idea is to develop different quantum technology outreach activities and test whether there are differences in participants' engagement in the activity. This way we could get a better understanding of how our controlled experiment compares to a real-world setting.

Our study used the scientific engagement measure outlined in [20], which includes the four variables: information seeking, internal efficacy, general interest and perceived knowledge. However, it can be argued that public engagement with science includes more elements, such as beliefs about science (e.g., [32]) and feelings of inspiration (e.g., [42]). Additionally, there are limitations to self-reporting, as participants may give socially desirable answers or assess themselves inaccurately. Therefore, future research should also measure actual behavioural engagement. For example, by including an option to receive additional information about quantum technology by clicking on a link, thereby measuring people's actual information-seeking behaviour.

Furthermore, consistent with our preregistration and based on the three potential issues highlighted in the literature (see Sect. 2.2), we focused on main effects and did not examine potential interactions between frames. Testing additional interactions could increase the risk of Type I errors (i.e., false positives) if conducted on the present data. We therefore suggest that future research explores possible interaction effects. For example, a respondent's reaction to a quantum physics explanation might differ depending on whether it was previously presented as enigmatic or not. Investigating such interactions could provide valuable insights into how the different potential issues influence each other.

Finally, our sample involved Dutch-speaking adults recruited by KiesKompas. This demographic scope could limit the generalizability of our findings to other cultural or linguistic contexts. Although there is some evidence that framing effects may be largely universal [43], to our knowledge, no papers have examined the effects of specific type of framing we studied across different cultural and linguistic contexts. Therefore, we advise future research to replicate our study in other countries.

5.5 Practical implications

In conclusion, our results give support to the following: communications that are effective in increasing engagement with quantum technology explain quantum physics concepts, emphasise the benefits, but avoid presenting both the benefits and risks. This conclusion leads to an interesting tension, as there have been pleas for media coverage to provide sufficient attention on both the benefits as well as the risks of quantum technology (see [8]). Widely reflecting on both the benefits and risks of quantum technology is important to ensure quantum technology will mostly bring public benefit [8]. In our opinion, this ethical consideration outweighs the fact that a balanced frame leads to a decrease in the perceived knowledge dimension of engagement. Therefore, we would still advise science communicators to present both the benefits as well as the risks of quantum technology.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1140/epjqt/s40507-026-00549-0.

Additional file 1. Data collected in this study (XLSX 476 kB)
Additional file 2. Code used for data analysis in R (R 5 kB)
Additional file 3. Appendices as referred to in the manuscript text (DOCX 33 kB)

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Author contributions
AM: Contributor roles: conceptualization, data curation, formal analysis, investigation, project administration, validation, writing - original draft preparation, writing - review & editing. CA: methodology, formal analysis, validation, writing - review & editing. PV: conceptualization, investigation, writing - review & editing. IS conceptualization, investigation, supervision, writing - review & editing. JC: conceptualization, funding acquisition, investigation, supervision, writing - review & editing.

Data availability
The author confirms that all data generated or analysed during this study are included in this published article. (will be made available when published).

Declarations

Competing interests
The authors declare no competing interests.

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