In a state of superposition: exploring (in)effective public communication about quantum technology

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CHAPTER 4

The Effect of Frames on Engagement with Quantum Technology

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Abstract

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.

4.1 Introduction

Quantum technology is an emerging technology which encompasses technologies like quantum computing, quantum networks and quantum sensors. All of these 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 (Busby et al., 2017; Outeiral et al., 2021), providing secure communication as a defence against hacking threats (Vermaas et al., 2019; Wehner et al., 2018), and identifying risks to ground conditions through accurate sensing (Stray et al., 2022). Examples of negative effects include concerns about how criminal organisations may use this technology (Busby et al., 2017; Vermaas et al., 2019), as well as unequal access to the technology depending on where you live (Ten Holter et al., 2022). Ten Holter et al. (2022) argue 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.

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 (Roberson, 2021). 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 (Roberson et al., 2021), and it could also lead to more public support and less public opposition (Kurath & Gisler, 2009; Mooney, 2010; Roberson et al., 2021). Moreover, citizens should be given the opportunity to participate from a democratic perspective, as this technology can significantly affect citizens' lives (Van Dam et al., 2020).

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 (Coenen et al., 2022; Vermaas, 2017).

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 (see Chapters 2 and 3). 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.

4.2 Theory

4.2.1 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 (Kurath & Gisler, 2009). According to Kurath & Gisler's (2009) historic overview, 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 (Van Dam et al., 2020).

Science communication scholars have since advocated moving to public engagement models (also called "upstream engagement"; Kurath & Gisler, 2009; Mooney, 2010; Rogers-Hayden & Pidgeon, 2007; Van der Sanden & Meijman, 2008), but this remains challenging. The domain of science and technology is alienating for some people (Brooks, 2017; Druckman & Bolsen, 2011), which hinders engagement. For example, Brooks (2017) found through a qualitative thematic analysis on students' reflective writings that a lot of the students thought science was inaccessible. 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, but in our study, we have decided to adopt the scientific engagement measure outlined by Shulman et al. (2020). They found that avoiding jargon has a positive indirect effect on participant's self-reported scientific engagement, which they measured via four variables. They assessed participants' intentions to seek additional information on the scientific technologies presented (self-driving cars, medical printers and robot surgeons), their beliefs about their own ability to understand and engage with information about the scientific technologies, their general interest in them, and their confidence in their knowledge of the scientific technologies. In this way, four different dimensions of scientific engagement were examined: information seeking, internal efficacy, general interest and perceived knowledge.

4.2.2 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” (Entman, 1993, p 52). By emphasising only some aspects while ignoring other parts of certain information, frames can influence how audiences interpret and perceive that information (Entman, 1993).

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 (Coenen et al., 2022; Vermaas, 2017); 2) not explaining the underlying quantum phenomena when explaining quantum technology, thereby leaving the technology as a black box (Grinbaum, 2017); 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 (Roberson et al., 2021); and 4) a strong focus on quantum computing at the expense of other quantum technologies (Roberson et al., 2021)[1]. In Chapters 2 and 3, we quantified the occurrence of these potential popularisation issues in English TEDx talks and Dutch newspaper articles, and found that all four issues are present to varying degrees in both datasets. Therefore, it is important to investigate whether these potential issues genuinely hinder public engagement.

4.2.3 The enigmatic frame

The first frame we studied is the enigmatic frame. According to Coenen et al. (2022) and Vermaas (2017), the enigmatic frame could make the domain of quantum technology unapproachable for non-specialist audiences. 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. Based on these two works, the enigmatic frame is therefore considered to mainly affect the internal efficacy dimension of engagement.

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.

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[1] To keep the design of the experiment feasible, we did not investigate the latter potential issue in the present study. However, we recommend that future research examine the effect of focusing exclusively on the possible impact of the quantum computing and simulation domain vs focusing on the possible impact on the full quantum technology domain on engagement.

However, the frame is clearly visible: in both English TEDx talks (Chapter 2) and Dutch newspaper articles (Chapter 3) 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.

4.2.4 The explanation frame

Secondly, we examined the effect of the explanation frame on engagement with quantum technology. Grinbaum (2017) 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. 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; Griffiths, 2014; Nielsen & Chuang, 2010). Entanglement means that particles share a state, making it no longer appropriate to refer to those particles as separate (Griffiths, 2014; Nielsen & Chuang, 2010). 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 G. Jaeger, 2019). According to Grinbaum (2017), not explaining these features leads to several weaknesses. 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 by Shulman et al. (2020), such a lack of transparency has the potential to undermine 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. Working on over a hundred outreach projects about quantum and solid-state physics, Bobroff (2017) observed that people are often fascinated by the underlying theory and not just by potential applications. This suggests that the explanation frame could positively influence the general interest dimension of engagement. However, since Bobroff's (2017) insight 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 phenomena may actually reduce engagement by lowering people's internal efficacy. As quantum phenomena are counterintuitive to everyday experiences, such explanations may alienate people in a similar way as the enigmatic frame (see section 4.2.3; Coenen et al., 2022; Vermaas, 2017). 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. This is "genuine quantum weirdness", according to Van Wezel et al. (2023). 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 phenomena such as superposition, entanglement, and contextuality (Chapters 2 and 3). This makes it particularly relevant to investigate how the presence or absence of an explanation frame affects public engagement.

4.2.5 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 et al. (2021) have emphasized the need for widely reflecting on how quantum technology may impact society. 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 (Chapters 2 and 3). Since this contradicts what Roberson et al. (2021) argues for, 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 (Druckman & Bolsen, 2011), carbon nanotubes (Druckman & Bolsen, 2011), artificial intelligence (Palm et al., 2025), hydrogen technology (Achterberg, 2014), and nanotechnology (Cobb, 2005). 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 from Shulman et al. (2020) 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 and general interest. For instance, Anderson et al. (2013) found that highlighting both the potential benefits and risks of nanotechnology increased participants' feelings that they needed more information before making decisions about nanotechnology. 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, Retzbach and Maier (2015) 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.

Furthermore, qualitative evidence suggests that emphasizing the benefits of quantum technology can increase engagement, specifically through an increase in interest. 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 (Busby et al., 2017). 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. 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; Griffin et al., 1999). 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 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.

4.2.6 Research questions

As introducing public engagement in an early phase of a technology's development is important (Kurath & Gisler, 2009; Mooney, 2010; Priest, 2010), 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 (Stichting Quantumdelta NL, 2020). Moreover, the Dutch public is likely to encounter the frames under investigation, as they already appear in varying degrees in their national newspapers (Chapter 3).

Our study aims to answer the following research questions:

> *Research Question 1*: Does the enigmatic frame influence the self-reported engagement with quantum technology?
>
> *Research Question 2*: Does the explanation frame influence the self-reported engagement with quantum technology?
>
> *Research Question 3*: Does the benefit, risk and balanced frames influence the self-reported engagement with quantum technology?

4.3 Method

Following our research questions, we used a survey design in which participants were randomly assigned in a 2 (enigmatic, not enigmatic) x 2 (explanation, no explanation) x 4 (none, benefit, risk, balanced) between-subjects 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 (https://osf.io/h6b7s). The Ethics Review Committee of the Faculty of Science, Leiden University gave ethical approval to conduct the study (reference number 2023 – 02).

4.3.1 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 Table A15 in the Appendix. Jargon terms such as superposition, entanglement and contextuality were avoided (as jargon has been found to hinder engagement; Shulman et al., 2020).

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.

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 (Slater et al., 2015). 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 phenomenon on participants' engagement, rather than the effect of a certain phenomenon or a certain type of explanation. We designed six different messages that explained a quantum phenomenon: 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 (Kristensen et al., 2021). Afterwards, we collapsed the results.

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; Busby et al., 2017).

4.3.2 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 of Shulman et al. (2020) such that all of the statements referred to quantum technology instead of science and technology in general. The statements per variable can be found in Table A16 in the Appendix.

Our quantum technology engagement measure consisted of 16 statements which participants were asked to answer to on a 5-point Likert scale (ranging from strongly disagree – strongly agree). The first variable assessed whether participants intended to seek out more information about quantum technology in the future (information seeking, a 3-item scale, Cronbach's α = 0.94). The second measure assessed whether participants' believed that they can understand and engage with information about quantum technology (internal efficacy, a 4-item scale, Cronbach's α = 0.859). The third measure was to assess participants' interest toward quantum technology (general interest, a 6-item scale, Cronbach's α = 0.892). And fourthly, we were interested in the confidence that the participants have about their own quantum technology knowledge (perceived knowledge. This scale originally had 4 items, with Cronbach's α = 0.446. A leave-one-out-analysis (cf. Nunnally, 1978) showed that the 3 item scale with items 1, 2 and 4, performed considerably better, Cronbach's α = 0.848, thus we work with these three items).

4.3.3 Analysis and statistical procedures

Data were analysed with R (version 4.2.2 RStudio Team, 2022). To evaluate the effects of the different conditions, we conducted a linear multiple regression analysis with dummy variables. We tested for main effects and did not analyse possible interactions. The model was run for each engagement variable: information seeking, internal efficacy, general interest and 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 $p < 0.0125$ (based on an α level of 0.05 and a Bonferroni correction for multiple testing). We also conducted a MANOVA to test the effect of the conditions on a linear combination of information seeking, internal efficacy, general interest and perceived knowledge, treating this as an overall measure of public engagement.

4.4 Results

4.4.1 Descriptives

The survey ran between May 16th and May 23rd 2023 and resulted in a total sample of n = 649 Dutch-speaking adults. The median time to complete the survey was 3

Table 4.1

Number of participants in each condition before and after weighting.

	Unweighted		Weighted	
Condition	Did not read frame	Read frame	Did not read frame	Read frame
Enigmatic frame	321	316	308.655	323.328
Explanation frame	319	318	318.180	313.804
Risk frame	309	328	294.669	337.314
Benefit frame	319	318	324.853	307.131

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 4.1 shows the number of participants that were assigned to each condition in the 2 (enigmatic, not enigmatic) x 2 (underlying explanation, no underlying explanation) x 4 (none, benefit, risk, balanced) design for the unweighted and weighted data.

4.4.2 Significant contributors to the regression models

The results of the regression models for information seeking, internal efficacy, general interest and perceived knowledge are shown in Table 4.3. 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.

4.4.3 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 4.5, the explanation condition correlated significantly (Pillai's trace $= 0.028$, $F(4, 626) = 4.491$, $p = 0.001$) whereas the other conditions did not.

4.5 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.

4.5.1 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 Coenen et al. (2022) and Vermaas (2017) argued that the frame would have negative implications for people's beliefs about their own ability to understand and engage with quantum technology. 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 (Chapters 2 and 3).

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 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.

Table 4.3

*Multiple linear regression analysis of the experimental conditions per outcome variable. p-Values in **bold** indicate significance at a level of <0.0125.*

				Information seeking
	Estimate	Std. error	t-value	p-value
Intercept	7.624	0.320	23.793	**<0.001**
Enigmatic frame	-0.412	0.251	-1.640	0.101
Explanation frame	0.258	0.251	1.027	0.305
Risk frame	0.310	0.352	0.880	0.379
Benefit frame	0.699	0.368	1.899	0.058
Risk frame × Benefit frame	-0.850	0.504	-1.687	0.092
				Internal efficacy
	Estimate	Std. error	t-value	p-value
Intercept	8.527	0.362	23.581	**<0.001**
Enigmatic frame	-0.527	0.283	-1.858	0.064
Explanation frame	0.310	0.284	1.091	0.276
Risk frame	0.542	0.397	1.366	0.173
Benefit frame	1.060	0.415	2.552	**0.011**
Risk frame × Benefit frame	-1.392	0.569	-2.449	0.015
				General interest
	Estimate	Std. error	t-value	p-value
Intercept	17.669	0.522	33.867	**<0.001**
Enigmatic frame	-0.774	0.409	-1.892	0.059
Explanation frame	1.171	0.409	2.861	**0.004**
Risk frame	0.626	0.573	1.093	0.275
Benefit frame	0.916	0.599	1.529	0.127
Risk frame × Benefit frame	-1.132	0.820	-1.380	0.168
				Perceived knowledge
	Estimate	Std. error	t-value	p-value
Intercept	6.003	0.259	23.142	**<0.001**
Enigmatic frame	-0.142	0.203	-0.698	0.486
Explanation frame	-0.042	0.203	-0.206	0.837
Risk frame	0.344	0.285	1.208	0.227
Benefit frame	0.673	0.298	2.259	0.024
Risk frame × Benefit frame	-1.040	0.408	-2.549	**0.011**

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

Table 4.5

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

4.5.2 The explanation frame affects general interest

Secondly, we found that an explanation of a quantum phenomenon increased participants' engagement and especially interest in quantum technology. Our finding is in line with the observation from Bobroff (2017) who noticed that people are fascinated by quantum phenomena. We conclude from this that the counterintuitiveness of these phenomena do not have negative effects, but positively influence quantum technology engagement. Given that many experts (Chapter 2) and journalists (Chapter 3) explain at least one of the three phenomena we included in our study - superposition, entanglement, and contextuality - in their popular communications, our finding is encouraging.

4.5.3 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 (Busby et al., 2017). 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 in Retzbach & Maier's (2015) study, where the risk frame did not significantly affect public engagement with nanotechnology. Based on the RISP model (Griffin et al., 1999), 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 Griffin et al., 1999), 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 (see Anderson et al., 2013) or interest (see Retzbach & Maier, 2015) in quantum technology. However, Retzbach and Maier (2015) 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.

4.5.4 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 Shulman et al.'s (2020) scientific engagement measure, 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., Retzbach & Maier, 2015) and feelings of inspiration (e.g., VanDyke & Yeo, 2024). 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.

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. Therefore, we advise future research to replicate our study in other countries.

4.5.5 Practical implications

In conclusion, our results give support to the following: communications that are effective in increasing engagement with quantum technology explain quantum phenomena, 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 Roberson et al., 2021). Widely reflecting on both the benefits and risks of quantum technology is important to ensure quantum technology will mostly bring public benefit (Roberson et al., 2021). 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.